Simulating Academic Entrepreneurship and Inter-Organisational Collaboration in University Ecosystems: A Hybrid System Dynamics Agent-Based Simulation

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Declaration of Authenticity

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Abstract

Universities are increasingly expected to actively contribute to socio-economic development. Academic entrepreneurship and the evolution of the entrepreneurial university within ecosystems have received increasing attention from both policy makers and academic communities over the last decades. However, most studies on universities' external engagement have focused on individual activities and single universities, hereby neglecting the feedback effects between different activities and how universities are linked through an overlap of their ecosystems. The result is an incomplete understanding of how universities interact with their ecosystem and the resulting inter- and intra-organisational dynamics. This research addresses this issue by developing a hybrid system dynamics agent-based model, which captures feedback structure and the internal decision-making of universities and companies. Both the conceptual and simulation model are based on a triangulation of the literature, interviews with representatives of Scottish universities, and secondary data for Scottish universities and UK businesses.

This research makes several theoretical, methodological, and empirical contributions. From a theoretical perspective, it contributes in two distinct ways to the field of entrepreneurship by defining university ecosystems in new way that provides a basis for future research and developing a multi-modal simulation model that can be applied in tested in different contexts. The methodological contributions to the field of modelling and simulation in management science include a modelling process for hybrid simulations, new practices for modelling the size of agent populations through different designs of stocks and flows in the system dynamics module in hybrid simulations, and complex events for recognising emergent behaviour. Lastly, this research makes two empirical contributions to the field of entrepreneurship. This research shines a light on the dynamics of academic entrepreneurship and how universities can partially overcome a low research prestige to increase academic entrepreneurship. Implications for policy and practice are outlined and opportunities for future research conclude this thesis.

The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe.

— P. W. Anderson (1972),
More is Different, *Science, 177*(4047)

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List of Abbreviations

ABM	Agent-based modelling
BE	Business ecosystem
CE	Complex event
CLD	Causal loop diagram
CR	Critical realism
CS	Complex system
DEL	Department for Employment and Learning in Northern Ireland
DES	Discrete event simulation
DT	Delta time
EE	Entrepreneurship ecosystem
EPSRC	Engineering and Physical Sciences Research Council
ESRC	Economic and Social Research Council
EU	European Union
FTE	Full-time equivalent
GIS	Geographic information system
HE-BCI	Higher Education - Business and Community Interaction Survey
HEFCE	Higher Education Funding Council England
HEFCW	Higher Education Funding Council Wales
HEI	Higher education institution
HESA	Higher Education Statistics Agency
HPC	High-performance computing
HS	Hybrid simulation
IE	Innovation ecosystem
IP	Intellectual property
KE	Knowledge ecosystem
MP	Modelling process
MS/OR	Management science and operational research
M&S	Modelling and simulation
NUTS	Nomenclature of Territorial Units for Statistics

OECD	Organisation for Economic Co-operation and Development
PDRA	Post-doctoral research assistant
R&D	Research and development
RBV	Resource-based view (of the firm)
REA	Research Excellence Assessment
REAP	MIT Regional Entrepreneurship Acceleration Program
REF	Research Excellence Framework
SD	System dynamics
SE	Simple event
SFC	Scottish Funding Council
SFD	Stock and flow diagram
SKIN	Simulating Knowledge Dynamics in Innovation Networks model
SME	Small and medium-sized enterprise
STI	Science, technology and innovation
THE	Times Higher Education
TTO	Technology transfer office
UE	University ecosystem
UI	University-industry
UK	United Kingdom
USA	United States of America
V&V	Verification and validation
WOM	Word-of-mouth (marketing)

Chapter 1

Introduction

1.1 Introduction

Universities are increasingly expected to actively contribute to socio-economic development. This thesis is the result of an exploratory research project to provide a new perspective on the dynamics of universities' external engagement. The aim of this chapter is to introduce the research project, including the motivation (Section 1.2), aim of the research and research questions (Section 1.3), the methodological approach and how these questions were addressed (Section 1.4), as well as an overview of the contributions of this work (Section 1.5). The chapter will conclude with an overview of the structure of this thesis (Section 1.6).

1.2 Research Motivation

Universities' engagement with the public and private sectors has gained increasing attention from both researchers and policy makers (Grimaldi et al., 2011). Over the past decades, emphasis has shifted from commercialisation activities to a wider range of activities as well as from a selected few successful universities to institutions across the whole spectrum from teaching-focus to research-intensive in a variety of environments, form rural areas to metropolitan areas and technology hotspots (Abreu & Grinevich, 2013; Perkmann et al., 2013). As a result, there is consensus that universities play an important role for innovation and socio-economic development (Guerrero et al., 2015; Saxenian, 1994; Shane, 2004a; Slaughter & Leslie, 1997). Furthermore, the roles and responsibilities of individuals, organisations, and institutions at different levels of aggregation, from individual academics, support services within universities and inter-organisational collaborations across geographical scales to regional and national institutions, have been closely examined.

However, there is a lack of understanding of the dynamic nature of the interaction of universities with their external environment. While our understanding of individual parts and aspects of these interactions is growing, most studies have investigated them in isolation. It is commonly concluded that actors and factors are interconnected, without providing an explanation of what this means. Some studies go even further and see this interconnectedness as a limitation due to the reductionist nature of the research. A variety of concepts have been presented in the literature in response to this issue, including *path dependency* (Krücken, 2003), *emergence* (Fritsch & Aamoucke, 2013; Garnsey & Hefferman, 2005; Youtie & Shapira, 2008), *embeddedness* (Casper, 2013; Chen & Kenney, 2007; Huggins, 2008; Lambooy, 2004), *complex networks, relationships, and patterns* (Azagra-Caro et al., 2017; Markman, Phan, et al., 2005; Miller, McAdam, & McAdam, 2018; Schartinger et al., 2002), *non-linearity* (Gur et al., 2017), *interdependence and multicolinearity* (Zucker et al., 2002), *complex social ecology* (Tuunainen, 2005), *co-evolution of elements or institutions* (Etzkowitz & Leydesdorff, 2000; Martin, 2012; Lawton Smith & Leydesdorff, 2014; Lehmann & Menter, 2016), or *triple helices* (Leydesdorff & Etzkowitz, 1996, 1998), to name a few.

The *ecosystem* concept is the latest in line that uses an analogy to complex systems, but is – like the previously listed concepts – mostly used metaphorically (Hayter et al., 2018; Siegel & Wright, 2015a; Stam, 2015). The interdependencies and feedback effects between different levels of aggregation (e.g. the individual researcher, the university, and the ecosystem) and different types of interaction are still unclear. There is a need for studying the link between the internal dynamics and resource allocations within universities, different types of entrepreneurial activities ('academic entrepreneurship'), their impact on businesses and the ecosystem, and how these outcomes in turn influence the behaviour of universities.

1.3 Aim and Research Questions

The aim of this research is to provide insights into the dynamics of academic entrepreneurship and the evolution of the university ecosystem. This approach is distinct to other prior research as complexity is a prerequisite and not a limitation, which sees universities as part of a larger system and explicitly models feedback and links levels of aggregation (i.e. decision-making and resource allocation within universities and companies, interactions at the organisational level, and systemic outcomes). The result is a more nuanced and multi-faceted understanding of the ramifications of academic entrepreneurship for universities, companies, and ecosystems. More precisely, this thesis will address the following research questions:

1. What is the dynamic relationship between universities' internal capabilities and resources (organisational arrangements), the volume and share of different entrepreneurial activities, and the evolution of the university ecosystem?

2. Is there a path dependency for universities based on different research and entrepreneurial profiles, resource endowments, historical backgrounds?

3. What are the temporal dynamics of different entrepreneurial activities in the evolution from ad hoc interactions to strategic partnerships between universities and firms?

4. What are the co-evolutionary dynamics between a university's research prestige, entrepreneurial reputation, organisational proximity, and social capital and how does this affect a university's entrepreneurial performance?

1.4 Methodological Approach

This study is based on complex systems and is rooted in the critical realist paradigm, which is centred around an objective reality that is shaped and perceived differently by different people based on their background, experiences, and other characteristics (Fleetwood, 2005). In line with this philosophical foundation, this research uses the ecosystem framework for a comprehensive view on society that bridges the functionalist (co-evolution and consensus) and radical structuralist (inequality and radical change) perspectives into a coherent theory of society as a complex system (Drazin, 1990; van den Berghe, 1963).

Based on this foundation, a model was developed that incorporates the defining characteristics of an ecosystem and can simulate the dynamics of academic entrepreneurship. System dynamics and agent-based modelling are widely used approaches to model complex systems in management science. Either method could be applied individually, but both excel at different parts of the research project and neither provides an ideal approach to this problem on its own (agent-based modelling is superior for Q3 and Q4, while system dynamic is superior for Q1 and Q2). Therefore, a hybrid simulation is developed that uses system dynamics and agent-based modelling for different parts of the model and combines their respective strengths.

This hybrid simulation approach is then tested based on the interaction of Scottish universities and UK businesses. A variety of data sources were used within the model development process, including a review of the literature; interviews with representatives of university senior management, technology transfer office (TTO) directors, and TTO staff; as well as secondary datasets on universities and UK companies. Triangulating all these sources has led to a comprehensive understanding of the causal mechanisms and enabled the parametrisation of a simulation model to experiment with different scenarios.

1.5 Contributions

This thesis makes several theoretical, methodological, and empirical contributions. From a theoretical perspective, this research contributes in two distinct ways to the field of entrepreneurship by conceptualising university ecosystems and developing a simulation model that can be applied in tested in different contexts. The novel conceptualisation of university ecosystems incorporates recent advances from a number of different systems of innovation/entrepreneurship. The aim is not to replace these concepts but to provide a foundation for synthesizing findings and further research. The simulation model focuses on the interplay between different entrepreneurial activities, research prestige, the universities entrepreneurial reputation and social capital. Many of these issues have been studied in isolation, thereby neglecting the feedback effects between them.

From a methodological perspective, the contribution of this research to the field of modelling and simulation in management science is threefold. In particular, this includes a modelling process for hybrid simulations with a focus on combining system dynamics and agent-based modelling; new practices for modelling the size of agent populations through different designs of stocks and flows in the system dynamics module in hybrid simulations; and complex events for recognising emergent behaviour in agent-based modules. While many categorisations of hybrid simulations have been developed, the role of feedback between different modules of a hybrid simulation and, therefore, different levels of aggregation, as well as emergent behaviour has not yet been addressed. This is the key to advance the use of hybrid simulations for modelling complex systems and this framework could be used for a variety of other problems.

Lastly, this research makes two empirical contributions to the field of entrepreneurship. Through triangulating primary and secondary data, this research shines a light on the dynamics of academic entrepreneurship and how universities can partially overcome a low research prestige to increase academic entrepreneurship. The former highlights that entrepreneurial activities should be seen as "mechanisms" and means of knowledge dissemination and exchange as opposed to targets in themselves. The latter shows how research-intensive universities benefit from the halo that is based on their reputation and research prestige, but also the tremendous opportunities for other universities to counter this by developing an entrepreneurial reputation.

1.6 Structure of the Thesis

This thesis is a monograph that consists of eight chapters as illustrated in Figure 1.1. To conclude this introduction, this final section provides a short summary of each chapter.

In *Chapter 2*, a comprehensive review of academic entrepreneurship in university ecosystems is provided. First, a new conceptualisation of university ecosystems is developed from an inter-organisational perspective, grounded in advancements in the knowledge and entrepreneurial economy as well as complexity economics. Within this framework, the entrepreneurial university is discussed with a focus on five formal entrepreneurial activities (licensing, spin-offs, consulting, contract and collaborative research), the drivers and implications of interactions with industry, and the decision-making processes of companies. The chapter concludes with a description of the gap in the literature and the research questions for this study.

In *Chapter 3*, the concept of complex systems is introduced and system dynamics and agent-based modelling are presented as potential methods to simulate academic entrepreneurship. In this particular case, neither method is sufficiently suited to answer the research questions and a hybrid simulation framework is developed. Answering the research questions requires the explicit recognition of emergent behaviour in the hybrid simulation, an issue that has not yet been addressed properly in the literature. Complex events are proposed as a mechanism to overcome current limitations.

Existing model development processes are reviewed in *Chapter 4* and a tailored modelling process for this thesis is presented subsequently. In the following, the philosophical and methodological foundations for this research are described. This study takes a critical realist perspective and shows, how a complexity approach in combination with a critical realist perspective can be used to combine a functionalist and radical structuralist approach to social science research. A particular focus of this chapter is the way information is gathered and how insights from interviews, secondary data, and the literature are triangulated throughout the model development process. This chapter sits outside the flow of the remaining chapters of this thesis as illustrated in Figure 1.1 as it links the modelling process, philosophical foundation, and data collection to the other chapters.

The conceptual model is described in *Chapter 5*, including the main assumptions of the model and the feedback structure of the system dynamics modules in the form of a causal loop diagram and the characteristics and rules of the company agents as part of the agent-based module. These structures are based on and supported by the previously described data triangulation.

In *Chapter 6*, the conceptual model is transformed into a simulation model and the parametrisation as well as the coding of the simulation and output analyses are described. After running the baseline scenario and performing sensitivity analyses on the relevant parameters, the model is used for experimentation with four different scenarios that were derived from the interviews and the results are presented.

The results from the simulation are discussed and contextualised in light of the research questions in *Chapter 7*. Furthermore, learning from the modelling process itself is described, including discrepancies between the literature, secondary data, and the interviews that were conducted for this thesis, as well as learning about the modelling process.

Lastly, a summary of the research is provided and the contributions to the fields of management science and entrepreneurship are summarised in *Chapter 8*. To conclude this thesis, the limitations of this research and opportunities for future research are outlined.

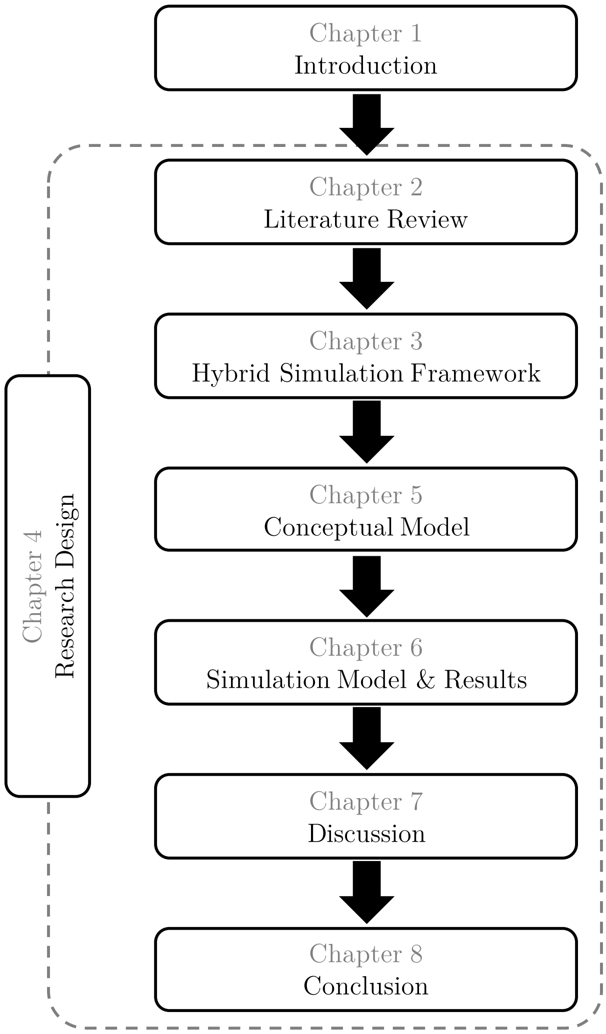


Figure 1.1: Structure of this thesis

Chapter 2

Academic Entrepreneurship in University Ecosystems

2.1 Introduction

Universities are no longer isolated ivory towers of knowledge production but are increasingly expected to provide “a wider social and economic benefit to the university ecosystem” (Siegel & Wright, 2015a, p. 585). While a growing body of research has aimed to address this issue, there is still no unifying explanation or model of the mechanisms that drive the interactions of universities with other actors and the resulting implications and feedback effects. This chapter starts conceptualising university ecosystems as a response to macro-level trends (Section 2.2). Adapted from complex systems, an ecosystem perspective allows to simultaneously account for different levels of aggregation (national, regional, institutional, and individual factors), heterogeneity among different actors, and their relationships (Grimaldi et al., 2011; Wright, 2014; Murray & Kolev, 2015).

Within this ecosystem framework, entrepreneurial universities are defined at the institutional (micro) level and how they engage with other ecosystem actors, with a particular emphasis on how these entrepreneurial activities manifested themselves in the university structure and its culture (Section 2.3). The chapter then discusses the relationships between universities and companies, emphasising the role of organisational proximity and social capital within ecosystems and the implications for universities (Section 2.4). Key internal and external drivers are considered, which initiate these relationships (Section 2.5) and link the university perspective to the industry perspective of the partnering company (Section 2.6). Lastly, the body of literature presented in this chapter is discussed in light of the nature of the research in this field (Section 2.7). To conclude, the gap in the literature is summarised and the research questions for this study are presented (Section 2.8).

2.2 Development of the Ecosystem Perspective

The aim of this section is to provide a theoretical foundation for *university ecosystems* and define them based on both inter- and intra-institutional dynamics. First, the ecosystem concept as well as existing applications in the areas of business, innovation, and entrepreneurship will be discussed before the focus turns to the role of universities and their ecosystems, which are essentially a combination of other ecosystem concepts.

2.2.1 The Ecosystem Concept

The term ecosystem originated in the area of ecology and can be described as "a biotic community, its physical environment, and all the interactions possible in the complex of living and nonliving components" (Acs et al., 2017, p. 2, based on Tansley, 1935). A wide range of ecosystem concepts have been developed in the areas of management and entrepreneurship that incorporate aspects from the knowledge and entrepreneurial economy as well as complexity economics with its focus on the self-organising interactions of heterogeneous agents. This section will review the different ecosystems concepts, which interactions and dynamics they explain as well as their limitations.

Ecosystems were first introduced to the management and strategy literature two decades ago as *business ecosystems* (BE) (Moore, 1993, 1996). BEs create leverage, either via innovation, production, transaction, or any combination of these three (Thomas et al., 2014) and can be "as small as the group of businesses and individuals on which the survival of a nine-square-meter mama shop in Singapore's high-rise apartment block depends, or as big as the Chinese business ecosystem" (Li, 2018). Three other ecosystem concepts have emerged that are linked to, but distinct from the BE concept due to a focus on either a central actor or certain activities or functions (Li, 2018; Radziwon & Bogers, 2019): innovation ecosystems (IE) (Adner, 2006; Adner & Kapoor, 2010), entrepreneurship ecosystems (EE)[1] (Isenberg, 2010), and knowledge-based ecosystems (KE)

[1] The terms entrepreneurial and entrepreneurship ecosystem are used interchangeably in the literature. For the sake of clarity, only the latter will be used in this thesis in line with the argumentation by Isenberg (2010).

(van der Borgh et al., 2012; Clarysse et al., 2014).[2] However, the boundaries between these four ecosystems concepts are not well-defined yet. For example, a BE that involves a significant amount of innovation is often referred to as an IE (van der Borgh et al., 2012; Li, 2018; Scaringella & Radziwon, 2018). Or the IE concept developed by Fiona Murray and Phil Budden at MIT would be classified as an EE by other scholars.

Applications of *IEs* focus on the dynamic behaviour of competition and collaboration in co-evolving technology intensive settings (Adner & Kapoor, 2010; Iansiti & Levien, 2004b). IEs are centred around certain platform technologies or products, resulting knowledge spillovers and general innovative behaviour of firms (which is where they overlap with e.g. platform ecosystems). They are not necessarily geographically bound and are in many cases international networks with a hierarchical structure, such as supply or value chains (Autio & Thomas, 2014). In addition to platforms or technologies, IEs can also be centred around a focal firm (Autio & Thomas, 2014). In any case, they integrate both the development/production side and the user side. The latter is, however, seen as an existing feature of the ecosystem, which represents a distinction to BEs, in which the customer/user needs to be approached and is not involved per se (Clarysse et al., 2014; Wright, 2014; Scaringella & Radziwon, 2018). IEs focus less on the demand aspect of customers (in contract to BEs) and more on the opportunities for co-creation with customers and users instead (Wright, 2014).

KEs are formed by "users and producers of knowledge that are organized around a joint knowledge search" (Järvi et al., 2018, p. 1). These users and producers include high-tech and R&D-intensive companies as well as universities and other research institutions that rely on each other's input to increase the effectiveness and efficiency of the knowledge search (Iansiti & Levien, 2004a; van der Borgh et al., 2012). A differentiation needs to be made between KEs "searching for a knowledge domain" and those "searching within an identified knowledge domain" (Järvi et al., 2018, p. 2). The aim of the KE is to foster knowledge creation through facilitating complementarities and enabling synergies rather than direct customer value like in BEs or IEs (Clarysse et al., 2014). However, the formation of a BE that involves the acquisition and involvement of users/customer is often seen as a natural transition after the KE matures (Clarysse et al., 2014). KEs are often based on a particular technological problem or opportunity or a societal issue that the participants want to address (Dougherty

[2]Other types of ecosystems include service, digital, platform, software, and technology ecosystems (Benedict, 2018). These are not included as they are less defined and overlap to a great extent with the above-mentioned four ecosystem types (Scaringella & Radziwon, 2018).

& Dunne, 2011). They require, but can also be the consequence of, different actors operating in close geographical proximity, which needs to be higher compared to other types of territorial innovation systems such as clusters. KEs emerge in the high-tech area with state-of-the-art scientific input, which is not the focus of constructs like business parks, although these do have the required proximity (van der Borgh et al., 2012).[3]

A fourth major stream of ecosystem research has emerged in the field of entrepreneurship and regional economic development. Bahrami & Evans (1995) first introduced the ecosystem concept when describing entrepreneurial activity in Silicon Valley. Prahalad (2005) uses the term ecosystem without further clarification, but refers implicitly to the EE concept. There is still no commonly accepted definition of what an EE is (O'Connor et al., 2018), but a first definition by Cohen (2006, p. 3) describes EEs as "an interconnected group of actors in a local geographic community committed to sustainable development through the support and facilitation of new sustainable ventures" remains up-to-date. The concept is mainly used by practitioners as an approach to explain entrepreneurial activity within certain geographical boundaries (Stam, 2015) and a broader interest was sparked by the work of Isenberg (2010).

Similar to the previously described ecosystems, EEs involve a variety of stakeholders beyond entrepreneurs, such as support organizations, universities and other research and education institutions, policy makers, established businesses, financial institutions and investors, among others (Isenberg, 2010). A mature EE is more than an accumulation of these actors and evolves through supporting and reinforcing relationships between the material, cultural, and social attributes (Spigel, 2015). EEs, more than any other type of ecosystem, reflect the recognition of *context* in entrepreneurship and innovation (Welter, 2011), entrepreneurial innovation (Autio et al., 2014), and its importance for theory development (Zahra, 2007).

BEs, IEs, and particularly KEs can be initiated and do not exist *per se*. A common error in reasoning is that a city or region[4] also has to build an EE. Instead, an EE does exist but it might not be very active, productive, or efficient, and is, hence, not recognised (O'Connor et al., 2018). EEs cannot be built and

[3] The High Tech Campus Eindhoven (HTCE) is an example of a campus-based (and top-down designed) project that shares many of the characteristics of a KE (Romme, 2017).

[4] There is no consensus in the literature regarding the boundaries of an EE. The systems of entrepreneurship model is a national perspective that is based on the ecosystem concept (Acs et al., 2014). Particularly practitioner work also often refers to national or even global ecosystems, but the more appropriate level or analysis are cities or small regions (Isenberg, 2010; Spigel, 2015; Startup Genome, 2018).

only *nurtured* or *fostered* instead (Isenberg, 2016).

Much of the existing work has focused on identifying the existence of ecosystems and its components, without providing insights into the interactions of the actors and the environment and the resulting dynamic behaviour (Mack & Mayer, 2016; Hayter et al., 2018). As an example, studies at the regional (macro) level have shown that some regions such as Silicon Valley and Route 128 host a vital EEs and exhibit growth, while others struggle (Saxenian, 1994). Yet, micro-studies do not confirm these results and create a discrepancy between entrepreneurs' perceptions of the ecosystem and the support available to them and the objective amount of resources available. Possible reasons for this are the imperfect knowledge of entrepreneurs, i.e. they are not aware of all types of support that are available and points of contact are not clear, or certain types of support or investment do not exist. A comprehensive theory is missing, particularly for EEs, that "specifically addresses the complexity and emergence" (Roundy et al., 2018, p. 2). The limitations of the EE concept (and, by extension, other ecosystem types as well as models like the RIS) can be summarised in following five key issues (Alvedalen & Boschma, 2017, p. 887):

1. Studies have often focused on EEs in single regions or clusters, but lack a comparative and multi-scalar perspective.

2. The EE concept lacks a clear analytical framework that makes explicit what is cause and what is effect in an ecosystem.

3. While being a systemic concept, the EE has not yet fully exploited insights from network theory, and it is not always clear in what way the proposed elements are connected in an ecosystem (*i.e. the system boundaries*).

4. It remains a challenge, what institutions (and at what spatial scale) impact on the structure and performance of an EE.

5. The EE literature tends to provide a static framework taking a snapshot of ecosystems without considering systematically their evolution over time.

A promising approach to address these shortcomings is to view ecosystems through the lens of complexity theory (Roundy et al., 2018). While all ecosystem concepts share many of the ideas from complexity economics, their developments have seen little involvement of researchers from fields such as (evolutionary) biology, ecology, or complex systems in general (Mars et al., 2012). Table 2.1 summarises the features of complex systems based on the work by Chandra &

Table 2.1: Features of complex systems and EEs

Feature	Examples from other systems	Application to EEs
Network of actors	Birds in a flock, neurons in the brain, social insects, social groups, cars on the road	Entrepreneurs, SMEs and large firms, skilled workers, support programs, investors, customers, and universities, among others
Self-organization	Flocking of birds, social behaviour of insects, herding behaviour, markets	Adjustment of support programs, angel investments, re-cycling of knowledge and capital
Emergence	V formation of bird flocks, termite nests, traffic jams, central place hierarchies	Value creation for customers, economic growth, novel and temporally limited initiatives
Sensitivity to minor perturbations	Butterfly effects, tipping points	Cultural change through sharing success stories
Parallelism (simultaneous interactions among actors across the network)	Local interactions amongst ants in a nest, interactions among people in a crowd, cars reacting to each other on the road	Networks of entrepreneurs, investors, and other agents
Conditional acting (if X exists, do Y)	Ants responding to other ants and pheromone trails, cars responding to signs/traffic lights and other cars	Aspiring entrepreneurs react to success stories, investors are attracted by fast-growing companies, entrepreneurs use recommended accelerators and incubators
Top-down effects	Ants responding to the emergent physical structure of the nest, cars responding to a traffic jam	Policy adjustments, public funding for research and innovative ventures
Adaptation and evolution	Evolution of ant species to different environments, people using alternative forms of transportations and driverless cars	Network evolution, adaptation of business models to technological change such as blockchain, attracting different types of talent, evolution of support programs

Wilkinson (2017), Holland (1995), and Mitchell (2011) and their relevance for EEs (as an example for the broader ecosystem approach) to underline the fit of this theoretical lens. A complex systems approach to ecosystems provides an opportunity to understand the mechanisms and their dynamics that create vital ecosystems in order to overcome the current issues.

Ecosystems comprising universities, companies, and other economic actors differ from biological ecosystems based on organisms, plants, or animals (Roundy et al., 2018). First, there is a misbelief that "biological ecosystems are both communal (supported by individual commitments to the greater good) and stable" (Mars et al., 2012, p. 279), which leads to the assumption that natural systems always experience stability as a result of the interaction of heterogeneous actors. This, however, guides the use of ecosystems as a metaphor and "simplistic explanations of economic and social evolution as a harmonious process of natural selection" (Papaioannou et al., 2009, p. 336).

On top of this, the ecosystem itself needs to be modified to account for the social complexity of innovative and entrepreneurial activity (Papaioannou et al., 2009). In contrast to organisms in biological ecosystems, economic actors (including universities and other non-profit organisations and governments), "can anticipate and even co-create their environment, making internal shifts to fit current or projected changes" (Levie & Lichtenstein, 2010, p. 336). This is a long-standing issue in organisational science and institutional theory. Behavioural rules are often rather rationalised myths (Meyer & Rowan, 1977) instead of actually being the cause for said behaviour (Weick, 1979). Therefore, the application of the ecosystem concept must focus on the mechanisms that govern the interaction and the decision-making of the involved agents.

2.2.2 Contrasting Ecosystems to Related Concepts

Systemic approaches are common in the area of regional development and a variety of "territorial innovation models" have been created (Moulaert & Sekia, 2003; Acs et al., 2017).[5] Table 2.1 provides an overview of the key concepts and their main characteristics. Most of the traditional approaches, much like the four types of ecosystems, are not well-defined and the boundaries are fuzzy, "despite some semantic unity among the concepts used (economies of agglomeration, endogenous development, systems of innovation, evolution and learning, network organization and governance)" (Moulaert & Sekia, 2003, p. 289).

EEs have been criticised for being industrial clusters or innovation districts in disguise (Stam, 2015; Scaringella & Radziwon, 2018). However, they are more than "old wine in new bottles" and have the potential to synthesize existing knowledge in the areas of innovation, entrepreneurship, and regional development, but also including social interactions and networks (Pugh, 2014; Stam, 2015). While all of these concepts share geographical proximity between actors as a similarity, ecosystems capture the co-evolution resulting from heterogeneous actors and their interdependencies based on cognitive proximity that are not included in this form in other models (Radziwon & Bogers, 2019). Universities (and other research institutes to some extent) are the main source of knowledge spillovers in clusters and regional/national innovation systems (Asheim & Coenen, 2005). Though these are important actors in ecosystems as well, the ecosystem concept explicitly involves other sources of knowledge and reciprocal knowledge flows between all actors (West & Bogers, 2014). Furthermore, ecosystems "consists of many informal structures and contractual agreements that are made possible due to high trust and relatively low transaction costs" (Radziwon & Bogers, 2019, p. 577). These informal and non-institutional relationships are less emphasised in e.g. regional or national innovation systems or clusters.

[5]Detailed comparisons of different models and discussions are provided by Moulaert & Sekia (2003), Acs et al. (2017), O'Connor et al. (2018), and Scaringella & Radziwon (2018).

Table 2.2: Comparison of territorial innovation models (adapted from O'Connor et al., 2018; Scaringella & Radziwon, 2018)

Model	**Territorial size**	**Key Actors**	**Key Concepts**	**Key Outcome**	**Key References**
Marshallian industrial districts	Small geographical area	SMEs	Labour market pooling; specialised goods and services; knowledge spillovers; market competition	Regional economic growth (productivity); competitiveness	Krugman (1991); Markusen (1996); Marshall (1920)
Italiante industrial districts	Geographic area	SMEs; local government	Flexible specialisation; inter-firm cooperation; trust (social extendedness)	Long-term regional economic growth (employment)	Becattini (1990); Harrison (1992); Piore & Sabel (1984)
Innovative Milieu	Limited geographical area	Innovative firms; universities	Emotional support of innovation; coopetition; culture; trust	Innovation; growing entrepreneurs; regional image; economic growth	Camagni (1995); Maillat (1995); Capello (1999); Crevoisier (2004)
Regional innovation system	Region	Large firms; start-ups; universities	Networks; inter-organisational learning; systems; similar norms and routines	Innovation; regional growth; economic performance	Cooke (1992, 2001); Cooke et al. (1997)
National innovation system	Country	Large firms; start-ups; universities; government	Networks; inter-organisational learning; knowledge flows; leverage points	Innovation and technical progress; economic performance	Braczyk et al. (1998); Freeman (1987); Lundvall (1992)
New industrial spaces	Region	Dominant firms; policy makers; universities	Economies of scale; local community dynamics; flexible production systems	Entrepreneurial initiatives; spin-offs; economic success	Saxenian (1994)
Learning region/ localised learning	Physical proximity	Firms; start-ups; market	Inter- and intra-regional learning	Innovative output	Florida (1995); Malmberg & Maskell (1997)
Cluster	City; region; country	Firms; start-ups; universities; market	Factor conditions; demand conditions; related and supporting industries; firm structure, strategy, and rivalry	National/regional competitiveness (productivity of particular industries)	Porter (1990, 1998)
Business ecosystem	Spatial or virtual proximity	Innovative firms; market	Coopetition; mutually influencing interactions	Value creation; innovation; competitive advantage; adaptation and evolution	Moore (1993, 1996); Iansiti & Levien (2004a,b); Li (2009)
Innovation ecosystem	Spatial or virtual proximity	Innovative firms; government; standard setters	Co-innovation; adoption chain; shared value proposition	Value creation and capture by the firms in the ecosystem; firm survival	Adner & Kapoor (2010); Nambisan & Baron (2013)
Knowledge ecosystem	Very confined space	R&D-intensive firms; start-ups; research institutions	Collective learning; mobility of personnel; local spillovers	Cross-realm transposition; knowledge; innovation	van der Borgh et al. (2012); Clarysse et al. (2014); Järvi et al. (2018)
Entrepreneurship ecosystem	City; region	Entrepreneurs; entrepreneurial firms; market; government	Mobility of entrepreneurs; symbiotic relationships; cross-sector fertilisation; complex networks	Radical innovation; GDP growth; venture creation; co-creation and evolution	Autio et al. (2014); Prahalad (2005); Isenberg (2010); Spigel (2015)

In conclusion, "ecosystem and [other] territorial approaches are two sides of the same coin: one broader side (entrepreneur, governance/orchestration, knowledge sharing, network/sharing tasks, complementary competencies, interdependence, coevolution, and co-creation) and one narrower inner side (territorial atmosphere, universities and research institutes, tacit knowledge, routine/path dependency, learning, social capital, agglomeration spillovers, and anchoring)" (Scaringella & Radziwon, 2018, p. 74). Ecosystems, particularly EEs (Stam, 2015) and IEs (Jacobides et al., 2018), have the potential to synthesise the existing literature and advance our understanding with their focus on the mechanisms that enable co-evolution and co-creation, respectively. The remainder will use the ecosystem concept as a basis, informed by insights from other models of innovation.

2.2.3 Rethinking the Role of Universities

In the Solow economy, which was based on capital and (mostly unskilled) labour, the contribution of universities to economic development was limited (Audretsch, 2014). Universities were also influenced by Humboldt and the ideal of free thinking, developing into places of intellectual exchange, without any expectations of direct contributions to the economy (Audretsch, 2007). With the rise of the knowledge economy, the importance of universities as producers of knowledge rose (Romer, 1994). In addition to the need of increasingly skilled labour, universities were commissioned to conduct research with commercial applications (Audretsch, 2014). An example are the land grant universities in the U.S. that were established with a focus on mechanical engineering and agriculture (Audretsch, 2007, 2009).

Today, universities are an integral part of economic development and regional competitive advantage (Goddard & Chatterton, 1999), although there is still an ongoing debate and some misconceptions regarding *how* they contribute (Laursen et al., 2011). This is also reflected in the more or less prominent role that they play in the different territorial models of innovation. The most important means is, indisputably, the provision of human capital through the production of graduates (see e.g. Florida, 1999; D'Este & Patel, 2007). This is also reflected in the IE literature (see e.g. Carayannis & Campbell, 2009) and even more explicit in the EE literature via the *human capital* pillar (Isenberg, 2010), *worker talent* as part of the social attributes (Spigel, 2015), or *talent* as a systemic condition for ecosystems (Stam, 2015), among others.

Universities are expected to support industrial innovation through both basic and applied research (see e.g. Berbegal-Mirabent, Sánchez García, & Ribeiro-

Soriano, 2015; Caddick, 2017). In addition to teaching and research, a Third Mission, consisting of different forms of research collaborations, knowledge exchange and technology transfer activities, has emerged. In the entrepreneurial economy, universities are expected to "contribute and provide leadership for creating entrepreneurial thinking, actions, institutions" (Audretsch, 2014, p. 319) and the creation of entrepreneurial capital (Audretsch et al., 2006). In regions with low economic activity, this has led some universities to actively foster a regional ecosystem that is centred around the university (Graham, 2014). The relevance of universities and their interactions with industry as a crucial driver in the knowledge economy has received increasing attention from regional to national as well as super-national levels such as the European Union (Grimaldi et al., 2011).

Universities' interaction with companies and public bodies and, by extension, their embeddedness in different IEs, EEs, BEs, and KEs does not follow a linear growth pattern, but can be best described by a dynamic states model (Levie & Lichtenstein, 2010). In each stage, universities try to "most efficiently/effectively match internal organizing capacity with the external [...] demand" (Levie & Lichtenstein, 2010, p. 335). For example, universities experience increasing/declining importance of different modes of interaction with industry based on changing government policies and incentives and technological evolution in different fields demands novel ways of exchanging knowledge. Furthermore, universities must adopt a holistic approach to technology commercialisation and knowledge exchange that involves and aligns teaching, research, and the aforementioned entrepreneurial activities (Levie, 2014).

The dynamic stages model also challenges the *liability of newness* and focuses on the *variability of newness* (Levie & Lichtenstein, 2010, p. 337). While world-leading universities like Stanford University or the Massachusetts Institute of Technology (MIT) receive disproportionally more attention, smaller universities and those with a shorter history (e.g. former polytechnics) have developed ways to collaborate with industry that fit their capabilities and resources and are also supportive to their mission. Hence, universities' contributions to economic development and regional dynamics are multifaceted and go beyond "overly mechanistic depictions" (Bramwell & Wolfe, 2008, p. 1175), but forming a socially constructed system that also involves reputational factors and partnerships, among others.

Universities are key actors in many ecosystems and have the ability to connect local companies to other companies beyond regional boundaries (i.e. link different ecosystems) (Roesler & Broekel, 2017). These links can be crucial as firms need to manage interactions among different spatial scales for effective (inter-organisational) learning and innovation (Malmberg & Maskell, 2002; Malecki, 2011). In turn, universities can also serve as a *landing pad* for companies who want to increase their engagement with the local ecosystem (e.g. working with government or public bodies, local start-ups, or other organisations) due to their wide range of activities and vast networks (Frølund et al., 2018).

Universities should be perceived as part *of* the economy and (regional) ecosystems, not institutions *for* economic development (Brennan et al., 2007). It is, therefore, important to conceptualise how universities interact with their own *university ecosystem* (UE) and manage their links with actors such as (entrepreneurial) students and alumni, a new generation of entrepreneurial academics, public bodies and other organisations that support and fund innovation and entrepreneurship, but also established businesses and start-ups and other academic and non-academic research institutions (Siegel & Wright, 2015a).

2.2.4 University Ecosystems

UEs are not a new concept but have predominantly been characterised by a university's efforts to create internal support structures for student entrepreneurship and faculty spin-offs (Graham, 2014; Hayter, 2016b; Hayter et al., 2018). However, universities are involved in entrepreneurial activities beyond their campus and engage externally to enable entrepreneurship and knowledge valorisation (Boh et al., 2012). Universities and other research institution are a distinct feature of a particular region or country (Asheim & Coenen, 2005), and both the university as well as the socio-economic environment derive benefits from an engaged university. For example, the reputations of the Silicon Valley and Route 128 ecosystems are linked to their proximity to Stanford University and MIT, respectively (Jaffe, 1989).

For the university, there is a reinforcing relationship between internal and external efforts (Levie, 2014; Boh et al., 2012). This research extends the UE concept and includes the external efforts. A UE is, therefore, defined as an ecosystem that is centred around a focal organisation and combines aspects from BEs, IEs, KEs, and EEs, to facilitate entrepreneurship and growth.[6]

While authors have highlighted differences regarding the different internal ele-

[6]For Li (2018), UEs are a special type of a BE. Limiting a UE to a BE does, however, not sufficiently acknowledge the differences between universities, their strategic focus, and the evolution of their respective ecosystem.

ments of UEs (some of which are only of semantic nature), the existing literature does agree that a comprehensive and university-wide approach to entrepreneurship is required (Audretsch, 2014; Hallam, Leffel, et al., 2014; Levie, 2014). The maturity and effectiveness of the internal part of the UE depends on "the collective and strategic actions of multiple academic and non-academic knowledge intermediaries" that outperform "other, single intermediary structures" (Hayter, 2016b, pp. 2-3). Key elements of the internal efforts include (Siegel & Wright, 2015a, p. 585):[7]

1. the rise of property-based institutions, such as incubators/accelerators and science/technology/research parks, to support technology transfer and entrepreneurship;

2. substantial growth in the number of entrepreneurship courses and programmes on campus (in multiple colleges/schools);

3. the establishment and growth of entrepreneurship centres;

4. a rise in the number of 'surrogate' entrepreneurs on campus to stimulate commercialization and start-up creation; and

5. a rapid increase in alumni support of various aspects of this entrepreneurial ecosystem, including alumni commercialization funds and student business plan competitions.

Not considered in this approach are the external efforts, i.e. the importance of knowledge exchange and research collaborations between the university, public and private partners. Entrepreneurs (and entrepreneurial academics by that means), who are lacking resources or support turn to intermediary organisations within their network, which often is the local EE or UE (Clayton et al., 2018). Since most inventions from academics are from the forefront of scientific research, it needs national and global links to find the right partners to take those technologies forward. Based on the four types of ecosystems, the following features are added to the UE:

6. provide services and support to the local EE, but also leverage these connections for student start-ups and faculty spin-offs;

[7] For case studies of particular approaches to nurture and manage these internal efforts see e.g. Levie (2014) and Eesley & Miller (2018) as well as Wright et al. (2017) for a conceptual model of an ecosystem for student entrepreneurship.

7. support commercialisation in BEs through scientific input and business model innovation;
8. collaborate with public and private organisations in IEs to co-create value for customers and users (particularly to solve societal, environmental, or economic problems from the university's point of view); and
9. closely engage with other universities and non-academic partners in KEs to push the boundaries of the scientific frontier and enable breakthroughs.

Figure 2.1 shows a conceptual model of a UE with a focus on the inter-organisational elements (excluding the internal efforts 1-5) and illustrates the relationship to BEs, IEs, EEs, and KEs. The UE is the base layer for the university and shows all connections that the focal university has.[8] This network can then be disentangled and divided into further layers, such as the local EE. Actors such as local companies or entrepreneurs[9] can be part of multiple layers. Understanding UEs as layered network addresses the lack of multi-scalar conceptualisations of ecosystems (Alvedalen & Boschma, 2017). The example of a BE is shown without the involvement of the focal university or any university because universities do not necessarily play a key role in these ecosystems.

The essence of this conceptualisation is the multifaceted way in which universities interact with their region but also connect their region (its actors, resources, research/commercial foci) with global, technologically leading companies and universities in the respective area (Carayannis, 2008; Malecki, 2011). Researchers and policy makers have identified that it needs global knowledge exchange to support regional innovation activity (Dohse et al., 2018).Furthermore, it shows universities as "cultural reference points for their communities", "key organisations and supporters in regional and national innovation systems", with "social responsibility and public engagement, linking generations as well as today and tomorrow's workforce, being the educative reference for students, lecturers, and the whole community" (Paleari et al., 2015, p. 369).

The university takes the role of a gatekeeper in this case. Gatekeepers are "actors that generate novelty by drawing on local and external knowledge" (Graf, 2011, p. 173) and well-connected to actors outside their region, which requires a certain level of resources to maintain these relationships (Morrison, 2008). Absorptive capacity is more important for a gatekeeper than size and it can be argued that universities fulfil this role better than for-profit companies (Graf, 2011;

[8]For the sake of clarity, links within the local EE are not included on the UE layer.

[9]Entrepreneurs are not depicted separately. A company in this illustration can be everything from an entrepreneur or start-up to a large company.

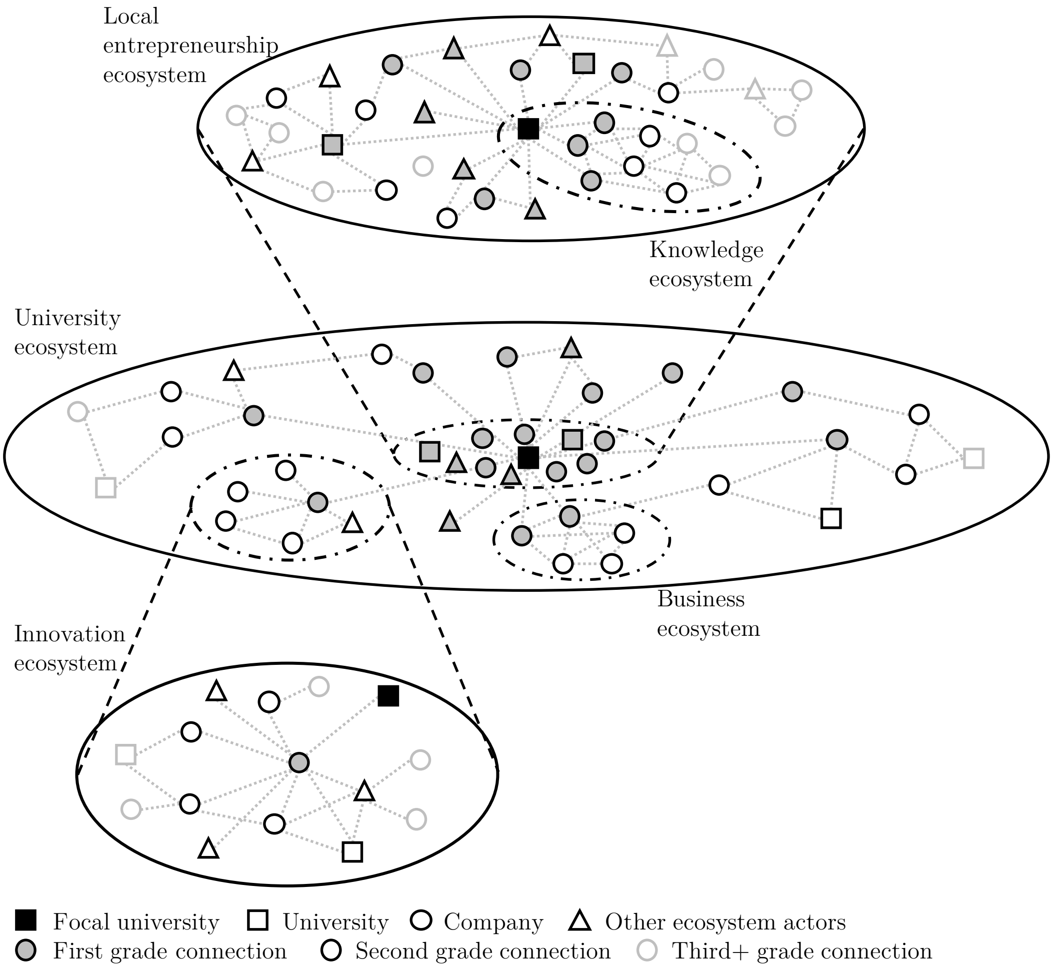


Figure 2.1: Inter-organisational perspective on university ecosystem (adapted from Malecki, 2011; Stuck et al., 2016)

Roesler & Broekel, 2017). With companies as gatekeepers, sharing absorbed knowledge within the regional system is more restricted than often assumed and limited to generic insights (Morrison, 2008). A university with no intention of profit maximisation would potentially increase the knowledge flow, but this also depends on the circumstances and the maturity and effectiveness of the ecosystems, whether it is a very dense KE or broader EE. Networks with gatekeepers outperform those without because they expand the available stock of knowledge, particularly when there is diversity within the region (Vermeulen & Pyka, 2018). Due to their involvement in multiple ecosystems, universities might have the best overview of the local knowledge base, at least in theory. In practice, this is to a large extent limited by available resources of the university and e.g. the time that academics have to engage in these activities.

This conceptualisation, as depicted in Figure 2.1, will serve as the basic level of analysis for this thesis and as a reference point for further research. Having established the ecosystem framework, the focus shifts now towards how entrepreneurial universities have evolved into the role that they are currently occupying in ecosystems and how they develop and manage their links with other economic actors.

2.3 Entrepreneurial Universities

Universities' engagement with the public and private sector has received an increasing amount of attention from both research and policy makers, particularly over the last 30 years (Geuna, 2001; Grimaldi et al., 2011).[10] However, this is not a new trend and university-industry interactions have a long history (Perkmann et al., 2013; Siegel & Wright, 2015a). This section will briefly review the evolution of the entrepreneurial university and outline current issues from an institutional perspective. The aim is to understand entrepreneurial activities by universities as a means and "an enabler of broader societal [and economic] impacts" as opposed to a goal in itself (Fini et al., 2018, p. 4).

[10] An indicator for the growing number of academic publications is the increasing number of literature reviews aiming at structuring the field and outlining new avenues for future research (Bozeman, 2000; Agrawal, 2001; Arbo & Benneworth, 2007; Drucker & Goldstein, 2007; Djokovic & Souitaris, 2008; Geuna & Muscio, 2009; Thune, 2009; Perkmann et al., 2013; Gilman & Serbanica, 2014; Ankrah & AL-Tabbaa, 2015; Bozeman et al., 2015; de Wit-de Vries et al., 2019; Hayter et al., 2018; Mascarenhas et al., 2018; Miller, McAdam, & McAdam, 2018).

2.3.1 Evolution of the Third Mission

Throughout history, the majority of universities and the university sector as a whole went through a number of transitions from the perspective of a dynamic states model (Levie & Lichtenstein, 2010), which are commonly known as "academic revolutions" (Etzkowitz, 2002a). Examples include transitions from *teaching* in the Napoleonic model of the university to *research-informed teaching* or the "unity of research and teaching" of the Humboldt university (Etzkowitz, 2003a; Lehrer et al., 2009; Sam & van der Sijde, 2014), to the early research-intensive universities in Germany and later in Great Britain and the USA (Ben-David, 1977; Freeman, 2004; Lehrer et al., 2009; Martin, 2012; Siegel & Wright, 2015a), the 'Mode 1' universities that produced knowledge within traditional academic disciplines under the norms and standards of academic research (Gibbons et al., 1994), 'Mode 2' universities, which are producing often interdisciplinary knowledge for problem solving in collaboration with external, non-academic stakeholders (Gibbons et al., 1994; Miller, McAdam, & McAdam, 2018; Sam & van der Sijde, 2014)[11], and 'Mode 3', including knowledge exchange from all disciplines with a wide variety of business and community partners (Carayannis & Campbell, 2009; Hughes & Kitson, 2012; Miller, McAdam, & McAdam, 2018).

In general, the aforementioned transitions towards more engagement with industry reflect the evolution of the knowledge economy, which makes academic knowledge more valuable for commercial exploitation (Mansfield & Lee, 1996; Sam & van der Sijde, 2014). It is, however, not just top-tier research universities (usually associated with a great amount of fundamental research) that interact with and contribute to industry, but also second-tier research universities (Mansfield & Lee, 1996). Other actors such as companies, hospitals, and government laboratories, among others, are getting more involved in knowledge production. Particularly R&D intensive firms are an important producer of knowledge and academics are ranking knowledge exchange as an important incentive for interaction with industry, thus underlining that industrial R&D is relevant for academia and not just contrariwise (Meyer-Krahmer & Schmoch, 1998). Universities, however, are still at the centre due to their capabilities and experience in conducting basic and applied research (Etzkowitz & Leydesdorff, 2000; Azagra-Caro et al., 2006) with strong links to those other actors (Godin & Gingras, 2000b).

In many countries, governments have recognised the contributions of uni-

[11] Given the linkages to industry that early German universities already had, followed by American and British universities, it becomes clear that the phase of Mode 1 knowledge production can be regarded as an anomaly when looking the whole history of academic institution and, hence, Mode 2 actually precedes Mode 1 (Martin, 2012; Siegel & Wright, 2015a).

versities to many industries and started establishing policies to foster university-industry relationships and the commercialisation of scientific research in the 1980s and 1990s (Fontana et al., 2006; Baycan & Stough, 2013), which also increased the pressure for universities to move closer to industry (Tether, 2002). Government policies and the co-evolutionary dynamics between government and universities evolve over time as universities make transitions as a reaction to the changing environment (Lockett et al., 2013).

These dynamics are also captured in the Triple Helix model of university-industry-government interactions (Etzkowitz & Leydesdorff, 1995; Leydesdorff & Etzkowitz, 1996, 1998). From an evolutionary perspective, the Triple Helix concept describes universities, industry, and government as co-evolving actors in a socio-economic system (Leydesdorff, 2000). In contrast to the co-evolutionary dynamics and selection mechanisms of technical trajectories in evolutionary economics, the Triple Helix model "endogenizes the knowledge infrastructure of a society as a next-order regime" (Leydesdorff & Etzkowitz, 1996, p. 280). The main focus is on the institutional level, but it also affects individual academics, whose role shifts from blue sky research to bridging the gap between basic science and technology and its application (Clark, 1998; Etzkowitz, 2003b; Shane, 2004a). Essentially, the Triple Helix concept is based on an innovation-push, with academia as the main producer of knowledge and innovation, which is then transferred to industry (Etzkowitz & Klofsten, 2005; Bercovitz & Feldman, 2006). Academic knowledge production is supported by government funding and investments from industry (Etzkowitz & Leydesdorff, 2000; Miller, McAdam, & McAdam, 2018), who also reap the benefits after the successful commercialisation of research results.

Universities have now fully incorporated the so called *Third Mission*, i.e. "all other university endeavours in addition to research and teaching, and are largely focused on the transfer of knowledge from the university to outside individuals and organisations" (Lockett et al., 2013, p. 237). Increased interaction between universities and industry has been witnessed globally, from the US and European countries to Asia, Australia, and Israel (Grimaldi et al., 2011). Criteria based on both academic and Third Mission standards are now combined in a "hybrid regime" to evaluate the success of universities, "where achievement in one realm is dependent upon success in the other" (Owen-Smith, 2003, p. 1081). In fact, most world-leading universities are actually world-leading in both areas (D'Este & Perkmann, 2011).

In the end, the evolution of the Third Mission is a way for universities to demonstrate how they serve society (Lockett et al., 2013) and universities are now generally perceived as an engine for (regional) economic development and as a major actor for addressing grand societal challenges (Feller, 1990; Rosenberg & Nelson, 1994; Etzkowitz, 1998; Etzkowitz & Leydesdorff, 2000; Shane, 2004b,a; Walsh et al., 2008; Grimaldi et al., 2011; Baycan & Stough, 2013). However, much of this is projected from a limited number of universities, which are exceptionally successful in terms of building links with industry and commercialising technologies such as MIT or Stanford, to the university sector as a whole (Etzkowitz, 2002b).

2.3.2 From Technology Transfer to the Entrepreneurial University

While the importance of the Third Mission has evolved over time, so has the way in which it is implemented and exploited by universities. In the 1980s, there was a clear focus on *technology transfer*, i.e. commercialising of technologies primarily via patenting and licensing. Even spin-offs were neglected for a long time in the hope of licensing *homerun* technologies (Siegel & Wright, 2015a). This has led to "overly mechanistic national and regional policies that seek to commercialize those ideas and transfer them to the private sector" (Florida, 1999, p. 67). Policies focused on the supply side and increasing returns from licensing activities and, thereby, neglected many of the previously mentioned co-evolutionary dynamics between universities, industry, and other ecosystem stakeholders.

A more recent trend is the evolution from technology transfer to *knowledge exchange*, which provides a more appropriate account for the two-way flow of information in university-industry interactions (Meyer-Krahmer & Schmoch, 1998). In addition to supply-side issues, it includes the demand side and issues such as partnering and trust (Santoro & Bierly III, 2006; Tartari et al., 2012; de Wit-de Vries et al., 2019), experience in working with academia and vice versa (Bruneel et al., 2010; Tartari et al., 2012), absorptive capacity (Fabrizio, 2009; de Faria et al., 2010; Spithoven et al., 2011; Rajalo & Vadi, 2017; Moon et al., 2019; de Wit-de Vries et al., 2019), and a collaborative culture (Baycan & Stough, 2013; West & Bogers, 2014; de Wit-de Vries et al., 2019), among others.

In addition to the traditional technology transfer mechanisms, this has led to a widening of the focus of university contributions to economic development (Santoro & Chakrabarti, 2002; Bekkers & Bodas Freitas, 2008; Grimaldi et al., 2011; Philpott et al., 2011; Breznitz & Feldman, 2012; Hughes & Kitson, 2012; Perkmann et al., 2013), even to the extent of being a "social critic" as an important function in some countries (Grimaldi et al., 2011). This involved complex processes that bring together the project, individual, and support dimension (Castillo Holley & Watson, 2017) as well as complex interactions among different entrepreneurial activities as well as between entrepreneurial and scientific activities (Carayol, 2003; Owen-Smith, 2003; Van Looy et al., 2006; Landry et al., 2010; Huyghe, Knockaert, & Obschonka, 2016).

Entrepreneurial universities are "a step in the natural evolution of a university system that emphasizes economic development in addition to the more traditional mandates of education and research" (Rothaermel et al., 2007, p. 708). By fully incorporating Third Mission activities, they are "able to take on several roles in society and in the [...] (eco)system" (Sam & van der Sijde, 2014, p. 901). This involves a greater number of internal and external stakeholders in addition to industry partners, such as government programmes and agencies to support entrepreneurship and economic development (external) and new generations of researchers and academics (internally) (Siegel & Wright, 2015a).

Universities, as facilitators of those complex processes and networks, are expected to contribute to the solution of complex social issues in a both global and local contexts, which requires universities to constantly evolve and adapt (Siegel & Wright, 2015a; Hayter & Cahoy, 2018). Lehrer et al. (2009) differentiate between "dynamic" (Clark, 1998; Etzkowitz, 2003b) and "commercial" (Siegel, Waldman, & Link, 2003; Lockett et al., 2005) interpretations of the entrepreneurial university. However, successful universities must combine both aspects to be able to align strategies and resources to this end (Hayter & Cahoy, 2018). Entrepreneurial universities are also driven by a combination of "the invisible hand of market forces and the visible hand of public R&D funding" (Lehrer et al., 2009, p. 269), the latter referring to a bidding system that is supposed to increase the societal return by directing public funding to the most promising projects (David, 2004).

Entrepreneurial universities play an important role, but are also not the only required ingredient within an ecosystem to achieve (regional) economic development (Florida, 1999). Universities engage with their local communities by supporting businesses and assisting with policy matters in "an unprecedented manner, [...] using these communities as labs to test new ideas and find better ways to achieve social and economic goals" (Breznitz & Feldman, 2012, p. 139). In some industries, academic research is crucial to industrial R&D (Cohen et al., 2002) and even "causes industry R&D and not vice versa" (Jaffe, 1989, p. 968).

A key aspect is the development of absorptive capacity among partnering companies in local EEs and KEs, but also supra-regional in IEs and BEs (Lester, 2005;

Bishop et al., 2011). This can be achieved through a variety of entrepreneurial activities, which will be explored in the next section.

2.3.3 Academic Entrepreneurship

There is no consistent use of key terms such as academic entrepreneurship or entrepreneurial activities in the literature. To account for the shift from technology transfer to knowledge exchange with a bi-directional flow of information, entrepreneurial behaviour is more than simply starting a new business (Shane & Venkataraman, 2000). Therefore, *entrepreneurial activities* are defined as "any activity that occurs beyond the traditional academic roles of teaching and/or research, is innovative, carries an element of risk, and leads to financial rewards for the individual academic or his/her institution. These financial rewards can occur directly or indirectly via an increase in reputation, prestige, influence or societal benefits" (Abreu & Grinevich, 2013, p. 408). Accordingly, *academic entrepreneurship* describes the sum of all entrepreneurial activities to promote innovation, entrepreneurship, and growth within the university ecosystem (Klofsten & Jones-Evans, 2000; Siegel & Wright, 2015a). It is worth highlighting that this includes various types of university-industry interactions beyond licensing and spin-off formation.

Much of the research has focused on the commercialisation of university-owned intellectual property (IP) (Shane, 2004a,b; Friedman & Silberman, 2003; Thursby & Thursby, 2007; Jensen et al., 2003; Siegel, Waldman, & Link, 2003; Grimaldi et al., 2011, among others). However, with regard to both the number of interactions and the revenue generated, these forms of knowledge exchange are outnumbered by activities such as consulting, contract and collaborative research (Schartinger et al., 2001; Agrawal & Henderson, 2002; Cohen et al., 2002; D'Este & Patel, 2007; Bekkers & Bodas Freitas, 2008). These activities also have a greater economic impact compared to licensing and spin-off creation (Schartinger et al., 2001; Cohen et al., 2002; D'Este & Patel, 2007; Caldera & Debande, 2010; Abreu & Grinevich, 2013). Furthermore, commercialisation activities are risky and speculative as only a small number of them actually lead to income (Lee, 1996; Lerner, 2005). Reducing the risk is a motivational factor for both universities and industry, particularly financial risks that can be mitigated by sharing R&D costs and facilities (Lee & Win, 2004).

The main entrepreneurial activities, different combinations of which are also the ones most commonly used in multi-activity studies, are licensing, spin-off formation, consulting, contract and collaborative research (Louis et al., 1989;

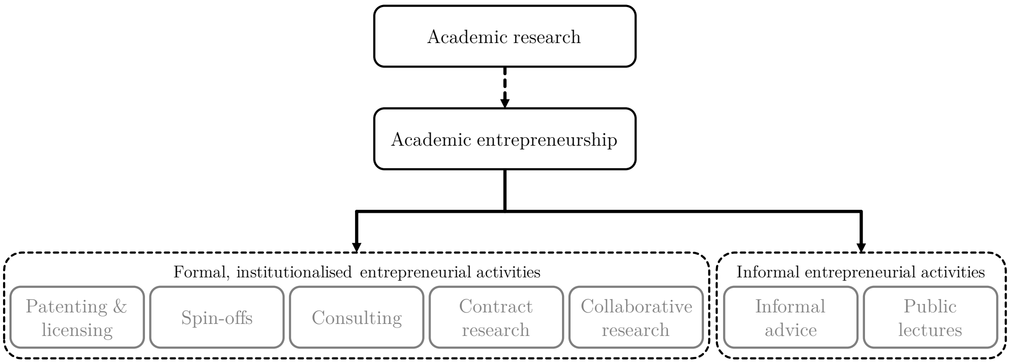


Figure 2.2: Notation of entrepreneurial activities (adapted from Abreu & Grinevich, 2013)

Brennan et al., 2007; Wright et al., 2008; Philpott et al., 2011). These five activities are also referred to as “institutional academic entrepreneurial activities” (Castillo Holley & Watson, 2017, p. 51) and will be classified as *formal* activities based on the contractual formalisation and the required institutional input/moderation, regardless of the appropriateness of IP protection (Grimaldi et al., 2011). With the focus on the ecosystem level and inter-organisational collaborations, these formal (or “institutional”) activities are the focus of this study. Combining commercialisation and collaborative forms of interactions provides a more balanced picture of universities’ engagement with their ecosystem compared to studies focusing on either group or single activities (D’Este & Perkmann, 2011). This notation is illustrated in Figure 2.2.

There is limited overlap in academics’ involvement in multiple of the activities, which suggests that different academics are involved in different types of activities and these activities are, therefore, to some extent substitutes for one another (Abreu & Grinevich, 2013). There is, however, ambiguity in the literature regarding the entrepreneurial activities themselves and their definitions, particularly with regard to different types of industry-funded research and consulting (D’Este & Patel, 2007; Grimaldi et al., 2011; Nilsson et al., 2010; Rajaeian et al., 2018). This ambiguity reflects the multi-disciplinary nature of R&D collaborations and knowledge exchange (Martínez-Noya & Narula, 2018).

The five formal entrepreneurial activities can have for-profit as well as government or other public/non-profit partners/collaborators (as conceptualised in the university ecosystem model). Prominent examples for the latter include consulting or contract research for governments (from regional to national and EU bodies) or other non-government organisations as well as research collaborations with publicly-funded, non-academic institutions. This study focuses on the interaction between universities and for-profit businesses and sees these activities as *mechanisms* in a complex and dynamic ecosystem (Jaffe, 1989).

2.3.3.1 Patenting and Licensing

Patent applications are filed "to achieve temporary protection of technologically new products or processes in the market place" (Meyer-Krahmer & Schmoch, 1998, p. 837). Patents are also a means to disclose information about an invention to a buyer or licensee without losing control over the IP rights. Only a small minority of academics actually use patents, even in engineering (Agrawal & Henderson, 2002), and they are not a substitute for publications, but both go hand in hand in many cases (Fabrizio & Di Minin, 2008; Geuna & Nesta, 2006). Nevertheless, an over-emphasis on patenting and licensing could harm the culture of openness and information sharing in academia (Mowery & Sampat, 2005) and recent research has shown that licensing might actually constrain "follow-on" research (Thompson et al., 2018).

Technology licensing is the traditional model of technology transfer. Licensing, in this case, is the act of granting a company the legal rights to use and commercialise university IP in exchange for a licensing fee or royalty payments (Thursby & Thursby, 2003, 2007; Lee & Win, 2004). Only a small number of universities actually generate profits from licensing activities, where a few patents are usually yielding the majority of this income. Most universities do not generate a substantial income stream, and even for those who do, it is only a very small portion of the total budget of the university (Lester, 2005; Geuna & Nesta, 2006). However, licensing and patenting "provides a 'shop window' for university research output, attracting industry attention" (Philpott et al., 2011, p. 163, original emphasis).

Licensing complements the strength of universities as upstream innovators and downstream commercialisation partners (licensees), even in large markets that usually justify higher internal R&D expenditures for companies (Hermosilla & Wu, 2018). Technologies should be commercialised by an economic actor with a comparative advantage, i.e. the lowest opportunity costs, which is usually not the inventor because it requires skills such as "identifying customer needs, developing product concepts, designing products and processes, prototyping, and manufacturing" (Shane, 2002b, p. 123).

The literature has highlighted the disclosure problem, i.e. the asymmetric distribution of knowledge about technologies and their commercialisation potential between universities and companies or entrepreneurs (Shane, 2004b; Macho-Stadler et al., 2007; Poyago-Theotoky et al., 2002). This issue can be best understood from an information economics perspective (Cohen & Levinthal, 1990; Nelson, 1959). Companies and entrepreneurs have more insights into market needs and commercialization opportunities and potential of particular inventions (Balakrishnan & Koza, 1993). However, it is difficult for them to evaluate the quality and, hence, the value of an invention based on the limited information of the patent (Macho-Stadler et al., 2007). Universities, and especially their researchers, have typically a better understanding of the performance potential and opportunities for further development of the invention, but usually struggle with evaluating the commercial value (Macho-Stadler et al., 2007). This asymmetric distribution of information can lead to failures in licensing negotiations (Bercovitz & Feldman, 2006; Gallini & Wright, 1990; Macho-Stadler & Pérez-Castrillo, 1991, 2010).

Licensing is neither a linear, nor a one-off process, and should be seen as one of a range of mechanisms for exchanging knowledge, not a means to an end. The involvement of the academic inventor throughout the commercialisation process is also a critical success factor. This varies to a large degree and about one third of all licensing activities have no involvement of the academic at all (Agrawal, 2006). Reasons for lack of involvement include that firms either undervalue this contribution or "do not know how much they do not know"; a varying degree of in-house experience where some companies really do not need the academic inventor; some technologies being more mature and in less need for further development; or the company has actually no desire to ever commercialise the invention (Agrawal, 2006, p. 77).

2.3.3.2 Spin-offs

Within the last years, university spin-off creation has received disproportionately more attention from both policy makers and academic researchers compared to any other entrepreneurial activity (Berbegal-Mirabent, Ribeiro-Soriano, & Sánchez García, 2015; Bercovitz & Feldman, 2006; Lockett et al., 2005). Spin-offs are a means of bringing university inventions to the market, exploit IP and create employment in the region (Philpott et al., 2011). More than any other activity, the creation of spin-offs raised the issue whether traditional academic norms are compatible with commercialisation efforts (Etzkowitz, 1983).

Forming a spin-off can be a viable option for universities, especially when trying to commercialise breakthrough inventions and in the absence of potential licensees (Rasmussen, 2008). There is no commonly applied definition of what a university spin-off is (Berbegal-Mirabent, Ribeiro-Soriano, & Sánchez García, 2015; Hayter et al., 2018).[12] In general terms, spin-offs are usually defined as "new

[12]There is also no clear distinction between spin-offs and spin-outs in the literature and the

companies formed by individuals (faculty members) related to the university or university research park to develop a technology that was discovered in, and is transferred from, the parent organization" (Bradley et al., 2013, p. 587).

In this traditional view, spin-offs only include companies created on the basis of a licensed technology (Shane, 2004a), which was later broadened to include those companies that are not based on disclosed inventions and patents (Fini et al., 2010; Miner et al., 2012). The existing literature on spin-offs has primarily focused on those based on codified knowledge, but those only account for half of university spin-offs in Germany (Karnani, 2013). Tacit spin-offs are common across disciplines, including engineering, and built around services as well as products. As a result, there is a huge untapped pool of resources for universities with regard to spin-offs based on tacit knowledge, both internally (e.g. promotion and tenure) and externally (e.g. exploitation and commercialising research, growing the university's network) (Karnani, 2013). These companies are also referred to as start-ups, including "any type of company, for instance a new venture detached from his or her academic research" as opposed to spin-offs, which are firms "initiated within a university setting and based upon scientific results" and usually codified IP (Huyghe, Knockaert, & Obschonka, 2016, p. 346, based on Rasmussen & Borch, 2010; Steffensen et al., 2000).[13]

In this study, spin-offs represent the totality of companies founded by staff members and are, therefore, defined as new firms founded on the basis of university research, which does not need to be within the core expertise of the academic and includes an optional transfer of IP rights (adapted from Philpott et al., 2011). Many of those spin-offs without university IP still go through official support processes and are in any case "a critical vehicle for the dissemination and commercialization of new knowledge" (Hayter, 2016b, p. 634). When codified and protected IP is involved, universities usually own a share in the spin-off and generate income through the initial public offering (IPO) and the sale of these shares (Philpott et al., 2011).

Similar to licensing activities, spin-offs are neither a linear process nor a one-off process (or an *outcome* of technology commercialisation), but have important functions within ecosystems. As resource mediators, re-combiners, or renewers, spin-offs "adapt resources to, or require changes among, business parties'

terms are often used interchangeably. Only the term spin-off will be used in this thesis as a general term, including spin-outs.

[13]A similar distinction is used by UK governments and funding councils, who distinguish start-ups from spin-offs "as they are not specifically based on IP emerging from a HEI, and may not even be directly related to the academic's area of expertise (although most certainly are)" HEFCE (2014, p. 21).

resources" (Aaboen et al., 2016, p. 157). Due to the existing links to the university, they offer opportunities for continuous interaction via collaborative or contract research and are also more likely to donate money in order to support the university/research group (Quintas & Guy, 1995). They are also more likely to publish findings from the funded research, which is important given the overall mission of knowledge production and dissemination of universities. Though in the context of spin-offs this is often based on the founder's intrinsic motivation and not necessarily caused by the mission of the university (Hayter & Link, 2018). University spin-off face some of the same challenges as other high-tech start-ups (Berbegal-Mirabent, Ribeiro-Soriano, & Sánchez García, 2015), but are also different in many ways (Vohora et al., 2004).

2.3.3.3 Consulting

Academic consulting covers a variety of interactions and can take different forms. A common distinction is made between opportunity-driven, commercialization-driven, and research-driven consultancy (Perkmann & Walsh, 2008). Consulting, in very broad terms, can be defined as "the sale of personal scientific or technological expertise to solve a specific problem" (Klofsten & Jones-Evans, 2000, p. 300). It can be carried out by both academic and non-academic staff and is usually regulated by contracts and a short-term activity compared to contract or collaborative research (Lee & Win, 2004). However, particularly research-driven consulting can be a long-term, strategic activity that is embedded in other types of entrepreneurial activities (Perkmann & Walsh, 2008). There is some overlap with contract research and the informal provision of (technical) advice. In contrast to contract research, consulting "may be the preferred method to access expert advice and less tangible knowledge. The knowledge itself may not be new, but it can often provide more immediate innovation [...] where IP rights are less important than the usefulness of the knowledge to a particular situation or problem" (HEFCE, 2014, pp. 14-15).

Consultancy and contract research are performed in greater volumes than other formal entrepreneurial activities (Klofsten & Jones-Evans, 2000), which is enabled by university policies that allow staff to carry out consultancy work for a certain number of days per year (Lee & Win, 2004). Academic consulting is popular among companies as they "free ride on government sponsored research of the faculty they hire as consultants" (Jensen et al., 2010, p. 1). But consultancy is also a preferred activity for many academics as it provides additional income "without the trials and tribulations of starting a new business, having no desire to learn the new competencies required to successfully manage an entrepreneurial venture" (Klofsten & Jones-Evans, 2000, p. 307). In addition to the direct monetary reward, consulting is a way of developing new links and relationships with businesses "that may lead to opportunities for future entrepreneurial activities" and carries less risk than other activities in this regard due to short-term nature of the projects (Philpott et al., 2011, p. 163).

2.3.3.4 Contract Research

Contract research describes a form of university-industry collaboration in the course of which the university (or a university research centre, a department or a single academic) performs research under a contract for monetary benefit (Lee & Win, 2004). In line with this, HEFCE (2014, p. 15) defines contract research "as a more simple transaction, where the benefit is assumed to be primarily on the side of the external partner, rather than the mutual gains obtained by collaborative research". For companies, these agreements also specify IP ownership a priori and, therefore, reduce the uncertainty and potential disputes over the results at a later stage (Berbegal-Mirabent, Sánchez García, & Ribeiro-Soriano, 2015). The existing literature is, however, not always clear about the boundaries of contract research. In fact, contract and collaborative research (Bekkers & Bodas Freitas, 2008) or contract research and consulting (D'Este & Patel, 2007; Grimaldi et al., 2011; Markman et al., 2008) are often treated together as one type of entrepreneurial activity.

Both contract and collaborative research provide a win-win situation for university-industry liaison (Berbegal-Mirabent, Sánchez García, & Ribeiro-Soriano, 2015). Contract research usually involves a particular research problem or question that the industry partner is concerned about in order to improve business performance or reduce the implementation time for new discoveries (Lee & Win, 2004; Lockett & Wright, 2005; Philpott et al., 2011). The company hereby commercialises the unique capabilities of the university and benefits without a substantial time lag; though projects can last from a few weeks to multiple years (Lee & Win, 2004; Van Looy et al., 2004; D'Este & Perkmann, 2011). The research that is conducted under this scheme is generally more applied in nature, compared to collaborative research (HEFCE, 2014). However, academic R&D for problem solving is as important from a business point of view as generating new ideas, which is usually attributed to collaborative research (Cohen et al., 2002). Universities can apply their knowledge to real-world problems and generate revenue as well as receiving indirect support such as equipment, human resources, IP, and materials, among others (Philpott et al., 2011). It might also open doors for student placements or student fellowships. Lastly, it might help advance the scientific frontier and inspire new basic research (Gulbrandsen & Smeby, 2005).

R&D contracts are an under-researched area compared to e.g. licensing or spin-off creation, even though they are an important source of revenue for universities (Caldera & Debande, 2010; Berbegal-Mirabent, Sánchez García, & Ribeiro-Soriano, 2015). Contract research is also an important mechanism to grow relationships with industrial partners and often forms the basis of further interactions (Philpott et al., 2011), a feature that is even less understood than contract research as a purely contractual agreement for knowledge transfer.

2.3.3.5 Collaborative Research

In contrast to contract research, collaborative research endeavours are characterised by a mutual benefit (Lee & Win, 2004). Collaborative research is regarded as a "bi-directional exchange of knowledge, whereas contract research is primarily a one-directional knowledge export from universities" (Meyer-Krahmer & Schmoch, 1998, p. 841). It involves a combination of public funding/sponsorship as well as contributions from companies or other non-academic organisations, including "funds, personnel, services, facilities, equipment, and other resources to conduct specific research or development efforts that are consistent with the laboratory's mission" (Lee & Win, 2004, p. 435).

Though collaborative research is further away from market introduction than any other entrepreneurial activity that is covered in this study, it still appears to be the *ideal* activity because it complements both partners' expertise and is in line with their goals (Lee & Win, 2004). Funding for academic research has diversified over the last decades, with increasing industry funds and support for academic R&D (Godin & Gingras, 2000a) and a growing "spirit of collaborative partnership in the pre-competitive domain" (Bloedon & Stokes, 1994, p. 44). This includes "basic and long-term strategic research, particularly in pre-competitive technologies; the sorts of research that many firms regard as excessively expensive to undertake alone, using only their own resources" (Tether, 2002, p. 953). The research is usually interdisciplinary in nature and unique (HEFCE, 2014).

For the industry partner, collaborative research leads to multiple benefits, including process (Maietta, 2015) and product innovation (González-Pernía et al., 2015), or the generation of new approaches and ideas in general (HEFCE, 2014). There is also a statistically significant increase in the share of employees working in R&D two years after finishing the project, which underlines the sustainability of this activity (Scandura, 2016). Collaborative research (together with informal contacts) was ranked by academics as the most important mechanism for engaging with industry and significantly more important than contract research, though these findings are not uniform across different scientific fields (Meyer-Krahmer & Schmoch, 1998). Academics who participate in collaborative research also outperform their colleagues who do not engage in this activity, but the journal quality (as measured by the impact factor) is lower for joint publications with industry compared to other joint publications and there is a higher level of interdisciplinarity compared to other publications in general (Abramo et al., 2009). Collaborative research can support academics in building a sustainable research programme and its importance for the academic sector is therefore sometimes compared to basic research and teaching (Klofsten & Jones-Evans, 2000).

2.3.3.6 Informal Entrepreneurial Activities

While formal entrepreneurial activities with industry partners (based on the definition used in this work) already go beyond pure commercialisation of research results, they only represent a small fraction of possible modes of engagement with non-academic institutions. There is also a range of *informal* entrepreneurial activities, which will be described briefly for the sake of completeness and to refine the boundaries of the activities that are relevant to this study. Informal activities are based on "personal contacts and hence the tacit dimension of knowledge transfer" (Grimpe & Hussinger, 2013, p. 683). They are particularly common in the arts and humanities as well as the social sciences (Abreu & Grinevich, 2013). Examples of informal activities include technical assistance (Link et al., 2007), informal advice (Cohen et al., 2002; Abreu & Grinevich, 2013; Perkmann et al., 2013), public lectures (Abreu & Grinevich, 2013), joint publications with industry (Schartinger et al., 2002), staff exchange (Cohen et al., 2002; Schartinger et al., 2002), joint student supervision (Schartinger et al., 2002), and conferences (Cohen et al., 2002). These activities are often perceived as being "less entrepreneurial" compared to formal activities (Philpott et al., 2011), which deviate more from the traditional mission of the university (Louis et al., 1989; Klofsten & Jones-Evans, 2000).

The existing literature is scarce about these types of entrepreneurial activities (Abreu & Grinevich, 2013; Grimpe & Fier, 2010; Grimpe & Hussinger, 2013) with limited theoretical work (Perkmann et al., 2013), which is often attributed to practical reasons as these activities and their outcomes are difficult to quantify (Bradley et al., 2013). They are also often not on the radar of technology transfer offices (TTOs) and university senior management (Abreu & Grinevich, 2013) and, therefore, represent a decentralised means of knowledge exchange with a long history (Cohen et al., 2002). In many cases, this forms the basis of formal entrepreneurial activities (Martinelli et al., 2008; Perkmann et al., 2013; Siegel & Wright, 2015a) and there are complementarities between these two forms in general (Siegel, Waldman, & Link, 2003; Link et al., 2007; Landry et al., 2010; Grimpe & Hussinger, 2013). Economic development, particularly on a local/regional level, is often attributed to a "complex, temporally unfolding sequence of interactions between formal and informal channels of knowledge transfer" (Azagra-Caro et al., 2017, p. 463). Support for commercialisation or other formal activities should not hinder or discourage those informal activities (Cohen et al., 2002; Grimaldi et al., 2011) and universities are encouraged not to institutionalise these activities, as the additional bureaucratic burden can lead to a reduction of these activities (Klofsten & Jones-Evans, 2000).

2.3.4 Institutionalising Formal Activities

Intermediary organisations, as boundary spanners, are crucial for the development of ecosystems and can be seen as the result of co-evolutionary dynamics. The existing literature deals with a number of intermediaries, such as "university technology transfer and licensing offices; physical space (incubators, accelerators, and co-working spaces); professional services providers; networking, connecting, and assisting organizations; and finance providers (including venture capital, angel investors, public financing, and crowdfunding)" (Clayton et al., 2018, p. 104). Many of these have been established both within universities to foster entrepreneurial behaviour internally as well as externally as a response to the wider needs within the entrepreneurship ecosystem. Universities have invested significantly in in-house capabilities to implement and support (mainly formal) entrepreneurial activities (Krücken, 2003; Perkmann et al., 2013).

The key institutional change was the establishment of TTOs[14] and associated policies, driven by the original focus on commercialisation activities (Krücken, 2003; Tijssen, 2006; Perkmann et al., 2013). Most of these TTOs were established in the 1980s and 1990s (Lockett et al., 2015). Earlier examples include

[14] Many universities have re-named (and re-branded) their 'technology transfer office' by using terms such as *innovation*, *outreach*, *engagement*, or *commercialisation*, among others, to reflect the shift towards knowledge exchange and a wider portfolio of entrepreneurial activities (Bradley et al., 2013). This study sticks to the traditional term, though explicitly acknowledging that the tasks of the TTO cover all entrepreneurial activities, not just licensing and spin-offs.

the German state North Rhine-Westphalia, which initiated pilot projects with TTOs in the 1970s and by the end of 1988, all universities had established TTOs (Krücken, 2003). These developments were characterised by top-down approaches and TTOs were "political role models", often with a lack of buy-in from relevant stakeholders and, therefore, more of a "gesture" as they did not have much of an impact as they were poorly embedded in the ecosystem (Krücken, 2003, p. 331). They only became a real factor mid-1990s in Germany and most of Europe (Abramson et al., 1997). Most universities around the world have established their own TTO today (Arvanitis et al., 2008; Colyvas et al., 2002).

The time lags between (1) recognising the need/opportunities for a TTO and (2) establishing a TTO as well as between (2) the establishment and (3) a recognisable impact can also be attributed to *institutional inertia* (Geuna, 1998; Krücken, 2003). Universities "customarily cope with heterogeneous, rapidly changing, and sometimes even contradictory expectations in their environment, without transforming these expectations directly into institutional change" Krücken (2003, p. 332). They show higher levels of inertia (bureaucracy, perceived inefficiency and less flexibility) than private firms, which has provided stability and helped them survive, in some cases for hundreds of years, in a very dynamic environment (Geuna, 1998; Lehrer et al., 2009). Particularly when universities try to implement entrepreneurial activities with the aim of immediate impact rather than long-term development, "the prevailing university culture and structure will exert resistance against change and will oppose the creation of appropriate structures to promote them, with deleterious effects for the university" (Horowitz Gassol, 2007, p. 489).

The entrepreneurial university manifests itself not only at the institutional level through the development of structures such as TTOs (Clark, 1998), but also at the departmental and research group level (Etzkowitz, 2003b) and even the individual level (Bercovitz & Feldman, 2008). However, TTOs play an important role in supporting and enabling entrepreneurial activities and are an integral part of the university ecosystem (see e.g. Krücken, 2003; Jacob et al., 2003; Degroof & Roberts, 2004; Hsu et al., 2007; O'Gorman et al., 2008; Fini et al., 2011; Levie, 2014; Jefferson et al., 2017). TTOs evolved from being part of the research structure of universities into separate organisational units with a variety of tasks (Etzkowitz & Goktepe, 2005). As "institutional entrepreneurs" (Jain & George, 2007), they help mitigate disputes and misunderstanding due different goals, cultures, and organisational structures in academia and industry (Siegel et al., 2004), provide financial support, technical expertise, and connections to other researchers and companies for spin-offs (Huyghe et al., 2014; Fernández-Alles et al., 2015). The former is mainly achieved by reducing search costs ("time and other resources necessary to search for potential collaboration partners"), reducing bargaining ("those associated with negotiation and coordination with potential partners, where it is often necessary to deal with asymmetric information"), and reducing other transaction costs ("related to motivation and incentive problems with regard to each of the parties joining the collaboration, and uncertainty about future results of the joint projects") (Kodama, 2008, p. 1226).

Different approaches are required for local-oriented spin-offs and initiatives compared to working with potential unicorns and global research collaborations (Clarysse et al., 2005). More broadly, TTOs can be categorised into four groups based on their strategic mission with different economic impacts: traditional shop (with very little to no economic impact), orchestrator of local buzz (local impact through spin-off promotion), catalyst (outreach impact through scientific leadership), and smart bazaar (not pertinent, public value creation through open dissemination of innovation) (Baglieri et al., 2018).

University administration and TTOs have the potential to foster entrepreneurial activities and the impact of academic research, but can also provide unsurpassable barriers and stifle collaboration and entrepreneurial activities (Berbegal-Mirabent, Sánchez García, & Ribeiro-Soriano, 2015; Caddick, 2017; Meoli & Vismara, 2016; Rasmussen & Wright, 2015). Various doubts and issues have been raised that prevent TTOs from achieving the best-case scenario of driving collaboration, ecosystem engagement, and shorten the time from lab to market for university inventions (Caddick, 2017). These include the tension between revenue generation from IP and fostering entrepreneurial activity in general (Markman et al., 2004; Swamidass & Vulasa, 2009; Fini et al., 2009, 2017), industry engagement (Perkmann et al., 2013), or relationship-building (Clarysse et al., 2014). For spin-offs, the effectiveness of TTO support beyond the initial stage, i.e. supporting the growth of businesses, has been questioned (Mosey & Wright, 2007; Rasmussen & Wright, 2015; Hayter, 2016b). Due to the long-standing focus of these activities, TTO might not possess the right skills and capabilities to effectively support other activities and having an impact in these areas (Lowe, 2006; Siegel et al., 2007; Clarysse et al., 2011). This might require a re-positioning of the TTO in terms of skills, size, and service portfolio (Grimaldi et al., 2011) and better linkages to other resources such as entrepreneurship faculty in the business school (Wright et al., 2009; Levie, 2014). Furthermore, TTO activities must be accompanied by incentives for academics to engage in entrepreneurial activities

(Degroof & Roberts, 2004; Wright et al., 2009). University IP policies and procedures have been identified as a critical element, yet there is no consensus in the existing literature about their effect on entrepreneurial activities by academics (Hayter et al., 2018).

Another issue that TTOs face is picking 'winners', i.e. identifying those inventions and technologies with the greatest commercial potential (Caddick, 2017). This issue is not exclusive to TTOs but is also faced by policy makers at a regional level and has received much attention in the context of cluster development. However, in an entrepreneurship ecosystem, policy makers are not encouraged to pick winners, i.e. favour different industries over others, but to allow cross-fertilisation among industries instead, which will allow self-organisation within the ecosystem (Isenberg, 2010, 2016). This is not directly possible for university TTOs as decisions must be made as to what technologies to protect and which spin-off ideas to pursue, for example, but it shows a need for relating those decisions to other activities to help evaluate their potential and build a strategic IP portfolio. However, this requires even more investments in TTO capacity and capability, but is necessary to increase the profitability of commercialisation (Caddick, 2017).

There have also been questions whether the organisational structures and policies are best suited for the benefit of society (Litan et al., 2007; Kenney & Patton, 2009), particularly a profit-driven focus on licensing (Hayter, 2016a; Mancha et al., 2013), given the many privileges that universities receive (Hayter & Cahoy, 2018). These issues underline the role that TTOs play in the university ecosystem beyond their classic role of marketing technologies and negotiating licenses. Given the changing environment with different demands from society and the ecosystem, universities must constantly adapt in a stage growth model and are increasingly experimenting with different policies, incentives and structures to encourage entrepreneurship and entrepreneurial behaviour (Grimaldi et al., 2011).

2.3.5 Trade-offs and Unintended Consequences

Most of the incentives that have been introduced in academia with regard to research and teaching over the last decades actually turned out to have perverse effects (Edwards & Roy, 2017), and similar unintended consequences and perceived risks are associated with entrepreneurial activities undertaken by universities (Kumar, 2010).

One of the most common concerns is that an increase in entrepreneurial activities will lead to a decline of basic research in favour of more applied research

(Blumenthal et al., 1986; Behrens & Gray, 2001; Lockett et al., 2015). However, there is no empirical evidence for such a shift (Van Looy et al., 2004; Welsh et al., 2008; Thursby & Thursby, 2011; Siegel & Wright, 2015b). In fact, a rise in entrepreneurial activities may even lead to an increase in basic research as the income from these activities gets re-invested in (basic) research (Siegel & Wright, 2015a). Academics also want to remain independent and avoid the "erosion of academic freedom" (Behrens & Gray, 2001, p. 179). Industry engagement should, therefore, complement and not replace their own research (D'Este & Perkmann, 2011).

Academia is traditionally guided by the principles of free knowledge dissemination and an open exchange of ideas for wider public benefits (Feller, 1990). Striving for public benefit is also seen as a return for the public funding of universities. However, due to closer interaction with the private sector, there is increased demand for secrecy (Feller, 1990; Poyago-Theotoky et al., 2002; Slaughter & Leslie, 1997; Geuna & Nesta, 2006), which slows down open knowledge diffusion (Nelson, 2004; Murray & Stern, 2007; Rosell & Agrawal, 2009). This might also result conflicts of interests and lower levels of research productivity among academics as it hinders publications (Slaughter & Leslie, 1997; Agrawal & Henderson, 2002), which also leads to a resource allocation problem among academics. Entrepreneurial academics are more likely to reject collaboration with other academics compared to their non-entrepreneurial peers, which could further harm *open science* and the academic culture (Blumenthal et al., 1996; Louis et al., 2001).

Universities have policies that both encourage and govern/regulate academics' engagement with industry within an allocated time budget (Perkmann & Walsh, 2008). While there is no evidence that industry interaction has shifted the focus from basic to more applied research, there is a risk that interaction with TTOs and industrial partners are very time consuming and may lead to reduced time for teaching and carrying out original research in general (Slaughter & Leslie, 1997; Owen-Smith & Powell, 2001). Only a small number of academics are involved in a large number of activities (Agrawal & Henderson, 2002; Balconi et al., 2004), so growing academic entrepreneurship requires increasing the number of entrepreneurial academics.

The small number of academics who are involved in these activities might explain why there is not a shift towards applied research. Such an effect could become apparent if the number of entrepreneurial academics is to be increased. Nevertheless, current data does not support a link between entrepreneurial activities and a decrease in both quality and quantity of (basic) research (Godin & Gingras, 2000a). The pressure to grow in terms of research and teaching activity, combined with additional responsibilities under the umbrella of the Third Mission as well as the ever-increasing complexity of science itself might lead to a 'demand overload' for universities (Clark, 1998). A potential result of this are similar stage transitions of universities and a convergence of the whole university sector towards a more homogeneous group, in which every university tries to address all responsibilities equally (Lehrer et al., 2009). The question remains whether all universities strive for this goal as countries benefit from diversity among academic institutions (Feldman & Desrochers, 2004). Strategic decision-making at the university must be monitored closely, particularly with an emphasis on potential unintended consequences and the dynamic interactions between these (Godin & Gingras, 2000a).

2.3.6 Strategic Implications for Universities

Strategic orientation of universities has implications for resource endowments and allocation, with significant differences between local teaching-oriented and world-leading research universities (Siegel & Wright, 2015a). This is also reflected in universities' efforts to support and promote entrepreneurial activities. In the past, academic entrepreneurship and licensing in particular, has been seen as a "short-term money spinner for universities" (Caddick, 2017, p. 1). Accordingly, their IP policies and the entrepreneurial strategies in general are perceived by academics to focus on revenue generation rather than providing societal benefits first (Welsh et al., 2008).

Most universities used to rely on *ad hoc* interactions with companies (Frølund et al., 2018) and behaved like a contractor, offering "knowledge on a market basis" (Fey & Birkinshaw, 2005, p. 601). The result is often a high volume of collaborations that comes at a price. There are seldom any synergistic effects between these collaborations and since legal aspects are negotiated on a case-by-case basis, it leads to a high workload for TTOs. More importantly, "opportunities for broader engagement and impact are lost" (Frølund et al., 2018, p. 4). Ad hoc interactions do have their place though, as they allow universities to assess a range of companies and identify "desirable and matching traits in potential partners" that form the basis of partnerships (Dahlander & McFarland, 2013, p. 69). Many leading universities have adopted such an approach already and other universities (and their industrial counterparts) are increasingly interested in strategic, long-term partnerships (Frølund et al., 2018). Though this shift is gaining momentum more recently, a similar trend was observed already in the early 1990s in Hong Kong (Chen, 1994).

The idea is to change from a contracting approach to a partnering approach and the "development of knowledge through relationships with specific partner firms" Fey & Birkinshaw (2005, p. 601). Partnership ties emerge from the many ad hoc interactions based on "long-term strategies and substantive assessments of a relationship's worth so as to draw extended rewards from the association" and persist, "when familiar people reflect on the quality of their relationship and shared experiences" (Dahlander & McFarland, 2013, p. 69). There is also a certain endogeneity involved in the partnership development process (Mindruta, 2013). If both parties are concerned with their partner's research capabilities, "endogeneity arises when top faculty teams with firms whose qualities reinforce their expertise and effort in innovation (i.e., scientists and firms match on complementary attributes)" (Mindruta, 2013, p. 645). Collaborating on R&D over an extended time span usually leads to the co-creation of very specific and often mainly tacit knowledge (Fey & Birkinshaw, 2005). Long-term, strategic partnerships also show that universities cannot only support industry with current problems but also address grand challenges in a more ambitious, uncertain, and exploratory setting (Frølund et al., 2018). This can also have a signalling effect, especially when working with leading companies, and attract new collaborators or potential licensees due to the perceived research excellence of the university.

Two issues need to be addressed in this context. First, there is an assumption underlying most research in this area that all entrepreneurial activities are valuable *per se*. Valuable, in this case, is defined as "linkages between universities and firms that have a higher potential to diffuse knowledge to other firms in their regional economy" (Giuliani & Arza, 2009, p. 906). The success of a collaboration and, by extension, the potential for a long-term partnership depends on a variety of factors, many of which are outwith the control of the university or the academic. Beside cultural aspects and experience with working with universities, the key factor is the absorptive capacity of the company. Selecting the right partner in the first instance is important, but also choosing the right entrepreneurial activity. This leads to the second issue and an underexplored area in the existing literature, the temporal patterns of university-industry interaction (Belderbos et al., 2015). If partnerships develop, what type of activities are performed with different partners and in what order? Entrepreneurial activities are mechanisms in ecosystems beyond the one-off transfer of knowledge and identifying the right activity for the right partner at the right time is important for developing partnerships.

Repeated interaction in the process of developing strategic partnerships build trust and experience among partners. It also leads to fading differences between the knowledge bases of the two partners (cognitive proximity), which can be harmful to innovation and lead to the need for exploring potential collaborations with other partners (Cantner et al., 2017). Hence, the relationship between any kind of proximity and collaboration is unidirectional (Ter Wal & Boschma, 2011). Particularly inter-organisational trust is important (Santoro & Gopalakrishnan, 2000) and "one of the strongest mechanisms for lowering the barriers to interaction between universities and industry" (Bruneel et al., 2010, p. 867). In the following section, social capital and different proximity dimensions in the context of inter-organisational collaborations will be discussed to explain, how universities build relationships and manage interactions with different partners within their UE.

2.4 Proximity, Social Capital, and University Ecosystems

Models of agglomeration such as RIS, EEs, as well as UEs are based on the "idea that local social capital yields economic benefits" (Kemeny et al., 2016, p. 1101). It often develops and accumulates at the regional or local level, with Silicon Valley being an example of a region that accumulated social capital relatively quickly (Lorenzen, 2007; Saxenian, 1994). Social capital is generally defined as "the process by which social actors create and mobilize their network connections within and between organizations to gain access to other social actors' resources" (Knoke, 1999, p. 18). This includes the "information, trust, and norms of reciprocity inhering in one's social networks" (Woolcock, 1998, p. 153).

For UEs, or any territorial system of innovation, it is not the simple agglomeration of companies, but the inter-organisational and personal networks that foster inter-firm learning, innovation, and entrepreneurship (Kraatz, 1998; Rocha & Sternberg, 2005; Spigel, 2015; Yli-Renko et al., 2001). Geographical proximity can be sufficient for one organisation to learn from another by observing their actions (Malmberg & Maskell, 2002), but this does generally not form a sufficiently strong basis for mutually-beneficial relationships. Different network types show clearly distinguishable social capital dimensions. For example, simple strategic alliances are based on non-competitiveness, shared goals, and the cognitive aspect of organisational proximity, whereas innovation districts or RIS are based on the social, cultural, and cognitive aspects (Inkpen & Tsang, 2005).

There is a conceptual overlap between social capital and different aspects of organisational proximity. In the most general sense, proximity is defined as "being close to something measured on a certain dimension" (Knoben & Oerlemans, 2006, pp. 71-72). Proximity along one or more dimension is a basic requirement for interaction and collaboration among organisations and, hence, knowledge exchange and acquisition (Gertler, 1995), which are crucial processes in the knowledge and entrepreneurial economy (Knoben & Oerlemans, 2006). Organisational proximity is defined as "the set of routines – explicit or implicit – which allows coordination without having to define beforehand how to do so. The set of routines incorporates organizational structure, organizational culture, performance measurements systems, language and so on" (Knoben & Oerlemans, 2006, p. 80, based on Rallet & Torre, 1999).

This definition includes social, cultural, institutional, and cognitive aspects.[15] Social proximity is mainly based on past interactions (Balland, 2012; Balland et al., 2014), which, particularly for SMEs, often leads to a path dependency ("collaborative traditions") that influences their collaboration behaviour and openness (Radziwon & Bogers, 2019). Cultural proximity establishes common norms, values, and interpretations among collaborating institutions. As a result, institutions collaborate easier and more effectively because there is an implicit understanding and no need to explicitly clarify every action (Burns & Stalker, 1961; Knoben & Oerlemans, 2006; Pettigrew, 1979; Wilkof et al., 1995).

Institutional proximity thus supports collaboration by providing a framework of shared norms, procedures, and rules, leading to institutional trust, which can result in either opportunistic behaviour or lock-ins if not monitored and managed properly (Boschma, 2005; Capello, 1999; Kirat & Lung, 1999). Cognitive proximity is defined as "the similarities in the way actors perceive, interpret, understand and evaluate the world" (Knoben & Oerlemans, 2006, p. 77, based on Wuyts et al., 2005). A shared understanding is essential for knowledge exchange, especially with increasing technological and economic complexity (Nooteboom, 1999). The key aspect of cognitive proximity is the *knowledge gap* between organisations (Boschma, 2005). In line with evolutionary dynamics, there is an inverted U-shape relationship between cognitive distance and learning (described as the product of novelty and understandability between partners) (Nelson & Winter, 1982; Nelson, 1995).

In this study, organisational proximity for universities is defined by its func-

[15] These four aspects are combined under organisational proximity because (1) there is an overlap between them individually and (2) organisational proximity as a summarising concept is most effective for inter-organisational collaborations (Knoben & Oerlemans, 2006).

tion, as the ability of an organisation to interact with external partners through a culture of openness, trust, less bureaucracy and shaped by working with a variety of different companies as well as developing long-term, strategic relationships with selected partners. The main idea is that universities can actively increase organisational proximity to industrial partners, with learning effects that go beyond a dyadic relationship and will help for future collaborations with other organisations. Therefore, increasing organisational proximity means that universities are able to more effectively initiate and grow relationships with companies. This is, however, subject to non-linear dynamics and long-term partnerships could reach a point at which the benefits for knowledge exchange and innovation performance decrease (inverted U-shape). Focusing on organisational proximity as the unit of analysis instead of social, institutional, cognitive, and cultural proximity separately is an approach that is easier to operationalise and eliminates the overlap between those aspects by acknowledging that they are still "mutually reinforcing" (Al-Tabbaa & Ankrah, 2019; Knoben & Oerlemans, 2006; Nahapiet & Ghoshal, 1998).

Social capital, therefore, focuses "not [on] single social relations, but matrices of different social relations, [...] because the clustering of some social relations spills over to others" (Lorenzen, 2007, p. 814). In this study, social capital is defined as the accumulation of past interactions with different individual partners, i.e. the organisational proximity and the social proximity aspect in particular (Adler & Kwon, 2002; Koka & Prescott, 2002). Social capital alone, like geographical or social proximity, provides limited benefits but can explain "why individual rational agents make quite different choices in different settings and, consequently, how economic organisation may differ between communities — an explanatory feat that, for example, transaction cost economics is not able to achieve on its own" (Lorenzen, 2007, p. 802).

Most issues related to university-industry interaction are based on different institutional norms in academia and the private sector (Dasgupta & David, 1994). Some of these issues in inter-organisational collaborations such as communication problems are often attributed to a lack of geographical proximity (see e.g. Cramton, 2001), even though the root cause is actually a lack of organisational proximity (Knoben & Oerlemans, 2006). The latter can enable and, by the same means, prohibit formal and informal interactions between organisations (Rallet & Torre, 1999). In the context of university-industry interaction, all aspects of organisational proximity, including cultural aspects (Bjerregaard, 2010), institutional aspects (Bruneel et al., 2010) and logic (Murray, 2010; Sauermann

& Stephan, 2013), regulatory (Jacobsson & Karltorp, 2013), and social aspects (Heblich & Slavtchev, 2014), have been investigated. Few studies have incorporated multiple aspects of organisational proximity (see e.g., Hong & Su, 2013; Giaretta, 2014; Küttim, 2016; Steinmo & Rasmussen, 2016; Villani et al., 2017). This is important because the proximity dimensions that are important when initiating interactions with universities are not equal to those that are important to maintain successful collaborations (Steinmo & Rasmussen, 2016). Different dimensions of proximity also influence each other and lead to changes over time (Knoben & Oerlemans, 2006).

Entrepreneurial universities contribute to the development of the local EE (and by extension their own UE) "by acting as a boundary spanner and by building and orchestrating the network of the stakeholders" (Schaeffer & Matt, 2016, p. 724), thereby having "an organizing effect on local social capital, yielding specific kinds of benefits for the firms to which they become affiliated" (Kemeny et al., 2016, p. 1117). Universities, with both local and global links can help companies to become better connected by sharing their social capital. In UEs, with an explicit focus on both local and national/global collaborations and relationships, social capital (network proximity) is more important for universities than geographical proximity. Furthermore, the assumption in this study is that companies only consider working with those universities and academics that have expertise in the required area and technological proximity will therefore also not be considered explicitly.

Different intermediary organisations can reduce proximity along different dimensions. They "address different proximity dimensions depending on the prior experience of academic and industrial actors and the nature of the knowledge that is transferred" (Villani et al., 2017, p. 86). They add value via these bridging or brokering functions, which is missed by studies that only focus on non-intermediated university-industry interactions (Al-Tabbaa & Ankrah, 2019; Tether & Tajar, 2008). TTOs play a particularly "central role in supporting academic entrepreneurship at the operational level based on its evolution from a revenue maximising model to a model that takes account of social and economic regional development" (Schaeffer & Matt, 2016, p. 724). Both internally and externally, they often work with inexperienced parties, which makes increasing the cognitive aspect of organisational proximity a core activity (Villani et al., 2017).

2.5 Drivers of Academic Entrepreneurship

Academic entrepreneurship is crucial for technological development and innovation and universities play a key role in many ecosystems for (regional) economic development (Cohen et al., 2002). It is, however, "a challenging process that is enabled by a combination of science-push, demand-pull, and institutional mechanisms that constitute a dynamic innovation system" Wright & Phan (2018, p. 2). Recognising different drivers of academic entrepreneurship is important for understanding the evolution of university-industry interaction and, by extension, the university ecosystem (De Fuentes & Dutrénit, 2012).

These drivers change over time as a result of co-evolutionary dynamics among the university (and the university sector as a whole), the industrial partners (and their evolving absorptive capacity), and the general environment, which represents national laws, policies, and institutions (Mowery & Sampat, 2005). The question whether to interact with universities is a business decision for companies, whereas academics make decisions within their academic framework and respond to different incentives (De Fuentes & Dutrénit, 2012). This section will focus on overarching drivers of university-industry interaction that shape the incentives and motivations of individual academics or companies, rather than these incentives themselves.

2.5.1 Research Intensity and Prestige

Universities' research performance and their research prestige are closely linked to their level of industry engagement (Mansfield & Lee, 1996; Tornquist & Kallsen, 1994). Empirical studies have shown that "general university prestige increases the licensing rate over that predicted by past performance, [...] this remained true across several measures of prestige, and after controlling for the rankings of engineering and other technical programs" (Sine et al., 2003, p. 491). Prestige increases licensor's legitimacy and, hence, increases the creditability of the patents (Ruckman & McCarthy, 2017). Other studies have only confirmed this correlation for collaborative research (Schartinger et al., 2001). This can still be interpreted as evidence that past performance is not sufficient to predict demand as argued by researchers in sociology and organisational studies (Podolny, 1993). In general, university prestige increases the probability of interactions with external partners through four mechanisms that go beyond the influence of past performance (Sine et al., 2003, p. 482):

- the halo effect;

- increased visibility;
- increased credibility; and
- buyer preferences to transact with more prestigious others.

Top-tier research universities are subject to a *halo effect* when it comes to the perception of the work of their academics (Crane, 1965; Pitsakis et al., 2015). A halo effect occurs when external individuals struggle to evaluate universities "as a compound of separate qualities and to assign a magnitude to each of these in independence of the others" (Thorndike, 1920, p. 28). In academia, this is evident across both different faculty as well as different activities. Submission for journal publications from researchers at leading universities, for example, appear to be of higher quality to the editors because of overall reputation of the university (Wilson, 1958). This reputation, however, might not be based on the achievement of this particular academic or the department or faculty. Similarly, universities can benefit from their research prestige, even in fields such as the humanities and social sciences, to increase their licensing of scientific and technical inventions (Sine et al., 2003). It is, however, not only the core activities that lead to a skewed perception of other activities, but also vice versa. For example, the social impact of university spin-offs has a positive effect on university research due to a *peripheral halo effect* (Pitsakis et al., 2015, p. 321). Hence, a holistic approach to engagement with industry is not only required to create synergies and make better use of resources (Levie, 2014), but to attract new collaborator or industry partners due to the their inability to separate different performance indicators (Cooper, 1981a,b).

Institutional prestige helps acquiring resources, which, in turn, will lead to increased performance, which will further strengthen the prestige, and so on (Podolny, 1993; Roberts & Dowling, 2002). With a halo effect for the whole university, this can lead to *Matthew effects*, i.e. the successful ones get more successful (Merton, 1968). This seems to be a more suitable explanation for the entrepreneurial performance of top-tier research universities compared to the argument that these institutions only develop superior know-how and technologies (Henderson et al., 1998; Sine et al., 2003).

In addition, university rankings (as a measure of prestige) are often used at face value by students, companies, and other stakeholders, even though they are sensitive to the conceptual framework, including the weighting of items or their aggregation, which favour some universities over other (Saisana et al., 2011). As an unintended consequence, many universities *play the game* in order to improve their ranking, which might compromise other goals and priorities. Consequently, research prestige is important for academic entrepreneurship and the evolution of the university ecosystem, but other factors require attention as well.

2.5.2 Entrepreneurial Reputation

While the overall institutional reputation works for top universities, there are also other universities that generate significant volumes of entrepreneurial activities despite not benefiting from halo effects. Research has shown that informal activities can lead to a gain in reputation, prestige, and influence for the university (Abreu & Grinevich, 2013). Other studies have shown that patents from universities "with technological prestige, experience at licensing, and combined technological depth and breadth have a greater chance at being chosen by licensees" (Ruckman & McCarthy, 2017, p. 667).

For this study, the proposition is that all entrepreneurial activities contribute to an institutional *entrepreneurial reputation*. Entrepreneurial reputation is an organisational reputation, which can be defined as "stakeholders' perceptions about a university's openness, flexibility, and ability to create value through formal and informal entrepreneurial activities relative to competitors" (adopted from Rindova et al., 2005, p. 1033).

Previous experiences with an academic partner can be a crucial factor for repeated interactions (social proximity), particularly when the interaction was deemed successful (Schartinger et al., 2001). There are clear reputational benefits for both the individual academic and the university for working with industrial partners that go beyond the dyadic interaction (Grimaldi & von Tunzelmann, 2002). Similar to research prestige, this can lead to an entrepreneurial halo effect (that makes a less research-intensive university attractive for collaboration), gains in visibility and creditability, and lead to an increased demand compared to other universities (Sine et al., 2003). The result can be a reinforcing feedback loop, in which e.g. increased income from commercialisation activities lead to a higher probability of licensing in the future and a higher entrepreneurial reputation, which means that "an initial prestige effect becomes embedded and strengthens status differentials in a circular flow of advantage to prestigious actors" (Sine et al., 2003, p. 495). There are, however, no empirical studies that show the relative impact of this reputation compared to e.g. the research prestige or how the entrepreneurial reputation develops over time and spreads through an ecosystem.

2.5.3 Individual Networks

Despite the institutional focus of this research, individual academics play a crucial role in academic entrepreneurship through fostering and maintaining relationships with other ecosystem actors (Hmieleski & Powell, 2018). In many cases, it is existing links and "strong, trusting relationships between people in business and academia" (Dowling, 2015, p. 2), rather than between the institutions that drive academic entrepreneurship (Hughes, 2011; Casper, 2013; Frølund et al., 2018). Individual beliefs and motivations of academics also determine in which ways and to what extent they engage with industry, despite the institutional values and strategies (Bercovitz & Feldman, 2008; Boardman & Ponomariov, 2009; Lam, 2011; Grimm & Jaenicke, 2012; Balven et al., 2018; Hmieleski & Powell, 2018).

From an industry perspective, many collaboration decisions come down to the creditability of the academic partner, i.e. "the ability to deliver the promised knowledge and experience of a particular field when entering into a collaborative linkage with a university, and represents the firms' assessment of the usefulness of the university as a potential partner" (Johnston & Huggins, 2018, p. 1). The subject of this evaluation is usually the individual academic rather than the university as a whole (Johnston & Huggins, 2018). However, this might be biased by a halo from a few entrepreneurial academics with a proven track record at the same institution or the university's history of delivering on different types of projects.

The network structure of the university ecosystem as well as the regional EE "will strongly influence the density of contacts linking university scientists with individuals in industry, and through doing so, impact the density of networks through which university knowledge can be commercialized" (Casper, 2013, p. 1313). The networks of academics and firms are often disjoint, which makes collaborating more attractive for both parties to get access to a wider network (Buenstorf, 2009). Furthermore, intermediary organisations such as TTOs often try to initiate contacts but are limited in their abilities in this regard (Krücken, 2003). Likewise, companies rely on the networks of their individual researchers to initiate and maintain relationships with universities, as they usually do not have a department dedicated to interactions with universities (Frølund et al., 2018). The external environment, including funding and project mechanisms, are also important factors shaping individual networks beyond the opportunity recognition and exploitation of the individual (Castillo Holley & Watson, 2017).

2.5.4 Government and Policy Push

Governments around the world have designed policies to stimulate academic entrepreneurship, which are increasingly specialised and sophisticated (D'Este & Patel, 2007; Godin & Gingras, 2000a; Wright et al., 2007; Rasmussen & Rice, 2012). These government programmes go hand in hand with the increasing institutionalisation of entrepreneurial activities, which assumes that university-industry interaction mostly driven by personal contacts is insufficient (Geuna & Muscio, 2009). The most common objectives of governments include "overcoming 'market failures' in R&D arising out of long time horizons, incomplete appropriability, etc.; making government laboratories more competitively conscious; harnessing the talents of university staff and graduates for national benefit; underwriting collaborative interaction of firms and academia; upgrading the country's international competitiveness in existing areas; and developing new areas of international strength" (Grimaldi & von Tunzelmann, 2002, p. 167).

Key government approaches targeting universities focus on changing the attitudes and the culture among academics, increasing competencies in different entrepreneurial activities as well as including market and demand factors in academic research (Rasmussen & Rice, 2012). A key factor is the decrease in public university funding, which results in funding gaps and makes it necessary for universities to explore other funding opportunities (Chrisman et al., 1995; Slaughter & Leslie, 1997; Gulbrandsen & Smeby, 2005). There is an overall trend within the EU towards competitive, contract-based funding. The UK is an example for a high proportion of mission-oriented, competitive policies, whereas Italy still has a higher share of proportional allocation mechanisms (Geuna, 2001). These changes in university funding combined with the legitimisation of economic development (Philpott et al., 2011) and addressing grand societal challenges (Fini et al., 2018) as functions of higher education had a massive impact on universities' entrepreneurial orientation.

In the UK, public funding is also essential for most university spin-offs (Hewitt-Dundas, 2015). Government and policy makers need to recognise the different needs of e.g. local (often lifestyle) businesses or high-tech companies that compete globally and require high upfront investments and support (Zahra & Wright, 2011) and develop support based on what type they want to grow (Wright, 2014). However, this can influence the commercialisation route as universities are keen on pursuing spin-off creation if funding is available rather than licensing deals (as most technologies are at an embryonic state) (Castillo Holley & Watson, 2017). Similarly, collaborative research projects leverage industrial funding and in-kind contributions, but depend heavily on the availability of public funding (D'Este & Perkmann, 2011). Governments can support academic entrepreneurship and commercial exploitation of academic research via direct investments in science parks (Zou & Zhao, 2014), entrepreneurship education (Rasmussen & Sørheim, 2006), innovation awards (Eesley et al., 2016), engineering research centres (Boardman & Corley, 2008), or national cross-sector programmes (see e.g. Ayoub et al., 2017; Niosi, 2006; Siegel & Wright, 2015a).

Furthermore, changes in legislation relating to the ownership of university IP rights have spurred in interest among universities to commercialise "their" IP (Geuna & Rossi, 2011; Powers, 2004). These changes have been witnessed predominantly in the US and Europe. The most popular example is the Bayh-Dole Act of 1980 in the U.S. (see e.g. Mowery et al., 2001; Mowery & Sampat, 2005; Sampat, 2006; Kenney & Patton, 2009; Grimaldi et al., 2011), but legislation also changed e.g. in Italy (Baldini et al., 2006), France (Mustar & Wright, 2010), Norway (So et al., 2008; Mervis, 2016), Finland (Ejermo & Toivanen, 2018), and Germany (So et al., 2008). Despite the recent changes, the national IP regulations are heterogeneous and vary significantly among countries in Europe (Grimaldi et al., 2011).

Many policies and funding mechanisms are based on myths around cases like Stanford University, which has recently been portrayed as the originator of Silicon Valley, thereby disregarding the circumstantial factors that led to the development of this ecosystem and making it look like a manageable, top-down process (Macdonald, 2016). This might be particularly problematical for teaching-led or even mid-range research universities, which do not have a world-leading research base or are embedded in mature ecosystems (Wright, 2014; Wright et al., 2008). This is further supported by uncertainty for policy makers about the drivers of e.g. contract and collaborative research and whether these can be stimulated in the same way that licensing or spin-offs are targeted by different policies (Perkmann et al., 2013). In general, this leads to four main issues (Godin & Gingras, 2000a, p. 626):

1. increased concentration of resources;
2. disproportionate incentives for short-term foreseeable research endeavour;
3. conflicting incentive structures; and
4. exacerbation of the impact of cumulative and self-reinforcement phenomena present in the process of scientific production.

Most policies and government initiatives aim to stimulate the supply side, i.e. create incentives (or needs) for universities to interact with industry, but in the absence of incentives for companies and other ecosystem stakeholders, i.e. stimulating the demand side, most policies will not be effective (Fontana et al., 2006). Key government approaches targeting industry focus on increasing competencies among firms, sparking their interest to work with universities, as well as schemes to mitigate risk and uncertainty on the industry side (Rasmussen & Rice, 2012). In addition, there are different mechanisms for partnerships between companies and universities to leverage industry funding for additional public support, mostly through research centres (Behrens & Gray, 2001). However, the complexity and bureaucracy of public support programmes can be a powerful barrier for companies and especially SMEs to engage with universities. Therefore, policy makers should "reduce complexity wherever possible and, where simplification is not possible, every effort should be made to ensure that the interface to businesses and academics seeking support for collaborative R&D is as simple as possible" (Dowling, 2015, p. 2).

While knowledge transfer and commercialisation instruments have traditionally been at the centre of attention of policy makers (Bekkers & Bodas Freitas, 2008), there has been a realisation that there is no 'one-size-fits-all' approach (Grimaldi et al., 2011). In particular, national policies for universities or academic entrepreneurship should include leeway and flexibility for institutions and regions, which allows them to evolve based on their history, track record in working with industry, existing links, culture, and individual strength as an institution (Clarysse et al., 2005; Jain & George, 2007). Furthermore, all policies should not overemphasize one single activity, but allow for diversity (D'Este & Patel, 2007; Bekkers & Bodas Freitas, 2008). Not all universities need to address all kinds of entrepreneurial activities with the same intensity, which is often a policy assumption, and the *optimal* portfolio depends on institutional and ecosystem characteristics (Grimaldi et al., 2011).

In relation to the dynamic states model, universities implement different strategies to respond to the environment set by governments and public policy, with unintended consequences such as inter-institutional competitions for funding and enrolment numbers that breaks down further to intra-institutional competition among faculties, departments, and research groups (Etzkowitz, 2003b; Galbraith, 1998). The variety of strategies and approaches by universities can be explained by the "complicated and disparate roles that universities play in all political economies" and ecosystems (Grimaldi et al., 2011, p. 1047).

2.5.5 Income Stream for Universities

Universities have a special role within society, economy, and various ecosystems as described in Section 2.2.3, but they do require funding like any other actor from an economic perspective (Florida, 1999). Yet, the relative share of public funding for universities and academic research has declined over the past decades (Godin & Gingras, 2000a). Together with the shift towards competitive, contract-based funding, generating additional income was ranked as the most important benefit of industry engagement for academics to sustain their research base, with knowledge exchange being a very close second (Meyer-Krahmer & Schmoch, 1998).

While commercialisation activities in particular are seen as a means of income generation for universities, only a few world-class universities are actually generating net profits (Lester, 2005). The success of these universities to attract substantial amounts of money through entrepreneurial activities leads to others struggling with continuously decreasing resources, which can ultimately amplify a Matthew Effect among universities and their research output in general (Geuna & Nesta, 2006). However, more research is required to understand the focus of universities on revenues from IP in general as well as in comparison to other entrepreneurial activities (Grimaldi et al., 2011).

In addition to the direct income, successful entrepreneurial activities attract donations from alumni and other private donors (Siegel & Wright, 2015a). This includes general donations to the university but also earmarked funds for technology commercialisation or student entrepreneurship (Levie, 2014; Siegel & Wright, 2015a). Even though entrepreneurial activities, and commercialisation activities in particular, are not profitable for most universities at the institutional level, most universities have policies in place that allocate a certain proportion of the income to the individual academic or their department. This can be crucial for sustaining future research activities (Buenstorf, 2009; Lai, 2011; Poyago-Theotoky et al., 2002). Support can also include equipment or access to industry facilities (in-kind support) as well as opportunities for student placements, graduate employment or staff exchange (Buenstorf, 2009; Caldera & Debande, 2010; Grimaldi & von Tunzelmann, 2002; Poyago-Theotoky et al., 2002).

2.5.6 Technology Push

Commercialisation activities such as licensing and spin-off creation are examples for technology push processes. This is also conceptualised in the Triple Helix model, with universities as the origin of knowledge and many inventions. These are developed outwith the private sector and then *pushed* out to industry for further development and introduction to the market, supported by government programmes (Etzkowitz & Klofsten, 2005; Bercovitz & Feldman, 2006; Gunasekara, 2006). The focus was on technologies and knowledge that is easily codified and, therefore, can be relatively easily further developed into marketable products and processes (Tidd et al., 2001; Rossi & Rosli, 2013). Many of these inventions do not have an established or even clearly identified target market at the time of transfer from the university to industry, particularly if they were developed without any input or funding from industry (Swamidass & Vulasa, 2009). These are interactions with the ecosystem, "where persuasion instead of listening is the goal" (Spivey et al., 1997, p. 365).

Yet, academics are also crucial during the initial stages of collaborative or contract research endeavours, which suggests that these activities are also "more a *technology push* from university to industry rather than a *technology pull* by industry" (Goel et al., 2017, p. 512, original emphasis). In sectors such as biotechnologies and life sciences, collaboration and co-financing of R&D have created a "long-term, sustained example of technology push" (Tait et al., 2002, p. 254).

In more extreme cases, there might be competition between universities with similar research foci, who are marketing technologies and know-how to the local entrepreneurship ecosystem or even globally within innovation ecosystems (Sine et al., 2003). A focus on technology push models is often recognised in embryonic or weak ecosystems, where there is a lack of R&D and demand from other actors (Clarysse et al., 2005). Nevertheless, an ecosystem cannot sustain on technology push, but requires active input from companies and "market-related considerations" (Mian, 2011, p. 117).

2.5.7 Pull from the Ecosystem

Basic research in academia is concerned with understanding natural, technical, social, or economic phenomena and the majority of academic research is basic in terms of trying to understand these phenomena at a fundamental level. Nevertheless, this research is still influenced by "the pull of important technological problems and objectives" (Rosenberg & Nelson, 1994, p. 323). Innovation is not simply a by-product of the creation of technical or scientific knowledge in an *ivory tower*, but stems from and is influenced by a variety of sources (Tidd et al., 2001; Rossi & Rosli, 2013).

Many academics who engage in entrepreneurial activities are in fact interested in receiving intellectual input and expand their research in addition to monetary rewards from these activities (De Fuentes & Dutrénit, 2012; D'Este & Perkmann, 2011; Lee, 2000; Meyer-Krahmer & Schmoch, 1998; Perkmann & Walsh, 2009). Activities such as collaborative and contract research as well as consulting are driven by *research-related motives*, exchanging ideas, receiving feedback from identifying and testing commercial applications, and developing new standards (D'Este & Perkmann, 2011; Grimaldi & von Tunzelmann, 2002). Furthermore, these activities positively influence curriculum design and industrial applications can be used for case studies (Grimaldi & von Tunzelmann, 2002; Poyago-Theotoky et al., 2002). This has also called "reverse technology transfer", i.e. knowledge and technological know-how that flows from industry to the universities and the academics' labs (Poyago-Theotoky et al., 2002, p. 17).

Entrepreneurial universities are trying to enable and nurture these interactions between their faculty and non-academic partners. Even though TTOs (as the most common intermediary and support unit) are established, there is often no significant growth in entrepreneurial activities as there is no internal support beyond the TTO, accompanied by a lack of capabilities both within the TTO and among academics, and the TTO has no track record due to its embryonic nature (Baldini, 2009; Lockett & Wright, 2005). Academic entrepreneurship needs a supportive ecosystem, including infrastructure, financial incentives, firms with absorptive capacity to utilise academic research and provide intellectual input (Degroof & Roberts, 2004; Grimaldi et al., 2011). Many non-elite research universities have developed an entrepreneurial reputation by reducing bureaucracy, simplifying their processes, and providing incentives for their faculty to engage with businesses. With the shift from ad hoc interactions to strategic partnerships, universities try to further incorporate the needs of their partners by becoming a reliable partner who supports the firm in many ways beyond simple problem solving.

Both technology push models and models of market pull are insufficient and have been replaced by non-linear models that employ evolutionary approaches and focus on networks and the co-evolution of institutions and technologies within ecosystems (Etzkowitz & Leydesdorff, 2000; Nelson, 1995). This raises the need to consider the firms' perspective, their engagement within the university ecosystem through different mechanisms and the relevance of partnerships.

2.6 Industry Perspective

Most companies conduct their R&D internally, without any (formal) collaborations (Tether, 2002). However, firms are increasingly under pressure to innovate and bring new technologies and processes to the market. With the rise of the knowledge economy, firms often want "to skew the flow of knowledge in their favor" (Sorenson et al., 2006, p. 994). Collaborations with different actors in the ecosystem to access external knowledge and resources can support the innovation process (Chesbrough, 2006a,b). The main reason for this is that "innovation occurs primarily through new combinations of resources, ideas, and technologies, a fertile R&D environment relies on a constant inflow of knowledge from other places" (Fey & Birkinshaw, 2005, p. 600). Therefore, most collaborations aim at *new-to-market* innovations, i.e. "higher level innovations", rather than *new-to-firm* innovations (Tether, 2002, p. 947).

2.6.1 Accessing External Knowledge

Firms turn to external sources such as universities, competitors, or suppliers, to gain competitive advantage through constant technological development (Cohen et al., 2002; Lee & Win, 2004; Fabrizio, 2009). There are many reasons why companies collaborate for innovation, but in the most general sense the reasons are a lack of internal resources and capabilities (including knowledge), mitigating risks involved in R&D, or a combination of both (Tether, 2002). Different types of partners have different impacts on innovation performance and outcomes (Belderbos et al., 2004; Nieto & Santamaria, 2007). There is no consensus in the existing literature in terms of ranking different types of partners according to their contribution to innovation, but a diverse network of collaborators is recommended (Nieto & Santamaria, 2007). In particular, the potential benefits involve:[16]

- economies of scale and scope in research;
- avoidance of unnecessary duplication of research and increase efficiency, synergy, power through network;
- acceleration of R&D and innovation process;
- share R&D, product, or process costs and investments in equipment and machinery;

[16]This list was compiled from Crawford & Gram (1978); Grimaldi & von Tunzelmann (2002); Hagedoorn et al. (2000); Lee & Win (2004); Martínez-Noya & Narula (2018); Sakakibara (2002).

- access complementary resources, research know-how, and related technologies to exploit own resources;
- use collaboration as learning vehicle to accumulate and deploy new skills and capabilities;
- mitigate risks through pooling of resources;
- improve competitive position or entering new markets;
- create new investment options; and
- enhancement of reputation and public image.

R&D collaborations have been studied predominantly through either transaction cost theory (Williamson, 1975), i.e. an economic perspective, or from a strategic management perspective. The latter has introduced a variety of theoretical lenses to this area of research, with the most commonly used ones being the resource-based view (RBV) of the firm (Barney, 1991, 1995; Barney et al., 2011; Das & Teng, 2000; Wernerfelt, 1984, 1995) and a dynamic capabilities approach (Teece et al., 1997). Other theoretical perspectives include a knowledge-based view and organisational learning (Kogut & Zander, 1992) and social network theory (Gulati, 1995).

A transaction cost approach does not account for "many of the strategic advantages that alliances can offer, such as market growth or inter-firm learning through alliances; motivations that during recent decades have become more important for firms to form R&D alliances" (Martínez-Noya & Narula, 2018, p. 5). Collaborations are not just based on cost-minimising considerations, but also involve the previously mentioned goals and benefits. The RBV assumes that "firms obtain sustained competitive advantages by implementing strategies that exploit their internal strengths, through responding to environmental opportunities, while neutralizing external threats and avoiding internal weaknesses" (Barney, 1991, p. 99), whereas a dynamic capabilities approach focuses on "the firm's ability to integrate, build, and reconfigure internal and external competences to address rapidly changing environments" (Teece et al., 1997, p. 516). Based on path dependencies and a certain market position that a firm occupies, the latter extends the RBV and includes the continuous development of capabilities. In general, strategic management approaches emphasise the need for forms to increase their resource base and capabilities, both organisational and technological (Das & Teng, 2000; Martínez-Noya & Narula, 2018).

A key driver is openness to new ideas, which can be seen as part of a company's absorptive capacity (Fey & Birkinshaw, 2005). Companies conduct R&D not just to increase their capabilities but also to increase their absorptive capacity, i.e. their ability to learn from external sources (Cohen & Levinthal, 1989, 1990). It also helps them to identify *economic knowledge* (Audretsch & Keilbach, 2004) and has been the most common approach for researching the integration of new knowledge, "with less attention given to the impact of competencies and culture (including 'not invented here')" (West & Bogers, 2014, p. 814). Absorptive capacity assumes that a company can appropriate knowledge equally from any other source (Lane & Lubatkin, 1998). This is, however, not the case. *Relative absorptive capacity*, i.e. absorptive capacity at the dyadic level, which includes the similarity of the two partners with regard to management structures, norms, R&D culture, and knowledge base, can better explain inter-organisational learning (Lane & Lubatkin, 1998).

Universities provide an almost "inexhaustible source" of new ideas, knowledge, and technical know-how (Berbegal-Mirabent, Sánchez García, & Ribeiro-Soriano, 2015). However, working with universities is distinctively different from collaborating with other partners, such as vertical collaborations along the value chain with suppliers and customers or horizontal collaborations with competitors (Fritsch & Lukas, 2001; Fey & Birkinshaw, 2005; de Faria et al., 2010). The latter is also known as *coopetition* (Bengtsson & Kock, 2000; Gnyawali & Park, 2011; Tsai, 2002), the "most complex, but also the most advantageous relationship between competitors" (Bengtsson & Kock, 2000, p. 411). Coopetition in the form of e.g. research consortia is often used as a means to develop industry standards (Gnyawali & Park, 2011). Working along the value chain is primarily used to reduce costs and to prevent the company from diverging from its core competencies (suppliers) as well as increasing user friendliness and the *job-to-be-done* (customers) (Bettencourt & Ulwick, 2008; Johnson et al., 2008; Belderbos et al., 2015; Liu et al., 2017).

Importance of universities as sources of knowledge and innovation is often over-estimated, particularly when focusing only on high-tech companies or certain sectors. When the focus shifts to the entire business population, including firms with and without internal R&D, the importance of universities decreases. The importance of customers and internal R&D outrank universities (Laursen & Salter, 2004). However, this does not diminish the role of universities in general but calls for more nuanced studies. Universities, along with customers, are "important sources of knowledge for firms pursuing radical innovations, which facilitate growth in innovative sales in the absence of formal R&D cooperation" (Belderbos et al., 2004, p. 1477). For projects funded under the European Commission FP7 Programme, those that include academic partners "appear to be able to reap higher knowledge spillovers" (Szücs, 2018). Collaborations with universities have an almost immediate positive effect on company R&D compared to working with competitors. The latter has a greater impact in absolute terms, but it takes longer because companies are usually more secretive whereas the open culture of academic forms a basis for organisational proximity (Belderbos et al., 2015).

A major driver for the engagement with universities is also to mitigate development risks. In the life sciences, for example, clinical trials "from single private companies are four times more likely to be successful than are trials in which public and private organizations collaborate" (Crispeels et al., 2017, p. 273). This is explained by firms actively looking for universities as partners for riskier projects. Large firms benefit the most from working with universities, which can be explained by a greater amount of resources that they can devote to the collaboration and the greater absorptive capacity that they possess. Furthermore, start-ups benefit more than SMEs, but this could partially be explained by a sampling bias and spin-offs included among the start-ups, which stem from the university and already share a high organisational proximity (Cohen et al., 2002). While there are reputational gains through collaborating with external partners in general, firms gain additional legitimacy from working with universities (Barringer & Harrison, 2000; Hong & Su, 2013).

The process of interacting with universities and other external partners can be divided into four phases, namely *obtaining*, *integrating*, and *commercialising* external innovations, with recurring *interactions* among the collaborators as feedback between the first three phases (West & Bogers, 2014). In the following, the partner selection (obtaining) and the formation of long-term-strategic partnerships with recurring interactions will be discussed in more detail in response to the shift in strategy of universities away from ad hoc interactions.

2.6.2 Selection of Academic Partner

Academic research often complements in-house R&D activities and thereby contributes to the company's ability to innovate (Tether & Tajar, 2008; Baba et al., 2009). In general, the criteria for partner selection depend on "differential levels of process manageability and outcome interpretability inherent in a strategic alliance" (Shah & Swaminathan, 2008, p. 471). Based on a meta analysis of the existing literature, companies look for trust (institutional/social proximity aspect), commitment and the complementarity of resources, as well as the financial/commercial return from the collaboration (Martínez-Noya & Narula, 2018; Shah & Swaminathan, 2008).

Engaging with a university regardless of the channels is a strategic decision (Mindruta, 2013). Firms prefer to work with local top-tier research universities and, if they have to compromise on either aspect, most firms prefer top-tier universities over local universities (Laursen et al., 2011). There is also a positive and statistically significant effect of the general university ranking and all innovation indicators of the industry collaborator (Szücs, 2018) and the attraction of companies to 'star scientists' (Zucker et al., 2002). Firms need to invest substantial amounts of resources to initiate and develop collaborations with universities, particularly when lacking proximity across either dimension and additional resources have to bridge the gap (García-Aracil & Fernández de Lucio, 2008; Simonin, 1999). From the firm's perspective, this investment might be too high for the expected returns from a more teaching-led university (Laursen et al., 2011). This is another indicator that proximity is less important, particularly when the firm possesses a relatively high amount of absorptive capacity based on in-house R&D activities (Beise & Stahl, 1999). Organisational proximity and particularly the cognitive aspect are important enablers for science-based firms, whereas engineering-based firms rely on the social aspect of organisational proximity and also geographical proximity still matters (Steinmo & Rasmussen, 2016).

Social proximity aspects are almost always a factor and can bias the decision regarding a collaboration partner and lead to the "paradox of embeddedness" (Uzzi, 1997). When firms must decide between a previous collaborator or an unknown partner, "they tend to show a preference for allying with familiar ones despite the latter sometimes offering a priori better technological capabilities" (Martínez-Noya & Narula, 2018, p. 7). On the other hand, companies might also be reluctant to depend too much on universities, not to mention a single university, especially for technologies or know-how that is relevant for their core competencies and creates their competitive advantage in the market place (Hamel & Prahalad, 1994). Universities can serve also as a "landing pad" for companies who want to increase their engagement in the local entrepreneurship ecosystem (other opportunities include working with government or local start-ups, among others) or gain access to a particular innovation or knowledge ecosystem (Frølund et al., 2018). The involvement of entrepreneurial universities in all of these ecosystems and the wide range of activities that they conduct, can provide companies with a good starting point for further interactions.

Therefore, it is important to learn from both, firms that collaborate with universities and those that do not (Bruneel et al., 2010). Only this combination will lead to an understanding of how barriers can be overcome, what incentives work, and what drives the evolution from ad hoc to strategic partnerships.

2.6.3 Relationships and Partnerships

Innovative companies should aim for many superficial and few intense, long-term partnerships (Dahlander & McFarland, 2013). Collaborating with universities has a positive effect on the R&D performance of firms, whereas contracting external partners (e.g. outsourcing of R&D activities or clinical trials) has a negative effect (Fey & Birkinshaw, 2005). In a partnership approach, more knowledge is being exchanged due to "the structure of social interaction, relationship quality, and partner network ties" (Fey & Birkinshaw, 2005, p. 616). Long-term partnerships with universities are desirable, yet many companies struggle to initiate and develop them effectively despite having sufficient financial and human capital (Frølund et al., 2018).

Firms are generally interested in sustainable, long-term benefits when conducting R&D and invest in the development of absorptive capacity as there is a significant time lag (Arvanitis et al., 2008; De Fuentes & Dutrénit, 2012). Capabilities required for the pursuit of "explorative innovation in firms are shown to be best nurtured in a collaborative relationship of strategic partnership and mutual understanding rather than an arms' length interaction beset by tensions, conflict, distrust and culture clash" (Ryan et al., 2018, p. 11). Long-term, strategic relationships are, however, not purely based on individual relationships but take into consideration the fit between organisations (organisational proximity) and the expertise of universities (the right degree of technological proximity and the cognitive aspect of organisational proximity) (Frølund et al., 2018).

Previous continuous R&D collaborations with institutional partners is "an antecedent to the establishment of new R&D collaboration with industrial partners, and that discontinuation of a particular type of R&D collaboration is likely to lead to a restart of such R&D collaboration efforts" (Belderbos et al., 2018, p. 285). Continuous collaborations are desirable because it builds trust and leads to learning and adaptation by both partners and develops organisational proximity (Gulati, 1995). This should also include learning from unsuccessful interactions. Collaborations can end naturally because the project fulfilled its goal or because the collaboration failed, with the rate of the latter being as high as 30-50% (Belderbos et al., 2015). This also varies depending on sectors and technologies. For example, firms reported that 76.8% of all collaborations (completed and failed) with universities are of no significant importance in the software development process (Segelod & Jordan, 2004). This can help firms to develop better partnering strategies and portfolios (Nieto & Santamaria, 2007; Faems et al., 2008; Estrada et al., 2016).

A long-term partnership allows for more effective knowledge exchange because it enables the flow of tacit and more detailed knowledge (Gilsing & Nooteboom, 2006). It also signals to potential partners that a company is a valuable partner in terms of a bi-directional flow of information as well as reliable and trustworthy (Nooteboom, 2004). The preferred entrepreneurial activities of universities are similar to those that contribute to these long-term benefits for firms, namely contract and collaborative research, obtaining property rights (formal activities), and staff exchanges or hiring of staff and graduates (informal activities) (De Fuentes & Dutrénit, 2012). For firms being able to adjust their practices and culture to the academic norms is more important for knowledge co-creation (particularly collaborative research) and less so for knowledge acquisition (De Silva & Rossi, 2018). Given the dynamic nature of many technological fields and the co-evolutionary dynamics of different ecosystems, and "because different contexts may offer different challenges or opportunities for value creation or appropriation, firms need to constantly update and adapt their alliance capabilities" (Wang & Rajagopalan, 2015, p. 254).

Ecosystems can be beneficial for companies due to close proximity across multiple dimensions, but they can also provide a barrier as multiple stakeholders need to be aligned and coordinated (Frølund et al., 2018). Firms must be aware that they do not become too focused on their IE, BE or platform (Cusumano & Gawer, 2002), but exploit opportunities outside the ecosystem that are important to the firm (Nambisan & Baron, 2013). Further analyses are required to understand "how collaborative links develop initially, so future research could focus on the process of partner selection and the way these innovation partnerships function" (Mascarenhas et al., 2018, p. 9) and what entrepreneurial activities of universities play a role and in which order (D'Este & Patel, 2007; Bruneel et al., 2010). In general, relationships between firms and universities are very heterogeneous in nature and this is important for designing effective policies (Fontana et al., 2006). Feedback structures need to be included in models, showing how different actors react to policy changes instead of relying on econometric analyses that treat institutional or ecosystem characteristics as control variables.

2.7 Nature of the Research in this Field

The main field of entrepreneurship research is highly interdisciplinary and lacks a general theory (Shane & Venkataraman, 2000). This is not surprising as it is still a young field and, with regard to Kuhn (2012), new research fields emerge at the borders of existing, more mature fields. Progress has been made as the entrepreneurship research has entered the most prestigious journals, however it appears to be in a stalemate due to a missing unifying paradigm or converging perspectives. Compared to organisational or strategic management, "entrepreneurship studies tend to be less sophisticated in sampling frames, hypotheses development, statistical analysis, and dynamic longitudinal analysis" (Busenitz et al., 2003, p. 237). In recent years however, entrepreneurship has slowly matured as a field of research and achieved legitimacy (Shepherd, 2015).

Academic entrepreneurship and the evolution of university ecosystems are a subdomain of the greater field of entrepreneurship and as a distinct field of research even younger than entrepreneurship itself (Rothaermel et al., 2007). Although principles of entrepreneurship have been applied to academic entrepreneurship (Aldridge & Audretsch, 2011; Clarysse et al., 2011; Kirby, 2006; Rasmussen et al., 2011; Rasmussen & Wright, 2015), it differs to some extent from the main field of entrepreneurship. Particularly in more recent years, academic entrepreneurship is maturing as an independent research field, but "the societal benefits of universities and academic entrepreneurship are the subject of much continuing policy debate" (Wright, 2014, p. 323).

A variety of theoretical perspectives have been applied to the study of academic entrepreneurship, including the theory of the firm applied to TTOs (Chapple et al., 2005; Siegel, Waldman, & Link, 2003); agency and contract theory applied to the relationship between the university and the TTO (Macho-Stadler et al., 1996, 2007, 2008; Markman, Phan, et al., 2005); RBV and entrepreneurial orientation for TTOs and spin-offs (Lockett & Wright, 2005; Mosey & Wright, 2007; O'Shea et al., 2005; Powers & McDougall, 2005; Rasmussen et al., 2011, 2014) as well as generally identifying important capabilities and resources that contribute to academic entrepreneurship (see e.g. Rothaermel & Thursby, 2005; Wright et al., 2009; Xu et al., 2011; Guerrero & Urbano, 2012; Urbano & Guerrero, 2013; Guerrero et al., 2014); dynamic capabilities in an attempt to explain how firms expand their capabilities, especially in non-core areas, or the dynamic orchestration of capabilities by universities to increase value extracted from academic entrepreneurship (see e.g. Santoro & Chakrabarti, 2002; Yuan et al., 2018); or institutional theory (see e.g. Abreu et al., 2016; Boardman, 2009; Jong, 2008;

Erikson et al., 2015). Additional theoretical lenses include transaction cost economics, resource dependency, strategic choice, stakeholder theory, learning theory, institutional theory, interaction theories (e.g. social network approaches) (Ankrah & AL-Tabbaa, 2015). A large portion of the literature fails to specify their theoretical assumptions.

Much research has been quantitative, particularly with regard to the contribution of universities to economic development (Grimaldi et al., 2011), with qualitative studies usually focusing on the individual or university level (see e.g. Mosey & Wright, 2007; Rasmussen et al., 2011), demonstrating the importance of soft and intangible factors that support academic entrepreneurship (Grimaldi et al., 2011). However, many of these approaches do not reflect the complexity of the ecosystem approach (Siegel & Wright, 2015a).

First, it is important to combine the macro, meso, and micro perspective (Cunningham & O'Reilly, 2018). The existing literature has examined the outcomes at the individual and institutional level and their relationship to specific characteristics, but "researchers have yet to make *vertical connections* between micro-level phenomena to macro-level outcomes, not to mention frame these connections in terms of complex interactions" (Hayter et al., 2018, p. 35, original emphasis). This requires "a more holistic systems perspective across different levels of analysis, rather than its current focus on distinct subsystems, which is a reflection of its fragmented and embryonic state" (Rothaermel et al., 2007, p. 740).

Second, only a small fraction of studies at the individual level have considered both the academic and industrial side (see e.g. Lee, 2000; Lam, 2007; Felin et al., 2012) and the co-evolutionary dynamics between them. These dynamics have been suggested and e.g. conceptualised in the Triple Helix model. Examples of these dynamics include resource allocation and utilisations within universities and within the local ecosystem (Rasmussen, 2008; Youtie & Shapira, 2008) or social networks among academics (Hayter, 2016b). However, most of these studies are rather descriptive and do not consider interactions of variety of ecosystem characteristics and actors (Hayter et al., 2018).

Third, it is important to recognise and acknowledge the complexity and dynamism of academic entrepreneurship and (university) ecosystems (Spilling, 1996; Motoyama & Knowlton, 2017).

> "Dynamism is an inherent property of any entrepreneurial ecology. However, extant models do little to explicate the origins and impact of dynamism in entrepreneurial systems. Dynamism is not the same

> as temporality. Dynamism implies a phase change in the structure of a system and the relationships between elements of the system that are triggered by factors, which are temporal, multilevel, and/or multidimensional in nature. Therefore, in contemplating a dynamic system, we should look for triggering factors, paths of change, and new equilibria that describe the new state. In sum, we should think about how the impact of a change in one variable cascades through an entrepreneurial system and leads to changes in the relationships between the other variables." (Phan, 2006, p. 149)

The ecosystem concept with its links to complexity economics and complex systems in general, but most work has been conceptual and adheres to a metaphorical use of the concept (Isenberg, 2016; Roundy et al., 2018). Particularly for UEs, it is important to understand "the ways in which support organizations [and universities] in this region interacted with each other and with entrepreneurs, including explicit cross-organizational collaboration and strategic structuring of resources, significantly impacted the way that entrepreneurs interacted with one another and with organizations, thus deepening our understanding of these connections and identifying intervening points within the ecosystem" (Motoyama & Knowlton, 2017, p. 1).

While many scholars have recognised complexity, linear approaches are still predominant in areas such as strategic management and entrepreneurship as well as academic entrepreneurship (Shook et al., 2003). These traditional approaches, especially mono-method approaches, "offer, at best, incomplete ways to capture the essence of complexity in entrepreneurship" (Najmaei, 2016, p. 33). There have also been suggestions to "open the black box in statistical research on clusters so to arrive at a better theoretical understanding of the type of firms that benefit from localization economies and the conditions, mechanisms and spatial scale through which such benefits are realized" (Frenken et al., 2015, p. 19). Therefore, new methods need to be developed to accompany theoretical advancements like the ecosystem concept (Ketchen Jr et al., 2008). In general, there should be an interplay between theory development and methodological advancements (Van Maanen et al., 2007), which also considers *neglected* methods that have yet to be fully established in addition to completely new ones (Berger & Kuckertz, 2016).

Research through the lens of complexity theory or on complex systems in general, requires research designs and methodological approaches based on *non-linear, dynamic and interrelated causality* (Poutanen et al., 2016). These are usually not mainstream methods and not part of most research training classes and therefore mostly neglected (Berger & Kuckertz, 2016). Multi-methodological research approaches based on different philosophical stances from positivism to interpretivism could be the solution to explain the complexity as they combine the strength of different paradigms and methods (Berger & Kuckertz, 2016). A particular focus should be on *hierarchies*, *agents with schemas*, *positive feedback loops*, *order at the edge of chaos*, and *evolution* (Najmaei, 2016).

While traditional methods try to reduce the system to a set of causal relationship and an error term, complex systems methods "typically show how complex outcomes flow from simple schemata and depend on the way in which agents are interconnected" (Anderson, 1999, p. 220). In line with the principles of complexity economics, the focus is on order creation rather than working under the assumption of equilibrium conditions. This is more relevant to the study of entrepreneurship and entrepreneurial universities because the "creation of new economic order in the form of new firms is what entrepreneurs do" and adding and re-combining knowledge for new innovations is what universities support through entrepreneurial activities (McKelvey, 2004, p. 314). The existing body of literature is not redundant or of less relevance as complex systems models complement other research in most cases by synthesising findings, extending causal structures, and adding levels of aggregation (Anderson, 1999).

As universities, their entrepreneurial activities, and the ecosystems around them are evolving, "so too must scholarly analysis of academic entrepreneurship" (Siegel & Wright, 2015a, p. 584). What is missing is an overarching theoretical and conceptual framework that can synthesise the literature and combine insights from both quantitative and qualitative studies, thereby turning what is often only anecdotal insights into evidence.

2.8 Conclusion and Research Gap

Academic entrepreneurship and the evolution of the entrepreneurial university in ecosystems have received exponentially increasing attention from both policy makers and academic communities over the last decades. Universities underwent radical changes with regard to their mission and activities, from the Humboldt type with a focus on research and teaching to entrepreneurial universities adding the Third Mission and even further towards the "university for the entrepreneurial society" (Audretsch, 2014; Krücken, 2003). This chapter has developed two conceptual contributions that will help synthesise and further develop this field of research:

1. a conceptual model for an inter-organisational university ecosystem that can synthesise emerging research on different types of ecosystems and lead to a better understanding of universities' role; and

2. applying a dynamic states model to entrepreneurial universities, which provides a better conceptual fit to the historical development of universities and how universities are able to affect such shifts in their path dependencies (Grimaldi et al., 2011, p. 1054).

This chapter has also provided a detailed review of the evolution of the entrepreneurial university and formal entrepreneurial activities (licensing, spin-offs, consultancy, contract and collaborative research). Universities differ significantly in terms of their resource and scientific base as well as their entrepreneurial focus and history, and have therefore developed different strategies (Mustar et al., 2006). In general, most universities try to move away from ad hoc interactions and towards strategic partnerships with unclear implications for the external outcomes and potential unintended consequences for internal resource allocations among the three missions of the university.

Furthermore, universities need to actively manage organisational proximity and their social capital in order to initiate and maintain effective collaborations but avoid locks-ins. This will be even more important in the future due to the increasing pressure for collaboration and outreach activities that is driven by a variety of factors. A crucial component was and always will be the industrial partner. Firms are the economic actors that ultimately commercialise technologies and translate scientific know-how into practical applications. Therefore, university strategies need to consider the needs as well as the characteristics and capabilities of firms across different ecosystems and geographical scales when developing new strategies and policies.

There are, however, still unanswered questions and shortcomings within the existing body of literature. A gap with regard to the dynamics of academic entrepreneurship is characterised by:

- The university ecosystem model shows that universities are part of a variety of networks and ecosystems and engage with these with varying intensity. The actual configuration of these different ecosystems is unclear, including the university ecosystem for different universities (Wright, 2014), how e.g. research-intensive and teaching-led universities are "adopting these roles to a different extent along different geographical scales (local, regional, national and international)" (Abreu et al., 2016, p. 2), leading to a more nuanced view how these ecosystems co-evolve with the university (Acs et al., 2014).

- Limitations in this area were previously attributed to a lack of longitudinal data, but more comprehensive datasets are available now and simply not fully exploited yet.

- By the same means, the perspectives of the university and other ecosystem actors have not been combined when studying the dynamics of academic entrepreneurship and evaluating policy implications (Grimaldi et al., 2011; Wright, 2014). Consequently, studies are required that adopt a multi-actor, multi-activity, and multi-scale research designs to understand the interplay between determinants (intra-organisational dynamics), interactions and mechanisms (entrepreneurial activities), and impacts (external/ecosystem dynamics) (Buenstorf, 2009; Gilman & Serbanica, 2014; Hayter et al., 2018). This also includes multiple universities with different characteristics and path dependencies and elasticities in the same study (Krücken, 2003; Siegel & Wright, 2015a).

- The outcomes of academic research are "so widely disseminated and their effects are so fundamental, subtle, and widespread" that there is still a debate about the extent to which universities influence commercial innovation and economic development (Mansfield, 1991, p. 11). Simple *count measures* of key outcomes are insufficient to determine the quality and value of academic research and entrepreneurial activities by universities (Grimaldi et al., 2011). Soft factors and qualitative evidence need to be included and the ways in which long-term partnerships between universities and industry evolve and how they differ from ad hoc interactions in ecosystems needs to be understood.

- Universities develop different types of reputation based on their research performance and entrepreneurial activities. The influence of research prestige has been addressed but how universities develop an entrepreneurial reputation, what the implications are, and whether halo or Matthew effects can explain different growth patterns due to shifts in resources remains unclear (Geuna & Nesta, 2006).

The limitations of the existing body of research are inherently based on the theoretical and methodological approaches that are used in this field, which has already led to calls for more diversity of research approaches (Agrawal, 2001; Berger & Kuckertz, 2016). Therefore, this thesis proposes a complex systems perspective on academic entrepreneurship and will address the outlined gap by answering the following research questions:

1. What is the dynamic relationship between universities' internal capabilities and resources (organisational arrangements), the volume and share of different entrepreneurial activities, and the evolution of the university ecosystem?

2. Is there a path dependency for universities based on different research and entrepreneurial profiles, resource endowments, and historical backgrounds?

3. What are the temporal dynamics of different entrepreneurial activities in the evolution from ad hoc interactions to strategic partnerships between universities and firms?

4. How do the co-evolutionary dynamics between a university's research prestige, entrepreneurial reputation, organisational proximity, and social capital affect its entrepreneurial performance?

The next chapter will further elaborate on the complex systems perspective and how academic entrepreneurship in UEs can be modelled to address these research questions.

Chapter 3

Modelling Academic Entrepreneurship as a Complex System

3.1 Introduction

Conceptualising the interactions between universities and industry as a complex system is a promising approach to address the research questions developed in Section 2.8 and to explore the temporal dynamics and the mechanics within university ecosystems. Section 3.2, however, takes a step back from the complexity economics perspective that has led to the development of the university ecosystem concept and introduces complex systems in more general terms as well as the implications for modelling academic entrepreneurship in university ecosystems. This complexity perspective forms the foundation of this research project. Different modelling and simulation (M&S) approaches have been developed to deal with complex systems, yet they are rarely applied in this area of research. From a management science/operational research (MS/OR) perspective, system dynamics (SD) and agent-based modelling (ABM) are presented as potential simulation approaches. SD and ABM will then be described in more detail and their applicability for academic entrepreneurship is discussed in Sections 3.3 and 3.4, respectively. A summary of both approaches concludes the first phase and outlines the need for a hybrid simulation (HS) approach (Section 3.5).

Based on the results from the summary, a conceptual framework for a hybrid SD-ABM simulation is developed, taking into consideration recent advances in the field of combining SD and ABM as well as HS in general (Section 3.6). This framework leverages advantages of SD and ABM for a better representation of the university ecosystem and to address the four research questions. A key difference between combinations of SD-ABM and SD-DES is that the model structure at the systemic level is not specified in ABMs. This offers tremendous opportunities for capturing emergent behaviour at the SD-ABM interface, yet no theoretical or practical work exists in the literature. This chapter addresses this gap and provides a novel conceptualisation of emergent behaviour based on the hybrid SD-ABM framework for modelling academic entrepreneurship (Section 3.7). The development of the actual SD and ABM models will then be described in the next step.

3.2 Modelling Complex Systems

Models are widely used in various fields and across several disciplines, from social sciences and economics to engineering, psychology, and natural science, among others. The basic understanding of what constitutes a model is to some extent shared among these disciplines, but there are also aspects that are unique to the area of MS/OR. Management science, when put together with operational research, is "the application of scientific [and] mathematical methods to the study [and] analysis of problems involving complex systems" (INFORMS, 2017). Since M&S approaches are not commonly applied to (academic) entrepreneurship, this section will introduce the fundamentals of complex systems and M&S from an MS/OR perspective as a basis for exploring SD and ABM in more detail afterwards.

3.2.1 Complex Systems

There is much ambiguity in the existing literature around the terms complex systems, complex adaptive systems, and complexity (science) (Ladyman et al., 2013). Mitchell (2011, p. 13) offers two definitions for *complex systems* by seeing them as "a system in which large networks of components with no central control and simple rules of operation give rise to complex collective behavior, sophisticated information processing, and adaptation via learning or evolution" and alternatively as "a system that exhibits nontrivial emergent and self-organizing behaviors". The first definition emphasises the interaction of agents, whereas the second one focuses on the widely used attributes self-organisation (macro-level behaviour in the absence of a central controlling unit) and emergence (macro-level behaviour that is hard or impossible to predict emerges from simple rules at the individual level).

The term *complex adaptive systems* emphasises the role of *adaptation* as opposed to non-adaptive complex systems such as many weather phenomena or systems studied in fluid mechanics (Mitchell, 2011). For the sake of clarity and in line with the argumentation by Mitchell (2011), the term 'complex systems' will be used throughout this thesis for all adaptive and non-adaptive complex systems. Complexity has emerged as a scientific field of its own, bringing together researchers from a variety of disciplines (Mitchell, 2011). Complex systems are fairly well understood qualitatively, but questions remain how complex a complex system is and how can complexity be measured? Many approaches and measures have been developed, yet there is no one universally accepted one (Mitchell, 2011). As a result, no single *science of complexity* or *complexity theory* exists yet, despite a wide-spread use of these terms. In general, complex systems are characterised by the following properties (Ladyman et al., 2013):[17]

- non-linearity;
- feedback;
- spontaneous order;
- robustness and lack of central control;
- emergence;
- hierarchical organisation; and
- numerosity.

When addressing socio-economic problems, complex systems provide a means of overcoming the Lucas critique due to the adaptive behaviour of the agents (Rand, 2015). Lucas Jr. (1976) postulated that the (macro-level) predictions from many econometric models for new policies must be wrong by definition, because the model is developed based on the current rule of behaviour at the individual level without taking into consideration that individuals will adjust their behaviour when new policies are introduced. Complex system approaches, on the other hand, offer a means by which analysts can model the adaptation at the individual level to make better predictions of the impact of new policies (Rand, 2015).

[17]Different lists of properties of complex systems have been developed and, while they differ in nomenclature, they agree on the key features (see also Lichtenstein, 2000; Mitchell, 2011).

This is an important aspect for modelling innovative and entrepreneurial behaviour of individuals and organisations. When reflecting on the history of academic entrepreneurship (see Sections 2.3.1 and 2.3.2), it is apparent that both universities and innovative companies have adjusted their strategies significantly based on changes in the external environment, e.g. new laws and policies, changes in public research funding, or increased global competition (Etzkowitz, 1998; Martin, 2012; Lockett et al., 2013). The challenge is to develop a model and identify the boundaries within a system in which "everything affects everything else" within a complex environment (Brailsford et al., 2010, p. 2293).

3.2.2 Modelling and Simulation

A model can be defined as "an external and explicit representation of part of reality as seen by the people who wish to use that model to understand, to change, to manage and to control that part of reality" (Pidd, 2009, p. 10). This definition includes two main aspects; namely (1) models are always a simplification of the real world and (2) every model is developed for a defined purpose. Hence, each model has its boundaries and limitations. There is no rule what degree of complexity is optimal or most appropriate. This degree of complexity, or in turn the degree of simplification, depends on the purpose of the model under given conditions (Pidd, 2010). Focusing mainly on computational modelling in the social sciences in general, Kollman (2012, p. 356) argues that "models should fit in the useful space between obvious and impenetrable". A model is dispersible if either the complexity is not high enough or if it cannot be understood and analysed because it is overly complex.

In a very general sense, a simulation is "imitating the behaviour of some situation or process by means of something analogous" (Chick, 2006, p. 21). In more practical terms, simulation can be seen as "driving a model of a system with suitable inputs and observing the corresponding outputs" (Bratley et al., 1987, p. ix). Similar to modelling in general, the value added by simulations cannot be measured in absolute terms but depends on how well the simulation is designed relative to its purpose. The main purposes of a simulation can be prediction, performance, training, entertainment, education, proof, discovery, or any combination of these (Axelrod, 2006).

Simulation is "a legitimate, disciplined, and powerful approach to scientific investigation, with the potential to make significant contributions to management theory" and research because "organizations are complex systems and many of their characteristics and behaviors are often inaccessible to researchers, especially over time" (Harrison et al., 2007, p. 1243). It can overcome limitations of other methodologies and is, consequently, seen as a suitable approach for management theorists and to reach general management and policy audiences (Shaw & Ertug, 2017). In particular, simulation approaches provide opportunities to contribute to research by (Shaw & Ertug, 2017):

- evaluating alternative models (as a starting point for "strong inference");
- as a triangulation tool ("triangulation validates findings from multiple sources");
- as an inductive exploratory tool ("a means to develop inductive theory"); and
- to evaluate robustness ("evaluate the robustness of a set of results against alternative sets of assumptions, distributional biases, and the like").

From a more practical perspective, simulation offers several advantages for managers and policy makers. First, simulation can foster creativity and experimentation. Many ideas are not pursued as a result of an employee's fear of failure, high risks and uncertainty, or ethical issues. Simulation approaches offer a test run in a risk-free environment (Sterman, 2000; Robinson, 2004; Gilbert, 2008). Furthermore, understanding and knowledge is created not only by analysing the results but also throughout the whole simulation modelling process. Even in the model development phase, a level of understanding and agreement can be reached that makes the actual simulation runs in the end unnecessary (Sterman, 2000; Robinson, 2004). Simulation can also support visualisation potential results, ideas, or strategies (benefits as well as risks) and make communicating these to others within and outside the organisation significantly easier. Lastly, simulation can help building a consensus by bringing together people with different perspectives and letting them share and test their opinions or concerns in order to reach the consensus (Robinson, 2004).

The diffusion of simulation approaches has been slower in business and management fields compared to other social science disciplines, mainly because the role of simulation and their advantages and limitations are not well understood among management researchers (Harrison et al., 2007). Modellers must, therefore, present and communicate simulation designs, assumptions, and findings to a wider audience in a clear and accessible form (Shaw & Ertug, 2017; Sterman, 2000). In addition to a lack of understanding among the researcher and practitioners, simulation-based research has limitations and trade-offs like any other research approach, including the costs and time for developing models and simulation software, data requirements, required expertise, and overconfidence in the results produced by a computer (Harrison et al., 2007; Robinson, 2004).

3.2.3 Simulation Approaches in MS/OR

There are three main simulation approaches in MS/OR that are widely applied the field of business and management (Jahangirian et al., 2010). *Agent-based modelling* (ABM)[18] focuses on a population of heterogeneous agents and the system behaviour emerges from the interaction among these agents and the agents and their environment (North & Macal, 2007; Gilbert, 2008; Wilensky & Rand, 2015). *System dynamics* (SD) models are built using stocks and flows that form feedback loops of cause and effect. By handling time as a continuous variable, the system behaviour emerges from the structure of the system (Forrester, 1961; Sterman, 2000). *Discrete event simulation* (DES) treats systems as a sequence of discrete events instead of a continuous time flow. DES focuses on queuing problems and the identification of bottlenecks in a system to improve the overall performance (Pidd, 2004; Robinson, 2004).

There is ambiguity in the existing literature whether these approaches should be classified as a *methodology*, a *method* or even qualify as an independent *paradigm* (particularly in the case of SD) (Howick & Ackermann, 2011; Mustafee, Brailsford, et al., 2015; Pruyt, 2006). A methodology is "the strategy, plan of action, process or design lying behind the choice and use of particular methods and linking the choice and use of methods to the desired outcome", whereas methods are "the techniques or procedures used to gather and analyse data related to some research question or hypothesis" (Crotty, 1998, p. 3). Mingers & Brocklesby (1997) avoid the notion of method to avoid confusion. Instead, they refer to *technique*, i.e. the "specific activity that has a clear and well-defined purpose within the context of a methodology" and *tool*, i.e. "an artefact, often computer software that can be used in performing a particular technique" (Mingers & Brocklesby, 1997, pp. 490-491). Clarifying the boundaries of different approaches and contrasting the way models and simulations are developed is a very important topic but outside the scope of this thesis. While acknowledging the ambiguity with these terms, all three simulation approaches will simply be referred to as 'methods' in this thesis.

[18] The acronym ABM is used in different ways throughout this thesis. If used in a plural sense (ABMs) or with an article (an ABM) then the acronym represents an agent-based model as opposed to the practice of agent-based modelling (Wilensky & Rand, 2015).

Research on entrepreneurship in general and academic entrepreneurship in particular can be divided into two major streams. The first stream focuses on the role of context in entrepreneurship (Autio et al., 2014; Welter, 2011) and takes a holistic and often systemic approach to explain entrepreneurial behaviour and the implications of entrepreneurial activity. Examples include the entrepreneurial ecosystem concept (Isenberg, 2010; Stam, 2015) or university ecosystems as characterised by Hayter et al. (2018), Miller & Acs (2017), and Wright et al. (2017), among others, or as conceptualised based on an inter-organisational perspective in this thesis (see Section 2.2.4). ABM with its focus on individuals or individual components within a system represents a suitable approach to model the interaction of different institutions and individuals within an ecosystem. SD and DES take a top-down perspective and specify the system structure first in order to understand its behaviour. University ecosystems are characterised by non-linearity based on feedback structures rather than queuing problems and discrete stochastic processes, which means that DES is not a suitable method.

The second stream focuses on the individual entrepreneur (Bruyat & Julien, 2001; Busenitz et al., 2003) or entrepreneurial academic (Balven et al., 2018; Miller, Alexander, et al., 2018). The role of the individual is emphasised more in the ecosystem concept compared to other territorial systems of innovation, making these two streams distinct but not mutually exclusive. The relevance of entrepreneurial academics has been highlighted throughout the previous chapter (see Section 2.5.3 in particular). ABM corresponds well to this stream by explicitly modelling the characteristics, decision-making processes, and networks among individuals. These dynamics are again not characterised by queuing problems but are embedded in and influenced and constrained by an environment that is shaped by the decisions and actions of individuals as well as external input. In conclusion, SD and ABM both represent potential approaches for modelling academic entrepreneurship as a complex system and to address the research questions in Section 2.8. Both methods will be introduced in the following and their applicability and limitations will be discussed in more detail.

3.3 System Dynamics

The existing literature provides a variety of definitions and descriptions of SD and some authors even argue that there is not an accurate and clear-cut definition (Richardson, 2011). SD is a "rigorous method of system description, which facilitates feedback analysis, usually via a continuous simulation model, of the

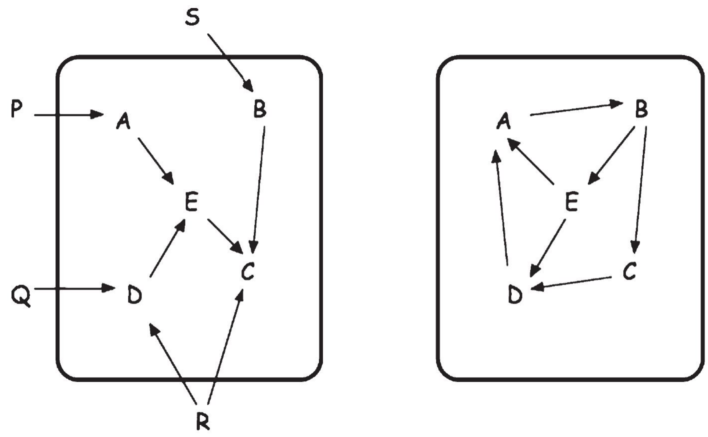


Figure 3.1: Endogenous point of view (Richardson, 2011)

effects of alternative system structures and control policies on system behaviour" (Wolstenholme, 1982, p. 547). Furthermore, it can also be characterised as "the use of informal maps and formal models with computer simulation to uncover and understand endogenous sources of system behaviour" (Richardson, 2011, p. 241). In more practical terms, system dynamics combines systems thinking, management insights, and computer simulation to develop endogenous explanations of systems to influence policy design and decision making in general. This section will elaborate on the foundations of SD, including the assumptions regarding the dynamics in a complex system, relevant features of the method, and eventually the applicability to the research questions in this study.

3.3.1 Endogeneity, Feedback and Emergence

An SD view of the world is characterised by feedback thinking (Sterman, 2001). The endogenous point of view and feedback thinking are essential elements of system dynamics. A key issue in the model development process is the definition of the model boundary "that encompasses the smallest number of components, within which the dynamic behavior under study is generated" Forrester (1968, pp. 4-2). Essentially, "dynamics do not simply happen, but that the states of the system depend on the system's history (as expressed in its current states), any exogenous inputs, and the policies by which the system attempts to regulate its own behaviour" (Coyle, 1983, p. 360). This means that the behaviour of a system is created inside the system boundaries (see Figure 3.1). Feedback loops are, on the one hand, a consequence of the endogenous point of view, but, on the other hand, also a requirement as they enable the endogenous point of view and provide the structure (Forrester, 1969).

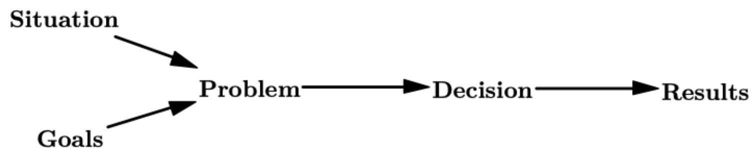


Figure 3.2: Event-oriented thinking (Sterman, 2000)

Caused by the way in which people interpret experience, "all too often, well-intentioned efforts to solve pressing problems create unanticipated side effects. Our decisions provoke unforeseen reactions. The result is policy resistance, the tendency for interventions to be defeated by the response of the system to the intervention itself" (Sterman, 2000, p. 8). This is caused by the way people interpret experience. In most cases, people take an open-loop perspective, which means that a problem is defined by comparing goals with the current situation (see Figure 3.2). As a result, experience is interpreted as a series or sequence of distinct events (Sterman, 2000). This *event-oriented thinking* also corresponds to the perception of academic entrepreneurship as a linear process that was predominant in the older literature. As outlined in Section 2.7, there has been a change in the nature of the research in this field towards understanding university ecosystems as complex systems because "linear process models may appear as overly simplistic; they may infer a lack of feedback or control; or may fail to properly capture the inherent complexity of a dynamic or adaptive process" (Philbin, 2008, p. 513).

Particularly when looking at the drivers and dynamics of academic entrepreneurship and the interactions between universities and their ecosystem, event-oriented thinking and research that follows such a train of thought have its limitations. The ecosystem reacts to a university's entrepreneurial activities and policy decisions. But the university makes these decisions not in isolation. Policy decisions are influenced by the ecosystem and "feedback loops from the outcomes back into the other main stages imply that the UIC [university-industry collaboration] could change as a result of the outcomes" (Ankrah & AL-Tabbaa, 2015, p. 401). Hence, the outcomes from entrepreneurial activities have the "potential for affecting the TTO activity both positively and negatively" (Rothaermel et al., 2007, p. 748). In addition, feedback loops also exist within different regions and different types of ecosystems that experience Matthew effects, i.e. the rich get richer and the poor get poorer (Breznitz et al., 2008).

Feedback thinking entails a particular worldview. As Forrester (1969, p. 107) explains, "this loop structure surrounds all decisions public or private, conscious or unconscious. The processes of man and nature, of psychology and physics, of medicine and engineering all fall within this structure". In general, a feedback

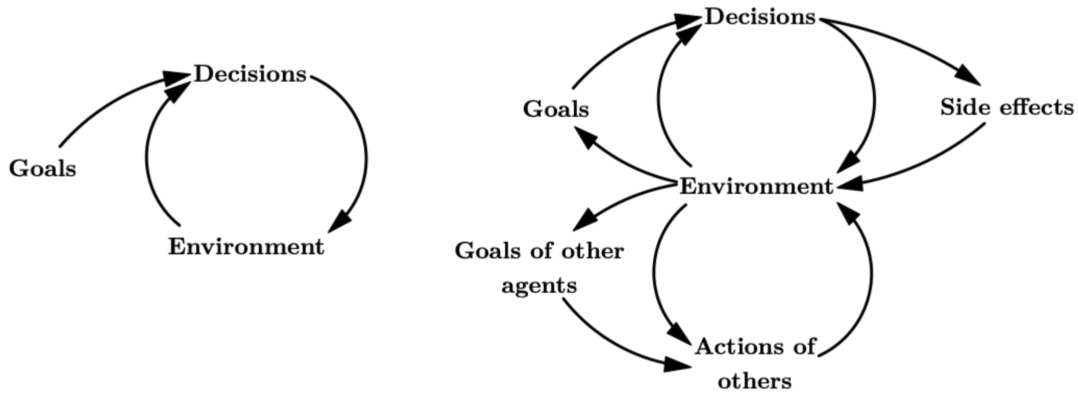


Figure 3.3: Feedback thinking (Sterman, 2000)

system exists "whenever the environment causes a decision which in turn affects the original decision" (Forrester, 1958, p. 39). Feedback thinking means that "the results of our actions define the situation we face in the future. The new situation alters our assessment of the problem and the decisions we take tomorrow" (Sterman, 2000, p. 12). This is illustrated in the left-hand side of Figure 3.3. Furthermore, decisions cause side effects that influence the environment and, therefore, the goals of others involved in this system. These other agents have their own goals and act accordingly, which differs in most cases from one's own goals and actions. The emerging feedback structure illustrates the role of unintended consequences of decisions and implemented policies (see right-hand side of Figure 3.3).

Feedback structures and the endogenous point of view, combined with the dominance of particular loops are applied in at least six ways as listed below, in addition to forming the philosophical aspect (the worldview). When trying to understand the dynamic behaviour of models, a focus should be on those variables and parts of the model that have a high impact on the observed patterns (understanding). When trying to find and evaluate sensitive parameters, those included in dominant structures are more likely to be significantly influential (evaluation). The same goes for policy analysis based on models. Leverage points can be found in dominant feedback loops (policy analysis). The dominance of particular loops and shifts in this dominance can help presenting and explaining insights from modelling in simplified terms to the client (communication). The dominant feedback loop concept could help combining research and theory building in the areas of bifurcating, chaotic systems and system dynamics with practical applications in policy design (theory). Lastly, generic structures that are extracted as a subset of complex systems are particularly vivid combinations of structure and behaviour that can be widely applied (generic structures) (Richardson, 1986a).

The implications and importance of the endogenous point of view and feedback thinking can be summarised by three key insights (Richardson, 2011, p. 224):

- There is a "closed boundary around the system" (see Figure 3.1), which means that SD models appear to have a characteristically "roundness" and there are no causal links coming from or going to a variable outside the system boundaries. This drives the formation of the feedback structure.
- These variables inside the system boundaries and their interaction are responsible for the dynamic behaviour of the system.
- By using the example of a market growth model by Forrester, Richardson explains what it means to model "for endogenous insight and understanding". Forrester put the company in a potentially infinite market and even though there is no such market, which makes the model unrealistic and invalid, this removes all possibility that the declining sales can trace to anything other than an endogenous source. Hereby, SD decouples the model from external influences and constraints.

In management and organisational studies, feedback thinking has been applied extensively in the area of organisational learning. Senge (2006), for example, uses systems thinking and system archetypes in particular to help companies become learning organisations. Argyris & Schön (1974, 1978) focused on the notions of single-loop and double-loop learning, the latter having the opportunity to go beyond adaptive learning and alter the theory of action of individuals. Cope (2003, 2005) has transferred these theories and constructs to explain entrepreneurial learning, i.e. the learning process of entrepreneurs. Based on the definition of learning as "an ongoing, dialectical process of action and reflection" (Marsick & Watkins, 1990, p. 8), the dynamics of entrepreneurial learning are characterised by "metamorphosis, discontinuity, and change" (Cope, 2005, p. 392). The importance of feedback thinking has also been stressed when outlining future trajectories in entrepreneurship research in general (Shepherd, 2015).

With regard to academic entrepreneurship, researchers have started developing new models that rely on systemic causality and explicitly involve feedback to capture the complex and reciprocal effects between universities and their ecosystems (see e.g. Ankrah & AL-Tabbaa, 2015; Bercovitz & Feldman, 2006; Hallam, Wurth, & Mancha, 2014; Philbin, 2008; Rothaermel et al., 2007). These models "portray technology transfer as a more complex and interactive activity, involving feedback loops across multiple dimensions" (Youtie & Shapira, 2008, p. 1191).

However, the vast majority of methodologies used to conduct research in the field of academic entrepreneurship remains event-oriented rather than based on feedback thinking. It was previously argued that the absence of longitudinal datasets limited further investigations of feedback effects as these only unfold over time (Rothaermel et al., 2007). This is no longer a valid argument as comprehensive datasets have been collected for the U.S., the UK and other parts of Europe (Mosey & Wright, 2007; Rasmussen & Borch, 2010; Rasmussen et al., 2011). System dynamics presents an effective approach to synthesise existing research and to address the current limitations of the existing research on academic entrepreneurship and can help draw a more comprehensive picture of systemic causation instead of focusing on single causal relationships.

System dynamics models are typically visualised using either causal loop diagrams (CLD)[19] or stock and flow diagrams (SFD) (Sterman, 2000). CLDs are usually used as a first step to capture the available information and map out the feedback structure. They are designed to capture mental models and serve as a tool for thought by simplifying reality (Sterman, 2000). However, their application is not limited to the first stages of the modelling process but they can be applied in a variety of ways, including (Coyle, 2000; Sterman, 2000):

- putting a very complex problem, which may require many pages of narrative explanation, onto one piece of paper;
- helpful reminder during discussions, effectively a form of agenda that, unlike the normal serial agenda, shows the relationships between the items being discussed;
- identifying feedback loops from the diagram may help to explain behaviour or to generate insights:
- studying of the CLD may identify the wider contexts of a modelling task; or
- supporting the communication of the results of an SD simulation.

The dynamics in any complex system can be reduced to a combination of only positive and negative loops (Sterman, 2000). While positive feedback loops

[19]The terms causal loop diagrams and influence diagrams are often used interchangeably, although they are not always the same (Coyle, 2001). Other forms of diagrams that capture feedback structures include causal maps and signed graphs (Morecroft, 1982). Only CLDs as defined in this section will be used throughout this thesis.

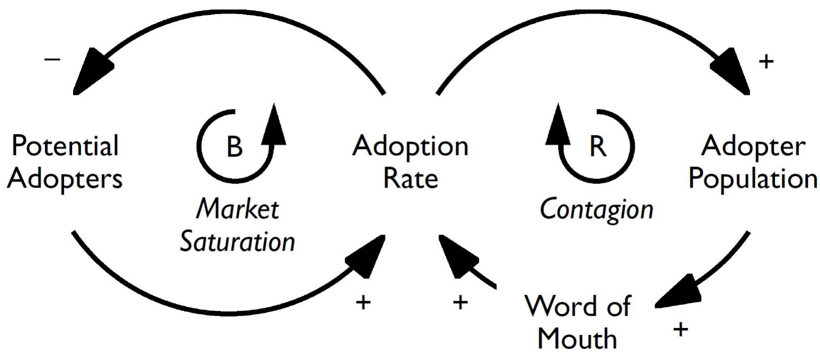


Figure 3.4: Causal loop diagram (Sterman, 2001)

produce reinforcing behaviour, negative loops are responsible for convergence towards an equilibrium or optimal state. An example is visual feedback when filling a glass of water or sensory feedback when adjusting the water temperature under the shower (Sterman, 2000). This goes for more complex systems like university ecosystems too. System dynamics has since its early days "emphasized the multiloop, multistate, nonlinear character of the feedback systems in which we live" to deal with these more complex systems (Sterman, 2000, p. 21, with reference to Forrester, 1961). Figure 3.4 shows an example of a causal loop diagram, which describes the system for adoption of a new technology based on a reinforcing loop focusing on contagion and a balancing loop that deals with market saturation. In order for causal loops to be effective and lead to new insights, it is important to select the best level of aggregation and to not necessarily merge all loops into one large diagram (Sterman, 2000).

Emergence is typically not addressed directly in system dynamics and not part of the standard vocabulary. Due to the fixed system structure, there cannot be any ontological emergence at the system level. However, learning based on adaptation and internal changes is modelled through changes in loop dominance caused by non-linearity. Furthermore, systems thinking also stresses that a system is more than the sum of its parts and "loses its essential properties when it is taken apart" (Ackoff, 1973; Forrester, 1961), so non-reducibility of complex systems is deeply embedded in SD.

3.3.2 Features of System Dynamics

Feedback thinking and the endogenous point of view are essential to system dynamics theory and practice. There are, however, additional features such as stock and flow structure, information and resources, delays, and non-linearity that contribute to the behaviour of dynamic systems (Sterman, 2000). These will be described in this section.

3.3.2.1 Resources and Information

System dynamics theory differentiates between resources and information. Resources represent physical entities that are transformed or change their state. Examples of resources include products, people, and money, among others. The transformation or state changes can be fundamental changes (e.g. raw materials are converted into products) or only a change in the location or treatment of the resource (e.g. when patients have been treated at the hospital and leave) (Pidd, 2009).

Information, on the other hand, is non-physical and controls the use and the transformation of resources (Sterman, 2000). This includes information about the current state of a resource as well as additional information. However, this is not necessarily a straightforward process as information might be delayed, misunderstood or twisted/misrepresented. Simulation can be very helpful in examining the intended and unintended consequences of delayed and twisted or misrepresented information, as this information is still used in the system for the decision-making process (Pidd, 2009).

3.3.2.2 Stocks and Flows

Stocks and flows are used in a variety of areas such as mathematics, physics, engineering, economics, accounting, and biology, among others, although sometimes a different terminology is used (Sterman, 2000). In system dynamics, the structure of a model goes beyond identifying and mapping out feedback loops. Stocks and flows are essential because accumulation cannot be captured by causal loop diagrams (Sterman, 2000). In practice, CLDs are often transformed into SFDs to develop a quantified model and describe the system as a set of equations to run the simulation (Coyle, 2000).

Stocks (or sometimes called levels) represent the accumulations and describe the current state of the system. Stocks also contribute to the dynamics of the system by providing it with inertia and memory, decoupling rates of flows and creating disequilibrium dynamics as well as being the source for delays. A simple way to identify stocks is the snapshot test. If the system would be frozen at a particular point in time, stocks are “those things you could count or measure” (Sterman, 2000, p. 199). In mathematical terms, stocks can be described by the following integral equation:

$$Stock(t) = \sum_{t_0}^{t}[Inflow(s) - Outflow(s)]ds + Stock(t_0) \tag{3.1}$$

Alternatively, a stock can be described using a differential equation:

$$\frac{d(Stock)}{dt} = Inflow(t) - Outflow(t) \tag{3.2}$$

Flows, controlled by rates, represent the activity within the system (Forrester, 1961). Rates are decision functions and informed by stocks, i.e. the current state of the system. The stocks are determined by its inflow and outflow rate (see equations above). A model can be illustrated without information about stocks and flows by using a causal loop diagram in an intuitive way. However, lacking information about accumulation (represented by stocks and flows) might lead to confusion or even incorrect explanations for the behaviour of the system (Richardson, 1986a, 1995). Stock and flow diagrams illustrate this version of the system structure. A commonly accepted notation is provided by Sterman (2000, p. 192):

- stocks are represented by rectangles;
- inflows are represented by a pipe with an arrow pointing into the stock;
- outflows are represented by a pipe with an arrow pointing out of the stock;
- valves control the flows; and
- clouds represent the sources and sinks for the flows. They are assumed to have an infinite capacity, which lies outside the system boundaries, and can never constrain the flows that they support.

Figure 3.5 illustrated the stock and flow diagram based on the causal loop diagram shown in Figure 3.4, which would enable quantitative analysis.

3.3.2.3 Delays

In the real world, delays, which can be defined as “a process whose output lags behind its input in some fashion”, are ubiquitous (Sterman, 2000, p. 411). In combination with feedback loops, they account for much of the dynamic behaviour in system dynamics theory. SD adopts a basic principle from control theory, which states that the greater the delay, i.e. the greater the time lag between observation

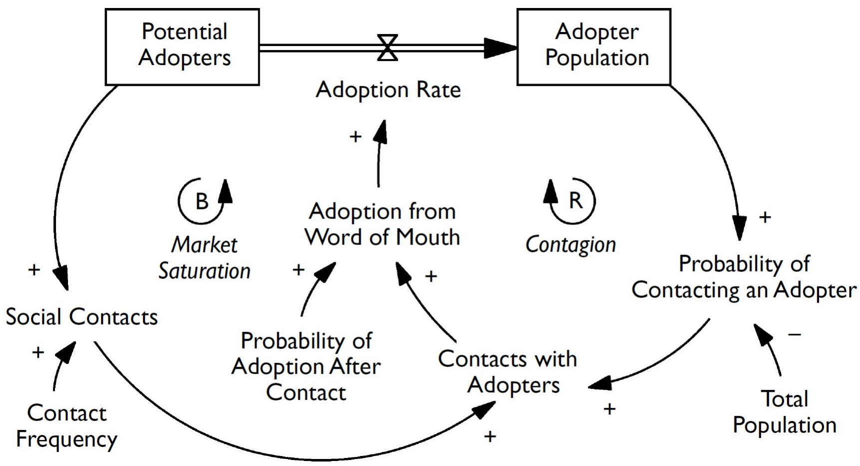


Figure 3.5: Stock and flow diagram (Sterman, 2001)

and action, the less effective the action is likely to be (Forrester, 1961). Thus, delays might be the reason for undesired oscillation or instability, but can also have a positive effect by supporting the screening of information and sort out noise (Sterman, 2000). Delays exist in every single process but including all of them in the model would cost a lot of time, effort and, by extension, money. The inclusion of all delays, regardless of their magnitude, would not necessarily contribute to understanding the dynamic behaviour of the system. Hence, the number of delays is reduced based on two simplifications: when the delay is seen to be too short to have an impact or when multiple, sequential delays can be combined to one delay (Forrester, 1961).

When building a system dynamics model, a distinction has to be made between physical and information delays, as they have different characteristics and effects on the system behaviour (Meadows, 1980). Physical delays, or sometimes referred to as material delays, refer to the physical flow of material and resources through a delay process. Examples include supply chains and the flow of a product or a product development process and the progression of design tasks. The simplest form of physical delays are pipeline delays, which have a constant delay and the exit order is the same as the entry order. In case there is mixing and variation in the individual time lags, first-order physical delays are usually used to model the system. Higher-order physical delays are required if there is not a perfect but some mixing (Sterman, 2000).

Information delays represent time lags in the "gradual adjustment of perceptions and beliefs" or in transferring, gathering and processing information (Sterman, 2000, p. 412). Different structures are required to model physical and information delays as the latter cannot be captured by conserved flows. The simplest and at the same time most commonly used way to model information delays is exponential smoothing. Much like physical delays, there are situations where a higher-order information delays need to be modelled and exponential smoothing is not the optimal choice (Sterman, 2000). Whether a system needs to be improved or just better understood, the model needs to account for resources and information, stocks and flows and delays in addition to the feedback structure. SD offers different model visualisation methods and a computer-based simulation approach to fulfil these requirements.

3.3.3 Qualitative and Quantitative System Dynamics

System dynamics can be seen as a quantitative and qualitative modelling approach (Coyle, 2000). Within the SD community, quantified simulation has traditionally been seen as the sine qua non (Coyle, 1998, 2000) and was at the heart of the literature from the beginning (Forrester, 1961). The main reason for this is that the dynamic behaviour of a system cannot reliably be predicted by looking at either causal loop or stock and flow diagrams (Coyle, 2001). However, with a too narrow focus on quantitative simulation and stock and flow diagrams instead of thinking through the feedback loops and the structure, there is a decrease in quality (Coyle, 1998).

The problem with quantification of SD models arises because they go beyond hard variables and usually include soft variables in order to consider strategic decision making (Coyle, 2000). Quantifying naturally qualitative aspects is one of the reasons for uncertainties in system dynamics practice. The counter-argument is usually that the focus is on general patterns of behaviour and not exact forecasts. As a final thought, system dynamics "is not simulation, and the simulation is only used for reasons of practical convenience. The essence of the method is the design of harmonious combinations of policies and feedback structures which are appropriate to the behaviour required of the system in the face of the shocks it might encounter" (Coyle, 1983, p. 369). Thus, a balance between quantitative and qualitative is required to deal with the trade-offs.

3.3.4 Advantages and Applications

System dynamics is "a powerful method to gain useful insight into situations of dynamic complexity and policy resistance" (Sterman, 2000, p. 39). Essentially, it supports the development of process-based theories "that explicitly examine the interactions between the physical and institutional structures of operational systems and the behavioral decision rules of the agents in those systems" (Morrison & Oliva, 2018, p. 287). It is important to consider these interactions between the physical and institutional structure and to look beyond organisational boundaries, because they often cover unintended consequences from those who are making decisions and implementing policies with a certain goal (Wolstenholme, 2003). With its high level of abstraction, SD has mainly been used for policy testing (Forrester, 1961), what-if scenarios (Morecroft, 1988) and policy optimisation (Kleijnen, 1995a) to uncover and mitigate these unintended consequences. Creating what-if scenarios and simulating the complex interactions of all system components simultaneously can be very valuable for people in order to understand the long-term impact of new policies.

The application of SD has several advantages such as the combination of soft and hard systems methodologies, which can be applied to a range of topics (Wolstenholme, 1982). System dynamics modelling requires the modeller to consult and triangulate a variety of data sources (Sterman, 2000). This includes both qualitative (e.g. expert knowledge through interviews or observations) and quantitative data (e.g. numerical databases, reports, scientific literature, or operation manuals). This process in itself can yield to new insights about the system and potential differences in how individuals perceive the state of the system and how it works. Despite the empirical and theoretical grounding of many system dynamics models, they are usually not exact forecasts but rather tools for thinking and as a basis for discussion. The aim is to predict the dynamic implications of new policies as opposed to exact values for certain parameters or stocks over time. SD models can be parametrised based on historical data though, which can be used as a baseline scenario against which other policies can then be measured.

One of the key benefits of SD is that "small models can yield accessible, insightful lessons for policy making stemming from the endogenous and aggregate perspective of system dynamics modeling and simulation" (Ghaffarzadegan et al., 2011, p. 22). Large and complex models are difficult to develop in the first place and, even more importantly, hard to analyse with confidence for both the modeller and the client or policy maker, who base their decisions on the model (Barlas, 2007).

Originally called *industrial dynamics* (Forrester, 1961), the first SD models have been applied to classic managerial, industrial, and R&D problems. A reason for this was that SD itself was rooted in engineering and most early adopters of the method had the same background or were interested in problems around R&D and innovation as well as the role of government and wider industry developments. Many of the early student theses from MIT were concerned with either the dynamics of R&D projects; organising R&D within organisations and resource allocations; or the interrelationships between R&D and the wider organisation, firm performance or government agency (Roberts, 1978, p. 279). But SD was soon used for other socio-economic issues and policy design in the late 1960's (Forrester, 1969). The focus was on tackling major socio-economic issues and these efforts peaked with the development of the *world model* (Forrester, 1971) that was also presented at the Club of Rome (Meadows et al., 1972).

Today, SD has evolved into a methodological approach that is used in a variety of fields. Examples include health care (see e.g. Brailsford et al., 2004; Cavana et al., 1999; Dangerfield, 1999; Homer & Hirsch, 2006; Lane et al., 2000), environmental issues and agriculture (see e.g. Noble & Walker, 2006; Stave, 2002; Zhang & Mitsch, 2005), supply chain and production (see e.g. Akkermans et al., 1999; Dangerfield & Roberts, 2000; Kleijnen & Smits, 2003; Spengler & Schröter, 2003; Towill, 1996), dynamic decision making (Sterman, 1989), police (Newsome, 2008), operations investments (Marquez & Blanchar, 2006), public policy (Cavana & Clifford, 2006; Ghaffarzadegan et al., 2011; Homer & St. Clair, 1991), project management (Howick & Eden, 2004; Williams, 1999), strategy (Torres et al., 2017) and safety issues (Ibrahim Shire et al., 2018).

Despite the development over more than five decades and many successful applications, SD has still not reached its full potential, neither in academia (outside the SD community), nor by policy makers and managers (Forrester, 2007). At the core of the limited adoption of SD as an approach to explore and address complex and dynamic problems is not the method itself but a lack of education, shortcomings in terms of communicating the benefits of SD and the limited awareness of how it can help to tackle different problems (Forrester, 2007).

There has, however, been an increase in applications of system dynamics in recent years to model territorial systems of innovation and knowledge accumulation and transfer among different organisations. In particular, six distinct activities or mechanisms have been modelled using SD, namely R&D, diffusion processes, absorptive capacity, science and technology, learning processes, and regional agglomerations (Uriona Maldonado & Grobbelaar, 2019). Despite the recent trend, "little is known about [system dynamics'] use in the innovation studies domain in general and in the innovation systems field in particular" (Uriona Maldonado & Grobbelaar, 2019, p. 28). This particular field of application will be reviewed in the following section with an emphasis on the applicability of SD to the impact of academic entrepreneurship in university ecosystems.

3.3.5 Applicability to Academic Entrepreneurship

SD, particularly a qualitative approach using CLDs, can help structure and synthesise the existing body of literature. For new research to 'stand on the shoulder of giants', CLDs are a promising approach for organising the exponentially growing amount of literature on academic entrepreneurship that can go beyond the scope of traditional literature reviews (Hayter et al., 2018). Examples of such approaches include modelling the dynamic structures at the inter-university, inter-departmental, and the individual academic level with regard to AE activities (Wurth et al., 2015) or a systems perspective on combining different entrepreneurial activities in one model (Hallam, Wurth, & Mancha, 2014). Administrative dynamics within academic institutions are modelled by Galbraith (1998), who uses system archetypes and builds on the work by Wolstenholme (2003, 2004) to model "'soft managerialism' as applied by institutional managers, in response to the 'hard managerial' context that has been set by national legislation and federal administrative action" (Galbraith, 1998, p. 72). Qualitative approaches have also been used to model entrepreneurial activities within companies. Bloodgood et al. (2015, p. 383) used a SFD to show "the connection to strategic assessment and entrepreneurial renewal that portray corporate entrepreneurship as an integration of entrepreneurial and strategic efforts".

After the early work on innovation systems, there has been a renaissance of applications of SD to territorial models of innovation. Similar to the aims of this research, most studies "have been used to explore assumptions, hypotheses and policy at the conceptual/theoretical level, as exploratory modeling tools" (Uriona Maldonado & Grobbelaar, 2019, p. 28). The majority of these studies have focused on the regional innovation system, but there have also been applications with regard to national systems of innovation, entrepreneurship, and academic entrepreneurship. Walrave & Raven (2016), for example, developed an SD model focusing on the dynamics of technological innovation systems that combines the concepts motors of innovation and transition pathways. The model is used to analyse "how technological innovation systems emerge, or decline, in the context of various socio-technical transition pathways" (Walrave & Raven, 2016, p. 1842). The same basic model is also used to "explore relations between transformational failures and (mixes of) policy interventions" (Raven & Walrave, 2020, p. 1).

Other applications in this area have focused on regional innovation systems (RIS) in emerging economies (Rodríguez & Navarro-Chávez, 2015) or knowledge flows within and between RIS based on an average EU NUTS-2 region (Fratesi, 2015). In the case of the bio-economy sector, an SD simulation was developed by “combining science, innovation and education elements, and assessment of different funding scenarios has been carried out” to develop more effective policies (Allena-Ozolina & Bazbauers, 2017, p. 350). Different dimensions of proximity can also be modelled and formalised with SD. Knowledge-based districts evolve when organizational proximity, particularly the cognitive aspect, increases to fully exploit the agglomeration of firms and other actors (Dangelico et al., 2010). With a holistic, qualitative SFD, Lin et al. (2006) show that the industrial cluster effect is positively influenced by all four interactive dimensions of competitiveness: manpower, technology, money and market flows. This shows that SD can be used beyond policy testing and experimentation for theory development as well (Buendía, 2005). On a national level, SD was used for comprehensive policy testing and optimisation of the R&D output of the system in general (Grobbelaar, 2006) and with a focus on product and process innovation based on a EU27 country with a below-average innovation performance (Samara et al., 2012). SD is used to develop a “holistic dynamic consideration of the NIS” (Samara et al., 2012, p. 624).

SD has been applied across micro, meso, and macro levels in entrepreneurship (Zali et al., 2014). While two thirds of the published studies develop simulation models to better understand a particular phenomenon, only 9% actually explore what-if scenarios in order to improve the system (Zali et al., 2014). Relevant examples include the model of an entrepreneurial system (Yearworth, 2010), the influence of innovative entrepreneurship for societal and socio-economic integration (Aparicio et al., 2016), or a model with separate SD structures for individual firms competing for market share, which are linked by the size of the market as a shared stock (Rahmandad, 2015). A similar structure could be adopted to model universities competing for external funding and partners. SD has also been used to explore capability and competency developments at the firm level to “assess the advantages and disadvantages of different technological innovation strategies and commitments” (Kim & Choi, 2009, p. 1) and the influence on market-level dynamics (Rahmandad, 2012).

SD has also been directly applied to academic entrepreneurship, mainly focusing on university spin-offs. Zaini et al. (2015) developed a model based on a case study on establishing and growing an aspiring world-class university, heavily based on the work on challenges for research universities by Salmi (2009). Other studies have shed light on the nature of the relationships between stakeholders in the process of university spin-off formation (Rodríguez Chávez, 2010) and showed that initial capital and TTO (higher long-term influence) support on business model generation are positively correlated to the number of new university spin-offs (Sidharta et al., 2014). Beyond academic entrepreneurship, Zaini et al. (2017) modelled the expansion of undergraduate tuition-depended universities and showed that policy decisions that are made without considering the whole complex system that a university is can lead to counter-intuitive (and in some cases irreversible) outcomes.

In conclusion, SD has been directly applied to different aspects of academic entrepreneurship and (eco)systems as well as related areas. Similar to the purpose of this study, most studies have explicitly emphasised the exploratory nature of the use of SD, with a smaller number of studies also exploring what-if scenarios (Samara et al., 2012). In various settings, SD has demonstrated to be a valuable approach to model multiple indicators in a single model (Rodríguez & Navarro-Chávez, 2015) and more effective compared to other approaches in "analyz[ing] the complicated relationship of factors affecting industrial cluster effect" (Lin et al., 2006, p. 473). A top-down modelling approach suits universities due to the organisational inertia and slow-moving nature (see Section 2.3.4) and can incorporate different parameters for different universities (research question Q2, see Section 2.8). It can also be applied to model the evolution of university ecosystems based on endogenous dynamics (Q1), including different dimensions of proximity (Q4) (Dangelico et al., 2010). However, the aggregated perspective of SD is not well suited to understand the evolution of partnerships. It is not possible to track relationships between individual companies and universities in order to understand which characteristics these actors have and the types of entrepreneurial activities that are used (Q3).

3.3.6 Limitations

A key strength of the SD method is its ability to capture high-level dynamics based on the endogenous structure of the system. This high-level focus and the use of averages and aggregated values are generally not well suited to model the heterogeneity of ecosystem actors, different types of companies, and the network structure within a university ecosystem (Rahmandad & Sterman, 2008; Sterman, 2000). While these features cannot be modelled directly, there are ways to address these issues. Network structures and how they impact the diffusion and flow rate of innovation can be approximated and limited. A great number of different agents could theoretically be simulated with a large number of individual stocks and flows. In practice, this would require a huge effort and would probably be limited by data constraints. Most problems that suit a system dynamics approach do not have highly disaggregated data readily available.

Furthermore, modelling adaptations at the individual level are hard to model and observe in an SD model. For example, different types of firms adjusting in different ways to positive or negative experiences with a particular university (Gilbert, 2008). This too limits the opportunities to model the evolution of partnerships. Lastly, opportunities to model discrete events are limited due to continuous nature of the simulation (Sterman, 2000). In many cases, a solution can be found, but it either requires further simplifications and additional assumptions or higher efforts compared to ABM or DES.

To conclude, SD provides a suitable approach for this research endeavour but would also require limitations with regard to question Q3, which is a key part of this thesis. In the next section, agent-based modelling will be reviewed and its applicability to this problem and the four research questions will be discussed before finally deciding on an approach for this thesis.

3.4 Agent-Based Modelling

There is a variety of definitions of agent-based modelling (ABM) and even different names.[20] In general terms, ABM is a computational simulation approach that allows the investigation and explanation of system behaviour and emergence based on the behaviour of individuals and their interactions (Gilbert, 2008; Wilensky & Rand, 2015). At the heart of ABM lies the assumption that "the whole of many systems or organizations is greater than the simple sum of its constituent parts" (North & Macal, 2007, p. 11). ABM is more than a simulation tool and based on an 'ABM mindset' that emphasis a worldview based on a bottom-up perspective through the individual parts which constitute the system. Some author's go even further and consider ABM not an alternative to differential equation models such as SD, but state that "a set of differential equations, each describing the dynamics of one of the system's constituent units, is an agent-based model" (Bonabeau, 2002, p. 7280). This section will elaborate on the foundations of ABM, including the assumptions regarding the dynamics in a complex system, relevant features of the method, and eventually the applicability to the research questions in this study.

[20] Agent-based modelling is also known as agent-based modelling and simulation, agent-based simulation, multi-agent simulation, or individual-based simulations, among others. These are often used interchangeably, while some authors emphasise conceptual differences between agent-based and multi-agent simulations. For the sake of clarity, only agent-based modelling as defined in this section and the acronym ABM are used in this thesis.

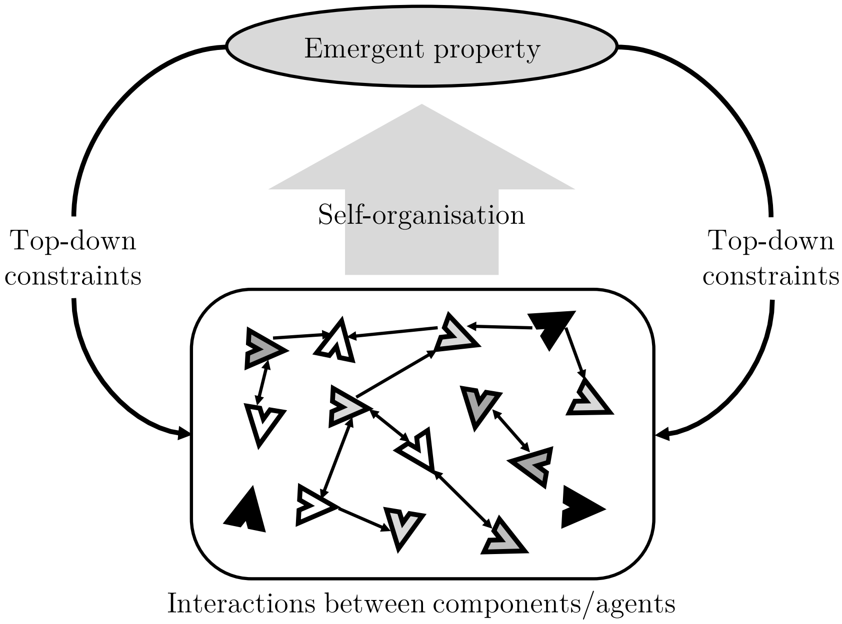


Figure 3.6: Interactions, self-organisation, and emergence (adapted from Chen et al., 2009)

3.4.1 Self-Organisation, Emergence and Feedback

Complex systems, self-organisation, emergence, and feedback are commonly used together without a proper distinction of the individual terms and their relationship. In short, emergence is the result of increased complexity in the system caused by autonomous actions and self-organisation among its components, which in turn are constrained and influenced by the emergent (systemic) properties (Chen et al., 2009; Wilensky & Rand, 2015). These relationships are illustrated in Figure 3.6. This section will define these concepts, explore their relationships in more detail, and the relevance to ABM.

Self-organisation can be defined as the "process whereby some system property occurs solely from the behaviours and interactions between the system's components" (Chen et al., 2009, p. 106). It forms the basis for the general conjecture that complex systems are based on bottom-up dynamics that lead to emergent behaviour at the systemic level. The process of self-organisation is usually based on relatively simple (compared to the emerging behaviour) and spatially bound (not necessarily geographically bound) actions of agents (Phelan, 1999). Self-organisation is, therefore, similar to the endogenous point of view in SD as it postulates that the cause of the dynamics in a system lies within the system itself. Theories of self-organisation can be divided into three main categories (Chen et al., 2009, p. 106):

1. "Complexity-based theories, which emphasise the description of the process

of itself and characterise it as a shift in complexity.

2. Design-oriented theories, which emphasise the discrepancy between the design of the system components and the functions that the system is able to perform as a whole (without these being explicitly specified in the components' designs). Self-organisation is the mechanism by which this discrepancy is able to exist.

3. Environment-oriented theories, which focus on the ability of the system to adapt to its environment and tend to be interested in the occurrence of different system properties in response to different environments through self-organisation."

Emergent behaviour or emergent properties are systemic conditions, which are not specified or cannot be reduced to properties at lower levels of the system (Johnson, 2002; Mitchell, 2011). Emergent properties can be completely de-coupled from the properties of the individual parts that form the system and can be counterintuitive (Bonabeau, 2002). Emergence is conceptually different from change or transformation. Change and transformation are the result of modification of existing structures and processes, whereas emergence is creation that is driven by aspiration (Lichtenstein, 2014). A fundamental assumption behind the concept of emergence is that a system consists of multiple levels of abstraction/accumulation, which can be described and investigated (but often not explained) individually (see e.g. Bonabeau & Dessalles, 1997; Crutchfield, 1994; Darley, 1994). Emergent properties are hard to predict because it is often unclear at which level of the system they occur and which interactions are the origin of this behaviour. These interactions tend to be non-linear, sensitive to small perturbations in the system, and typically not static but change over time (Chen et al., 2009).

These changes are caused by the emergent properties themselves, which influence the system components at lower levels of aggregation. In reality, bottom-up emergence is never purely spontaneous and entirely disconnected from any top-down control structure, influence, or constraints such as leadership or bureaucracy in complex social systems (Uhl-Bien et al., 2007). In fact, "in all of the formal experiments that reveal self-organization, the outcomes are possible only because of constraints, containers, boundaries, and external structures" (Lichtenstein, 2014, p. 13). This can bias people's perception and let them attribute an emergent phenomenon to central, top-down control mechanisms rather than seeing them as the result of bottom-up emergence that is only influenced by top-down feedback

(Wilensky & Rand, 2015). In any case, a top-down influence is a mandatory feature of an emergent property (Silberstein & McGeever, 1999).

Many ABMs simulate emergent behaviour or emergent properties of some kind, often as a result of very simple rules and few varying characteristics among the population (Wilensky & Rand, 2015). In contrast to other modelling approaches such as SD, the full effects of this explicitly modelled heterogeneity among agents can be simulated to observe emergent behaviour at the systemic level (Macal & North, 2010). While descriptions of agent-based models focus on rules, feedback is deeply rooted in the interactions among agents, between agents and their environment, and the emergent properties that influence agent interactions (Railsback & Grimm, 2012; Salamon, 2011). This is also referred to as "micro-macro-micro feedback" and is central to ABM (Lorenz & Jost, 2006, p. 8). ABM represents a promising approach for modelling complex systems with potential emergent properties when (Bonabeau, 2002, pp. 7280-7281):

- "Individual behavior is nonlinear and can be characterized by thresholds, if-then rules, or nonlinear coupling. Describing discontinuity in individual behavior is difficult with differential equations.

- Individual behavior exhibits memory, path-dependence, and hysteresis, non-markovian behavior, or temporal correlations, including learning and adaptation.

- Agent interactions are heterogeneous and can generate network effects. Aggregate flow equations usually assume global homogeneous mixing, but the topology of the interaction network can lead to significant deviations from predicted aggregate behavior.

- Averages will not work. Aggregate differential equations tend to smooth out fluctuations, not ABM, which is important because under certain conditions, fluctuations can be amplified: the system is linearly stable but unstable to larger perturbations."

ABM, in combination with general insights from complexity theory, has the potential to unite a variety of scientific fields in their quest to explore emergent phenomena, just as game theory has united strategy research among fields such as the social sciences and evolutionary biology (Axelrod, 1997). Despite this promise, a general problem with computational complexity science and ABM is "their reliance on effects that are programmed into the agents, rather than being truly emergent results of their interactions" (Lichtenstein, 2014, p. 8).

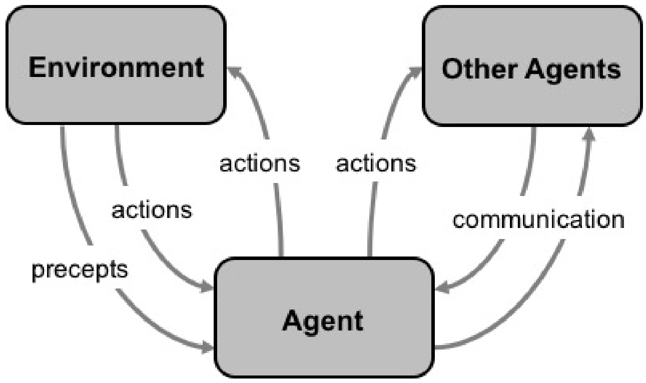


Figure 3.7: Features of agent-based models (Salamon, 2011)

Furthermore, concerns have been raised whether the simple rules that are used for most ABMs can actually explain complex emergent behaviour, how these rules can be found in a rigorous way, and what the implications of the localised nature of agents' activities are (Lichtenstein, 2014). In the following section, the key features of ABMs will be explained to understand the roots of these concerns and how they can be used as an advantage to help develop a better understanding of complex phenomena.

3.4.2 Features of Agent-Based Models

The existing literature provides a different accounts of what constitutes an ABM, which is referred to as the "features", "building blocks", or "components" of an ABM (Gilbert, 2008; Macal & North, 2010; Wilensky & Rand, 2015). Agents are the core feature of ABMs, but an agent population alone is not sufficient to form a complex system capable of producing emergent behaviour. Agents may interact with other agents as well as their environment and are capable of adapting to their behaviour based on the interactions (see Figure 3.7). This section will focus on agents, their environment, and the interactions as the key features of ABM.

3.4.2.1 Agents

ABM is distinct from other modelling approaches such as SD or DES as it explicitly models the individual agents or parts of a system (Macal & North, 2010). An agent can generally be defined as "an autonomous computational individual or object with particular properties and actions" (Wilensky & Rand, 2015, p. 1). There is no consensus in the existing literature beyond the required autonomy of an agent, i.e. its ability "to act on its own without external direction in response to situations it encounters" (Macal & North, 2010, p. 153). These autonomous

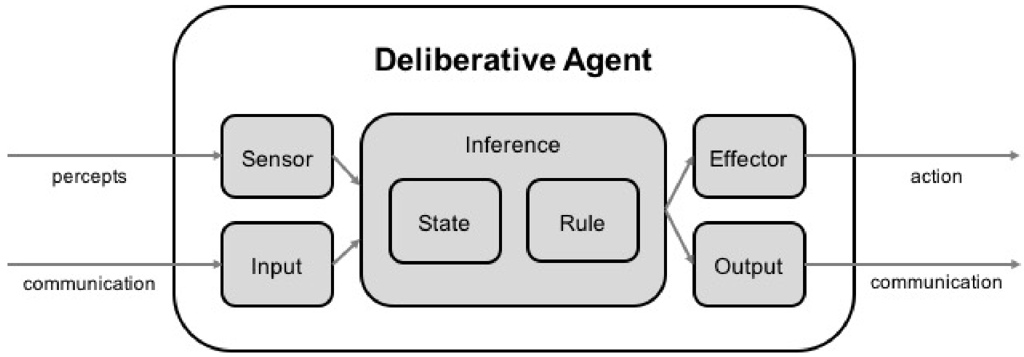


Figure 3.8: Architecture of deliberative agents (Salamon, 2011)

agents are also referred to as "deliberate agents" (Salamon, 2011) and a schematic representation of their structure is presented in Figure 3.8.

Individually, each agent assesses the situation by combining information about its state, input from other agents, and perceptions about the environment, and follows its pre-defined rules to take action and/or communicate a certain output to other agents (Bonabeau, 2002; Salamon, 2011). States and rules of each agents are not static but typically change over time as agents adapt their behaviour to their environment and the behaviour of other agents (Macal & North, 2010). From a more practical point of view (how agents are modelled) and the purpose of ABMs (why agents are modelled), an agent has several essential and optional characteristics. According to Macal & North (2010, p. 153, original emphasis), an agent:

- is a *self-contained*, modular, and uniquely identifiable individual;
- is *autonomous* and self-directed;
- has *behaviours* that relate information sensed by the agent to its decisions and actions;
- has a *state* that varies over time; and
- is *social* having dynamic interactions with other agents that influence its behaviour. An agent
- may be *adaptive*, for example, by having rules or more abstract mechanisms that modify its behaviours;
- may be *goal-directed*, having goals to achieve (not necessarily objectives to maximize) with respect to its behaviours; or
- may be *heterogeneous*.

3.4.2.2 Environment

The environment is an artificial space in which the agents move and act, that can be "an entirely neutral medium with little or no effect on the agents, or in other models, the environment may be as carefully crafted as the agents themselves" and a complex construct in itself (Gilbert, 2008, p. 6). While agents do not necessarily interact with the environment directly, an environment is a required feature of ABMs to define how agents are connected and which agents interact and how (Macal & North, 2010). This goes as far as the environment (temporally) constraining agent's actions and forcing them to adjust their behaviour (e.g. congestion in a traffic/transportation models). A more passive environment can be used to simply track agents as they move in space or acquire/gather resources.

ABM environments can take multiple forms and are not limited to a geographical space. Some authors, therefore, refer to the environment as the 'typology' or 'connectedness' of the ABM (Macal & North, 2010). Figure 3.9 provides an overview of common types of agent environments. Cellular automata represent one of the earliest examples of ABMs, going back to the work by von Neumann (Heath & Hill, 2010) and are mainly used for modelling social spaces in a variety of fields (Keilbach, 1998; Macy & Willer, 2002; Schelling, 1971). Agents are represented as cells in these models and the environment restricts their interactions with other agents to their direct neighbours. The Euclidean space allows agents to move in an n-dimensional space, with 2D and 3D spaces being the most common approaches. These geometric landscapes allow the tracking of agents' movements and their distance to each another (Wilensky & Rand, 2015). Euclidean spaces are often used to model analogues to geographical spaces such as knowledge spaces (Bagley, 2017; Folcik et al., 2007).

Network structures can be used either statically (constant over the duration of the simulation) or dynamically (endogenous changes based on model rules) for a more general representation of an agent's connectedness (Macal & North, 2010). Geographic information system (GIS) are "spatially explicit" and provide a rich set of information based on a realistic geo-spatial environment in which the agents can move (Gilbert, 2008; Macal & North, 2010). GIS are usually based on real-world data (Wilensky & Rand, 2015). Lastly, so-called soup models (aspatial models) store agents in one or more containers without assigning a particular location or links to other agents. Pairs of agents are drawn from each container and interact, before being returned to a particular container where they stay until selected (activated) again (Holland, 1995; Macal & North, 2010). These environment designs or typologies are not mutually exclusive and many ABMs

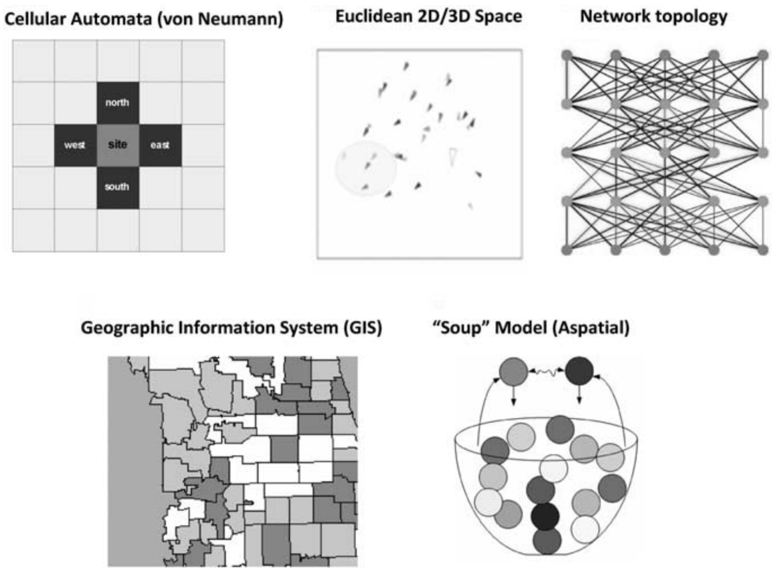


Figure 3.9: Topologies of agent-based models (Macal & North, 2010)

are based on a combination of two or more, e.g. agents that are connected by a particular network structure move on a 2D Euclidean landscape (Macal & North, 2010).

3.4.2.3 Interactions, Bounded Rationality and Learning

The dynamics in an ABM emerge as a result of the interaction among agents, potentially constrained or further enriched by the environment. These interactions take different forms, from transferring simple information to exchanging complex information that is subject to the receiving agent's cognitive limitations or biases (Gilbert, 2008). Agent behaviour is conceptually a simple input-output model as shown in Section 3.4.2.1, but core benefits that distinct ABM from other modelling approaches are only realisable when two important aspects are considered: bounded rationality and learning.

In economics, for example, many models assume a "hyperrationality" among agents, i.e. they assume that humans are able to use highly complex reasoning approaches to and are able to understand this kind of reasoning of other agents (Simon, 1955). However, there are "limits upon the ability of human beings to adapt optimally, or even satisfactorily, to [a] complex environment" (Simon, 1991, p. 132). These limitations of rationality are caused by risk and uncertainty, incomplete information about alternatives, and complexity in the problem/environment that prevents humans to calculate the optimal choice (Simon, 1972). People should therefore be modelled as *boundedly rational*, which explicitly acknowledges these limitations and constraints an agent's capability to find the optimal solution (Kahneman, 2003).

ABM corresponds well to the concept of bounded rationality and allows for an easy integration into individual agents' behaviour. First, ABMs represent decentralised systems without a controlling unit that could distribute information across all agents or coordinate their behaviour to optimise the system (as required for complete rationality). Second, agents interact directly with some agents, but not with all agents, which leads to localised information just like in the real world (Macal & North, 2010).

This has an impact on the abilities of agents and the system as a whole to adapt and learn, making theories of learning at different levels more relevant with an increased diffusion of ABMs (Macal & North, 2010). In the real world, organisations or societies can learn in only two ways, either via individual learning of its members or by bringing in new members with knowledge or skills that did previously not exist among the population (Simon, 1991). These types of learning can be implemented and simulated in different ways in ABMs (Gilbert, 2008).

Individual agents can learn through trial and error, in which they keep repeating effective actions and forget inefficient ones (Gilbert et al., 2006). Similarly, agent populations can learn over several generations when agents "with predispositions to carry out effective actions are more capable and are therefore more likely to reproduce, transferring a version of their genetic material to their offspring" (Gilbert et al., 2006, paragraph 1.4). Society can also learn without any learning at the individual level, e.g. through the use of game theory and an iterated prisoners dilemma (Epstein & Axtell, 1996). These types of learning link ABM to approaches such as neural networks or evolutionary or genetic algorithms, among others, for more sophisticated implementations of learning (Bonabeau, 2002). Lastly, agents can also develop completely new rules (Epstein & Axtell, 1996), either through individual learning or by teaching each other ("social learning") (Gilbert et al., 2006).

3.4.3 Advantages and Applications

The term ABM includes a variety of configurations and designs (an overview of different agent and environment designs was provided in Section 3.4.2). But ABM also covers the entire spectrum from elegant, minimalist academic models that are based on "a set of idealized assumptions, designed to capture only the most salient features of a system" to large-scale decision support systems, which "tend to serve large-scale applications, are designed to answer real- world policy questions, include real data, and have passed appropriate validation tests to establish credibility" (Macal & North, 2010, p. 156). Regardless of where on this continuous spectrum, ABMs are only an appropriate approach for a certain type of problems.

These problems are dynamic and time-dependent, involve a large number of (heterogeneous) agents that interact with each other and the environment, and might have an optional spatial component (Bonabeau, 2002; Macal & North, 2010; Wilensky & Rand, 2015). ABM is most suitable for population sizes from tens to millions (Casti, 1996). It is less useful for very small numbers of agents (e.g. billiard balls colliding) or extremely large numbers (e.g. modelling individual molecules for the purpose of measuring the temperature in a room) (Wilensky & Rand, 2015). Other problem characteristics include a certain level of complexity in the interaction among agents and between agents and their environment, when past actions and interactions are important (e.g. path dependencies), or learning and adaptation are relevant or expected (Bonabeau, 2002; Wilensky & Rand, 2015). However, the application of ABM is driven more by the promise of modelling adaptation and emergent behaviour than any of the other benefits (Bonabeau, 2002).

ABM can serve a variety of purposes across the whole spectrum of model purposes in MS/OR, including description, explanation, experimentation, providing sources of analogy, communication/education, providing focal objects or centrepieces for scientific dialogue, as thought experiments, and prediction (Wilensky & Rand, 2015, p. 28). An ABM is in some cases easier to understand than an SD simulation, because the former are "constructed out of individual objects and simple rules for their movement of behavior, as opposed to equational models that are constructed from mathematical symbols" and is therefore closer related to reality (Wilensky & Rand, 2015, p. 2).

Agent-based modelling has been applied in a variety of scientific domains, from natural sciences to the social sciences. In the field of biology, for example, ABM as has been applied at all scales from modelling molecular self-organisation (Troisi et al., 2005), the immune system (Folcik et al., 2007), and cancer (Preziosi, 2003), to the spread of epidemics (Bagni et al., 2002). A recent model in epidemic and disaster control includes environments of cities and 730,000 agents with the statistical characteristics of the actual population (Waldrop, 2018). While models of this size are not the norm, they show the potential that ABMs have for providing forecasts rather than more abstract conceptual insights, but also the huge reliance on computational power compared to differential equation models such as SD.

Applications in the social sciences span a wide area (Billari et al., 2006; Epstein, 2006; Squazzoni, 2010), from the emergence of cooperation (Axelrod, 1997), the behaviour of crowds of people (Pan et al., 2007), geographical systems (Heppenstall et al., 2012), history and ancient societies (Barceló & Del Castillo, 2016; Kohler et al., 2005), and public policy (Colander & Kupers, 2014), to a large body of literature in economics (Morini et al., 2015; Tesfatsion, 2002, 2003; Tesfatsion & Judd, 2006; Westerhoff & Franke, 2012), urban economics (Olner et al., 2015), economic policy (Vermeulen & Pyka, 2016), and innovation policy (Ahrweiler, 2017).

In the field of business and management, the applications of ABM can be divided into four main areas (Bonabeau, 2002): flows of people, traffic and transportation (Batty, 2001; Davidsson et al., 2005); markets (Tran & Cohen, 2003; Tseng et al., 2010); organisations (North & Macal, 2007), marketing (Rand & Rust, 2011), supply chain management (Swaminathan et al., 1998); and the diffusion of innovation and customer behaviour (see e.g. Bohlmann et al., 2010; Garcia, 2005; Kiesling et al., 2012; Pegoretti et al., 2012; Schramm et al., 2010; Shim & Bliemel, 2017; Sonderegger-Wakolbinger & Stummer, 2015; Twomey & Cadman, 2002).

ABM has a promising future in many social sciences disciplines (Cioffi-Revilla, 2002). In the following section, the applicability of ABM for modelling academic entrepreneurship and (university) ecosystems in general as well as the ability of ABM to address the four research questions in this study is discussed in more detail.

3.4.4 Applicability to Academic Entrepreneurship

ABM (Fioretti, 2012; Yang & Chandra, 2013) and complexity theory (Lichtenstein, 2014; McKelvey, 2004) have been proposed as means for the study of entrepreneurship. Similar trends have been observed in related fields such as organisational studies (Fioretti, 2012). Entrepreneurship is a multi-faceted and multi-level process and best explained by a microfoundations approach, which states that "an explanation of these collective phenomena [entrepreneurship and growth] requires consideration of lower-level entities, such as individuals or processes in organizations, and their interactions" (Felin et al., 2012, p. 1352). This has been applied to entrepreneurship but also to regional systems and the triple helix concept (Ryan et al., 2018). A summary of the correspondence between ABM and entrepreneurship is provided by Najmaei (2016, p. 28):

"Agents in entrepreneurship exist in many forms. They can be individuals or teams of entrepreneurs working privately to establish and grow a business or be executives of publicly listed firms whose job is to boost innovativeness, creativity and growth prospects of their business in domestic or international markets. Other types of agents can be angel investors, venture capitalists and even authorities whose actions and decisions affect the way entrepreneurs pursue they dreams. Agent populate complex systems and their actions shape behaviors of systems and sub-systems. Every agent has a mental picture of its task environment and develops a set of assumptions about his/her tasks. Social interactions provide agents with information that help them adjust or reinforce these assumptions which in turn affect their subsequent behaviors and actions of other agents with whom they interact in the business ecosystem."

ABM can model and integrate these different levels, from conceptualising entrepreneurship as a journey rather than an act for the individual (McMullen & Dimov, 2013), individuals' performance in opportunity creation is significantly influenced by "who they are, what they know, and who they know" (Wu & Ho, 2009), whether agents become entrepreneurs under asymmetric information distribution and varying levels of awareness (Minniti, 2004), search processes in the entrepreneurial problem space (Mauer et al., 2018), interactions among members of an organisation and between organisations (Fagiolo & Dosi, 2003), the early venture growth process (Shim et al., 2017), and the effects of entrepreneurial capabilities (alertness, risk-taking, efficiency) on firm performance (Ross & Westgren, 2009), to the importance of investments in the entrepreneurial process for economic growth (Shim et al., 2012) and how the emergence of high-tech clusters can be explained by a few local entrepreneurs inspiring others (Zhang, 2003).

ABM is a promising approach to understand ecosystems and other territorial systems of innovations and a means to synthesise existing work on these (eco)systems in the model development process (e.g. identification of relevant agents, patterns of behaviour) (Carayannis et al., 2016; Roundy et al., 2018). A general approach to modelling innovation networks is the SKIN model (Simulating Knowledge Dynamics in Innovation Networks) (see e.g. Ahrweiler, Gilbert, & Pyka, 2011; Ahrweiler et al., 2004; Gilbert et al., 2007), which has formed the basis for studies with different foci around the role of learning and innovation.[21] The SKIN model is based on "empirical research about innovation networks in

[21] Further information can be found at http://cress.soc.surrey.ac.uk/skin/.

knowledge-intensive industries with procedures relying on theoretical frameworks of innovation economics and economic sociology" (Ahrweiler, Pyka, & Gilbert, 2011, p. 218).

ABM has been applied to study a variety of related dynamics in territorial systems of innovation (Fioretti, 2005). Relevant examples include reputational dynamics in industrial districts (Giardini et al., 2008), the role of innovation processes in industrial districts to increase sustainability in highly competitive environments (Albino et al., 2006), supra-regional innovation and implications for regions (Vermeulen & Pyka, 2017), and the influence of network topologies and knowledge distribution in regional innovation systems based on OECD patent data (Vermeulen & Pyka, 2018). However, more studies similar to Vermeulen & Pyka (2018) are required to examine the role of gatekeepers and the resulting macro-level behaviour. Business entities that work in rapidly changing sectors have a huge demand for partnerships within their (innovation) ecosystem (Engler & Kusiak, 2011). A potential partner and gatekeeper in regional (eco)systems are universities.

An application of the SKIN model to academic entrepreneurship confirms that "university-industry links improve the conditions for innovation diffusion and enhance collaborative arrangements in innovation networks" (Ahrweiler, Pyka, & Gilbert, 2011, p. 219). Further studies have shown that these relationships lead to an increase in university patenting (particularly driven by interactions with large companies) without a decrease in the innovative value of the patents and provide incentives for a shift towards applied research in academia. This shift can be counteracted by an increase in public funding for basic research (Triulzi & Pyka, 2011; Triulzi et al., 2014). Interestingly, the financial support from industry is more important to strengthen universities' innovation capabilities than the intellectual input and the cognitive resources of the industry partner (Triulzi et al., 2014).

ABM has also been used to model general policy diffusion (Luyet, 2014) and innovation policy in an artificial science, technology, and innovation (STI) world based on the SKIN model that allows "scenario analysis, experimentation, policy modeling and testing prior to any policy implementations in the real world" (Ahrweiler, 2017, p. 391), as well as the resulting innovation and technological change (Dawid, 2006).

In conclusion, ABM has been applied to a variety of problems around academic entrepreneurship and ecosystems. It is particularly useful when the history of interactions matters, and therefore well-suited to address question Q3 (see Section

2.3.4), the temporal dynamics of entrepreneurial activities and the emergence of partnerships (Wilensky & Rand, 2015). Tracking individual companies throughout the duration of the simulation and their interactions with universities enables the identification of which companies collaborate, with whom they work, and if and how long-term partnerships emerge.

Existing ABM research on innovation systems and reputational dynamics in particular have demonstrated the ability of ABM to model evolutionary dynamics among universities and other actors from the university ecosystem (Giardini et al., 2008). A fundamental, yet still unanswered question in the area of academic entrepreneurship is whether research drives industry engagement or vice versa. An ABM approach can shed light on the dynamic interplay of research prestige, entrepreneurial reputation, and organisational proximity (question Q4).

3.4.5 Limitations

There are two related, yet distinct limitations for the use of ABM to the study of academic entrepreneurship in university ecosystems. First, modelling academic entrepreneurship involves human agents, "with potentially irrational behavior, subjective choices, and complex psychology — in other words, soft factors, difficult to quantify, calibrate, and sometimes justify — [and] because of the varying degree of accuracy and completeness in the input to the model (data, expertise, etc.), the nature of the output is similarly varied, ranging from purely qualitative insights all the way to quantitative results usable for decision-making and implementation" (Bonabeau, 2002, p. 7287).

There is a substantial amount of additional, individual-level knowledge required about the system compared to a SD approach (Wilensky & Rand, 2015). The focus of this work is on the inter-organisational dynamics between universities and other agents in the university ecosystem. Therefore, modelling universities as a population of individual academics would increase the number of assumptions and require a substantial amount of confidence building efforts. Furthermore, some of the causal relationships are hard to realise with typical agent designs.

Second, university characteristics and properties such as the share of entrepreneurial academics, the amount of entrepreneurial activities, and the generated income could be sufficiently represented by aggregated values to address research questions Q1 and Q2. Describing academic entrepreneurship at the individual level would also be extremely computationally intense and time consuming. While computing power is increasing and cost are constantly decreasing, the computational requirements of large-scale ABMs remain an issue that comes with the benefit of producing a rich, disaggregated data (Bonabeau, 2002; Wilensky & Rand, 2015). In conclusion, ABM is a capable approach and superior to SD for parts of this study (Q3 and Q4), but is also inferior to SD with regard to other parts as outlined in this section (Q1 and Q2) and limited by practical considerations.

3.5 Summary of Mono-Method Approaches

The gap in the literature and the research questions were developed first, without a pre-selected method to address them (see Section 2.8), which is generally regarded good modelling practice (Randers, 1980; Sterman, 2000; Robinson, 2004; Salamon, 2011). SD and ABM have then been presented as two potential modelling approaches that could address these research questions. The two methods are based on different assumptions regarding the cause of a system's dynamic behaviour and are, therefore, often seen as opposing ends (top-down and bottom up) of a spectrum of M&S approaches in MS/OR. They are, however, not incompatible modelling paradigms but instead "regions in a space of modelling assumptions" that can even both be applied to model the same problem (Rahmandad & Sterman, 2008, p. 1001). Both approaches have been applied in a variety of fields, including few applications in academic entrepreneurship, (eco)systems, and related areas. Table 3.1 summarises the applicability of both methods to the research questions of this study individually.

The results show that neither SD or ABM are capable of providing sufficient details to address the research questions on their own. As a consequence of the different assumptions regarding the origins of the dynamics within a system, both approaches have their respective strengths and shortcomings at opposing aspects of this research problem. SD is limited when it comes to representing heterogeneity among entities within the system and tracking individual interactions (Rahmandad & Sterman, 2008). This is essential for modelling a vibrant ecosystem with different types of companies that have different needs and resource endowments and, hence, favour different entrepreneurial activities. ABM, on the other hand, is capable of representing such heterogeneity among different agents, but is limited when modelling the dynamics within universities and the feedback from the interactions with the ecosystem.

As a conclusion, SD and ABM "align well when used simultaneously and, contrary to some common misconceptions, should be considered complements rather than substitutes" (Gräbner et al., 2019, p. 763). Each method has its

Table 3.1: Applicability of SD and ABM

Research question	System dynamics	Agent-based modelling
Q1: What is the dynamic relationship between universities' internal capabilities and resources (organisational arrangements), the volume and share of different entrepreneurial activities, and the evolution of the university ecosystem?	*Yes.* Capabilities and resources can be easily modelled using SD and an aggregated overview of entrepreneurial activities is sufficient to answer the question.	*Possible, but ineffective.* Modelling the behaviour of individual academics is not required to answer the question. Furthermore, generating such disaggregated insights is computationally intensive, potentially constrained by available data, and hard to validate.
Q2: Is there a path dependency for universities based on different research and entrepreneurial profiles, resource endowments, historical backgrounds?	*Yes.* Historical background can be reflected in the current state of the system and the model can be parametrised for different universities. And a fixed system structure fits universities due to organisational inertia.	*Possible, but ineffective.* ABM again requires more fine-grained data and insights than required to address this question.
Q3: What are temporal dynamics of different entrepreneurial activities in the evolution from ad hoc interactions to strategic partnerships between universities and firms?	*No.* SD is not well suited to show and observe individual relationships between universities and other ecosystem actors.	*Yes.* ABM is most useful when heterogeneity and individual interactions matter. These can also easily be tracked.
Q4: What are the co-evolutionary dynamics between a universities research prestige, entrepreneurial reputation, organisational proximity, and social capital and how does this affect a university's entrepreneurial performance?	*Yes.* Reputational effects can be modelled as resources in SD and the evolutionary dynamics can be conceptualised in a feedback structure.	*Yes.* Evolutionary dynamics and the interactions among different actors in an ecosystem can be easily modelled using ABM.

advantages but also limitations and combining different methods can be a way of overcoming the limitations of a single-method approach – a fundamental idea that is more than 30 years old (Jackson & Keys, 1984). The opportunities for combining both methods in one simulation will be discussed in the next section.

3.6 Hybrid Simulation Framework

Combining different methods to generate insights and learning that a mono-method approach is neither new nor exclusive to this particular study. In the following, the terminology regarding the combination of simulation methods and hybrid simulations will be clarified and existing approaches and classifications in the literature are explored. An HS framework is then provided that shows, which aspects are modelled in SD and ABM, respectively, and how the two methods contribute to the outcome of the simulation. Methodological challenges are discussed, with an emphasis on the role of feedback. Feedback is a key concept for both SD and ABM, yet it has been overlooked in many HS studies. A theoretically sound conceptualisation of the feedback between different modules in an HS is essential for building confidence in the model. The contribution of this section is the conceptual hybrid SD-ABM framework for modelling academic entrepreneurship in university ecosystems.

3.6.1 History and Terminology

In very general terms, hybrid simulations (HS) are "the combined use of at least two simulation approaches" (Martinez-Moyano & Macal, 2016, p. 134). Combining simulation methods has a long history in MS/OR (Fahrland, 1970; Mingers & Brocklesby, 1997; Morgan et al., 2017) and is also used in other disciplines such as mathematics (Shanthikumar & Sargent, 1983), ecological modelling (Martin & Schlüter, 2015; Villa & Costanza, 2000; Vincenot et al., 2011), cyber-physical systems (Rovers et al., 2011), construction management (Nasirzadeh et al., 2018), and expert systems (Lättilä et al., 2010), among others. The term HS was first defined by Shanthikumar & Sargent (1983) as different designs of combinations of simulation and analytical models. Some argue that an HS is characterised by the combination of continuous and discrete simulation approaches (Mosterman, 1999). However, this would exclude the combination of approaches that belong to the same category, such as DES and ABM (Mustafee, Brailsford, et al., 2015).

HS are a special case of a hybrid M&S study (Powell & Mustafee, 2014, see Figure 3.10) and relates to the general work on *multimethodology* (see e.g. Mingers, 1997; Mingers & Brocklesby, 1997; Pollack, 2009) or *mixing methods* (see e.g. Howick & Ackermann, 2011; Howick et al., 2017) in MS/OR. Compared to hybrid M&S studies, HS are defined by combining simulation approaches in the implementation stage in contrast to including other methods during at least one other stage in the model development process. This does not definitely exclude other aspects from hybrid M&S studies. For example, ABMs are based on stochastic processes and often require a large number of simulation runs for each scenario, which might require parallel computing to reduce the time for running the simulations.

The first academic papers with hybrid SD-ABM simulation approaches in MS/OR were published in the late 1990s (Kim & Juhn, 1997; Parunak et al., 1998), followed by a wave of publications in the early 2000s (Akkermans, 2001; Borshchev & Filippov, 2004; Größler et al., 2003; Pourdehnad et al., 2002; Schieritz, 2002; Schieritz & Milling, 2003; Scholl, 2001a,b; Scholl & Phelan, 2004). The topic has been of interest again within recent years (Heath et al., 2011; Lättilä et al., 2010; Swinerd & McNaught, 2012, 2014). Nevertheless, combinations of SD and ABM are still relatively rare (Lättilä et al., 2010) and hybrid SD-ABM simula-

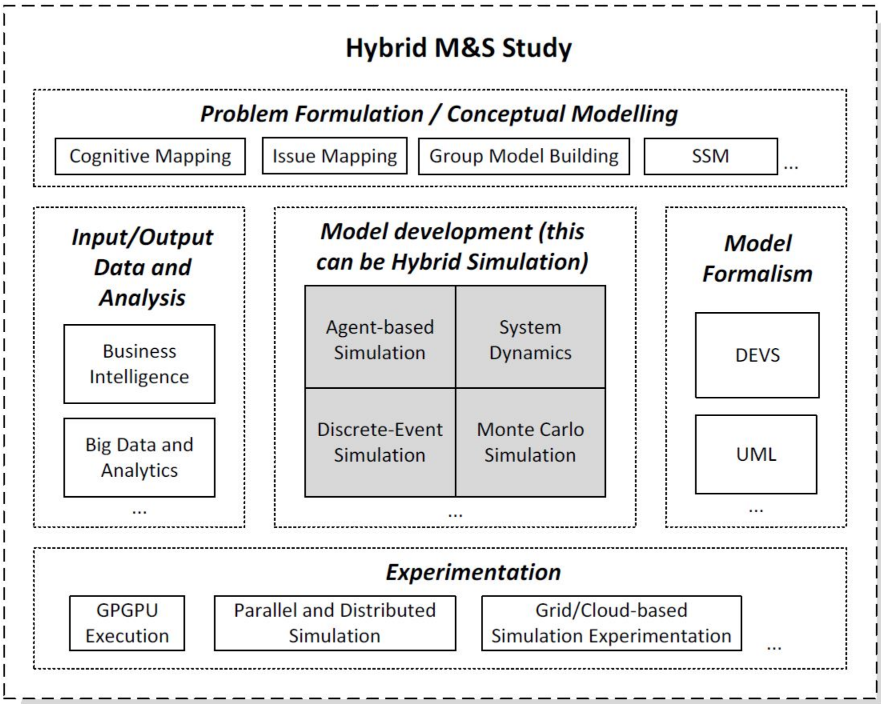


Figure 3.10: Hybrid studies and hybrid simulations (Powell & Mustafee, 2014)[22]

tions are less researched than hybrid SD-DES simulations (Swinerd & McNaught, 2012).

For consistency, the term *module* will be used to describe a component of an HS that is implemented using a particular method (Swinerd & McNaught, 2012). This is an important notion because it is possible to have multiple modules of the same method in one hybrid simulation, e.g. the combination of one ABM module and two SD modules. The two SD modules in this example are not directly linked to each other and interact with the ABM module at different points.

3.6.2 Reflections on the Need for HS

Different modellers can see a problem differently and use different methods to address the issue and each method can contribute to an increased understanding of the problem and lead to different insights (Morecroft & Robinson, 2005). There is, however, "no single best possible modeling approach" (Martinez-Moyano & Macal, 2016, p. 133), because every method comes with benefits, limitations and underlying assumptions. The selection and application of the most appropriate method is crucial, especially when working in an interdisciplinary context with a variety of stakeholders and collaborators (Chick, 2006). Modelling aca-

[22]This Figure includes Monte Carlo Simulation as a distinct method, but it is rather used as a means of adding uncertainty to methods such as SD or ABM if required.

demic entrepreneurship in university ecosystems is an example of a problem, for which a single method is not the most appropriate approach. The desirability of combining (simulation) methods has been outlined in the literature (Kotiadis & Mingers, 2006; Mingers, 2003; Mingers & Brocklesby, 1997; Shanthikumar & Sargent, 1983; Villa & Costanza, 2000).

There are different ways in which combining SD and ABM can complement each other. Two rationales have been presented so far that support an HS approach: a combination of SD and ABM is a better representation of reality to answer the research questions and a hybrid SD-ABM simulation reduces the compute intensity. First, since the world as a whole and the problems in MS/OR are highly complex, single modelling approaches cannot always cope with this complexity and richness to answer a specific question sufficiently (Mingers & Brocklesby, 1997). For example, the complexity of decision making problems often span multiple scales and levels of aggregation (e.g. organisational structures, spatial distributions) and combining these within a single simulation model is where hybrid simulation are often superior to mono-method simulations (Swinerd & McNaught, 2012; Villa & Costanza, 2000).

ABM can complement SD when heterogeneity or interactions between entities is essential for the dynamics of the system or the model needs to account for spatially distributed dynamics or network structures (Brailsford et al., 2013; Rahmandad & Sterman, 2008). For HS research, "the ultimate methodological goal is to include elements which best leverage the core concepts of the individual paradigms, whilst also showing interesting ways to combine them at different levels of granularity" (Brailsford et al., 2013, p. 267). Using the strength of individual methods in a combined fashion can also reduce the complexity as fewer assumptions have to be made (Chahal et al., 2013).

Second, HS also provide a means to reduce the compute-intensity to find solutions or generate the behaviour over time (Shanthikumar & Sargent, 1983). Different simulation methods require different levels of computational performance. SD is usually on the lower end, given that differential equations are relatively easy to solve. In contrast, ABM can easily become very compute-intense with a large agent population and complex agent rules and interactions. Using SD to model parts of a system that does not rely on heterogeneity and low levels of aggregation such as the internal structure of the university and the resources dedicated to academic entrepreneurship, could reduce the required computational power significantly.

Two further rationales for HS are commonly mentioned in the literature: research and interventions as a process with different stages that might require different approaches and that practice is already ahead of theory (Lättilä et al., 2010; Mingers & Brocklesby, 1997). These will be briefly discussed in the following and how they could play a role in this study.

Research and practical interventions in MS/OR are a process, potentially with multiple phases, rather than a single one-off event. Some methods are more appropriate and effective in some phases compared to others. Hence, a combination of methods can yield deeper insights and richer outcomes (Mingers & Brocklesby, 1997). This is a justification for hybrid M&S studies and less for HS, as methods are combined here in the same phase (Powell & Mustafee, 2014). However, simulation approaches are not very common in the field of academic entrepreneurship. Introducing SD and ABM at different times of the model development process can help show the value of the respective approach and build confidence in the overall model. For example, a qualitative SD approach can be used to structure the problem and understand the endogenous nature of the problem, before introducing ABM module to replace parts of the SD structure.

Lastly, combining different methods and the development of HS is becoming increasingly more common in non-academic work. There are three reasons for this: first, more and more modellers get exposed to more than one simulation method (Swinerd & McNaught, 2012; Villa & Costanza, 2000). Second, the development of software platforms like AnyLogic make the realisation of HS easier and require only limited coding skills, hereby making them more accessible to a wider audience (Borshchev & Filippov, 2004). Third, in the age of big data and open data, the amount and the disaggregated nature of data that is available to researchers and also practitioners open up new opportunities for using HS to model complex problems (Villa & Costanza, 2000).

While HS are becoming increasingly popular, there is still a lack of conceptualisation (what are different ways of combining simulation methods) and theorisation (what is the theoretical, methodological, and philosophical foundation for these combinations) (Swinerd & McNaught, 2012). HS research driven not only by solving real-world problems but academic curiosity as a "natural experiment in model building" can address these issues (Brailsford et al., 2013, p. 263). The issue of conceptualisation will be addressed in the following, exploring different types of HS models (Section 3.6.3) and how SD and ABM can be combined in particular (Section 3.6.4). A hybrid SD-ABM framework is developed based on this review and methodological (Section 3.6.6) and theoretical issues (Section 3.6.7) are covered afterwards.

3.6.3 Categorisation of Hybrid Simulations

Various typologies of HS and hybrid M&S studies have been developed for the combination of different methods and in different contexts. These generic structures are designed to provide guidance for the modeller in the process of developing a conceptual model (Swinerd & McNaught, 2012). Early work on categorising HS approaches date back to the 1980s and work by Bennett (1985), who defined three distinct approaches, and the four classes by Shanthikumar & Sargent (1983). More recently, Swinerd & McNaught (2012) developed a categorisation particularly for combinations of SD and ABM and Morgan et al. (2017), who provide the most detailed comparison to date based on a comprehensive review that also included working on mixed methods in MS/OR is general. A comparison of these four categorisations and three additional ones is shown in Table 3.2. The aim of this comparison is to show the breadth of existing categorisations as well as the overlap and vagueness based on the level of detail (depth) of the definitions.

This thesis uses the notation by Swinerd & McNaught (2012) that differentiates between interfaced, sequential, and integrated HS designs (see figure 3.11). These three design approaches are adapted from the early work by Shanthikumar & Sargent (1983) and represent the most basic categorisation of how different modules can be combined in an HS as it only considers whether a link exists between modules or not. In particular, there can be no link between modules during the simulation run and both inform the outcome (interfaced), one module can be linked to another and only the second one is relevant for the simulation output (sequential), or there can be feedback between both modules and both contribute to the outcome (integrated). All three types will be introduced in the following and briefly compared to other categorisations to show how they could be refined.[23]

[23]For a comprehensive discussion see Morgan et al. (2017).

Table 3.2: Comparison of different combinations of M&S methods and HS categories

Morgan et al. (2017)	**Swinerd & McNaught (2012)**	**Mingers & Brocklesby (1997)**	**Schultz & Hatch (1996)**	**Bennett (1985)**	**Shanthikumar & Sargent (1983)**	**Martinez-Moyano et al. (2007)**
Isolationism		Isolationism *				
		Selection *				
Parallel	Interfaced	Combination ***	Parallel **	Comparison**	Class I	
Sequential ***	Sequential ***		Sequential ***	Enrichment ***	Classes III & IV	Scenario exploration
Enrichment ***		Enhancement ***	Bridging			Crisis response
Interaction	Integrated		Interplay			
Integration ****		Multimethodology		Integration	Class II	Intertwined

* Isolationism uses one method only, whereas selection might use different methods at different stages indepedently (Mingers & Brocklesby, 1997).

** One method might be more dominant for comparison, whereas parallel assumes equal terms (Morgan et al., 2017).

*** The definitions of sequential, combination, enrichment and enhancement are not very precise in the literature. Accoring to Morgan et al. (2017), the differences are that in a sequential approach one methods feeds into the other (not necessarily on equally weighted), combination combines whole methods on equal terms, and enrichment develops a final method based on one core method. Enhancement is similar to enrichment, without the core method (but a method can be dominant). Swinerd and McNaught (2012) focus on one module informing the design (enhancing/enriching), application (sequential/combination) or starting conditions of another (sequential), hereby including a variety of designs that others separate under the umbrella of seqential HS.

**** Integration and multimethodology produce a single final method, but integration is based on selecting elements from methods and multimethodology on partitioning and combining methods (Morgan et al., 2017).

In the interfaced design, there is no direct link between the two (or more) modules (Figure 3.11a). Both are modelled based on the same problem and "the output of each module is combined to provide the final model output" (Swinerd & McNaught, 2014, p. 232). The interfaced design as defined here corresponds to class I (Shanthikumar & Sargent, 1983), but parallel HS (Morgan et al., 2017; Schultz & Hatch, 1996) and comparisons (Bennett, 1985) can also be forms of interfaced designs. A review by Swinerd & McNaught (2012) did not reveal any published examples of interfaced SD-ABM simulations, but an interfaced combination of DES and ABM (Dubiel & Tsimhoni, 2005). However, the comparisons of SD and ABM (Rahmandad & Sterman, 2008) and SD and DES (Morecroft & Robinson, 2005) can be seen as interfaced designs. The former, for example, uses a SEIR model, a common approach in epidemiology to model the individuals of a population as being either susceptible, exposed, infectious, or recovered from a disease, to show different insights that both methods can provide e.g. with regard to network structures and heterogeneity.

In a sequential approach, "one modelling technique is used to inform the design, use or starting conditions of another" (Swinerd & McNaught, 2012, p. 129). The flow of information between the modules in a sequential design is always unidirectional, but can be either cyclic, i.e. two modules interact only before and after the simulation run, or parallel interactions, i.e. both modules interact during the run time of the simulation (Chahal et al., 2013) based on the definition by Swinerd & McNaught (2012). This explains why a sequential design corresponds to classes III (simulation module influences analytical module) and IV (analytical module influences simulation module) by Shanthikumar & Sargent (1983) and the sequential approach by Schultz & Hatch (1996) and Morgan et al. (2017), but also includes other forms of sequential designs such as enrichment (Bennett, 1985; Morgan et al., 2017), bridging (Schultz & Hatch, 1996), some types of enhancement or combination (Mingers & Brocklesby, 1997) as well as scenario exploration and crisis response (Martinez-Moyano et al., 2007). Sequential approaches are useful for enriching a particular method with another, e.g. implementing some discrete components into an SD model or including processed real-time data in the crisis response approach (Martinez-Moyano et al., 2007). The review by Swinerd & McNaught (2012) identified applications of this approach in areas such as workforce planning (Homer, 1999), population dynamics (Schieritz & Milling, 2009) and land use (He et al., 2005). Using a different simulation method to generate data as an input for another model can be a handy option if data is not readily available at the required level of aggregation,

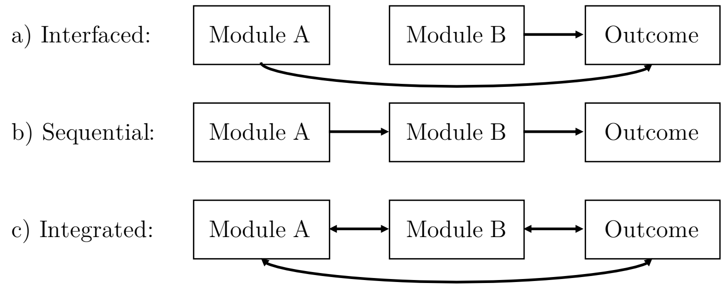


Figure 3.11: Categorisation of HS designs (Swinerd & McNaught, 2014)

but should be used carefully and all other potential data sources are exhausted because it adds a different set of assumptions to the model (Homer, 1999).

Integrated approaches are characterised by "sustained feedback" between different modules (Swinerd & McNaught, 2012, p. 121). These modules, which are based on different methods and contribute the required capabilities for the problem at hand, whether they are philosophical or methodological, are no longer distinct after the integration and work as a single model (Heath et al., 2011; Morgan et al., 2017). This HS design is based on the class II model by Shanthikumar & Sargent (1983) and is similar to integration (Bennett, 1985) and multimethodology (Mingers & Brocklesby, 1997). Furthermore, intertwined models (Martinez-Moyano et al., 2007) and interplay (Schultz & Hatch, 1996), also referred to as interaction (Morgan et al., 2017), can represent forms of integrated designs. Integrated models show the greatest potential for modelling complex systems as they provide an opportunity to simulate the dynamic interaction among multiple scales of a system (Swinerd & McNaught, 2014). A review by Swinerd & McNaught (2012) showed that integrated SD-ABM simulations have been applied to scientific revolutions (Sterman, 1985; Sterman & Wittenberg, 1999), pension funds (Chaim & Streit, 2008), supply chains and production (Akkermans, 2001; Kieckhäfer et al., 2009; Schieritz & Größler, 2003), population dynamics and social networks (Duggan, 2008), as well as in land ecology (Gaube et al., 2009; Verburg & Overmars, 2009). Other areas include e.g. agricultural systems (Feola & Binder, 2010; Feola et al., 2012) and firm strategy (Rahmandad, 2015).

The selection process whether to use an interfaced, sequential, or integrated approach can be systematically described in five decisions as shown in Figure 3.12. Modelling the effects of entrepreneurial activities by universities in university ecosystems requires both aggregate state variables and investigating the behaviour of individual firms, as shown in Section 3.5 (D1: yes). The key idea is that entrepreneurial activities by universities are not isolated actions but influence the ecosystem, leading to dependences between SD and ABM modules (D4:

yes). This dependency is cyclic, i.e. based on feedback, as decisions by universities regarding their priorities or resource allocations affect the ecosystem, but the ecosystem also provides the environment in which universities makes these decisions (D5: yes). As a result, an integrated approach is required and the next section will explore how this design can be realised in practical terms.

3.6.4 Integrated SD-ABM Simulations

The focus of this section will turn towards the actual design of the HS and how SD and ABM modules can be linked in an integrated approach. Generally, it can be differentiated between static, i.e. each aspect of the system is modelled using one method in a fixed structure, and dynamic HS designs, in which an aspect can be modelled by different methods depending on the fulfilment of a pre-defined condition (Swinerd & McNaught, 2012; Vincenot et al., 2011). The actual mechanisms for implementing are described by Swinerd & McNaught (2012), whereas Borshchev & Filippov (2004) and Vincenot et al. (2011) provide complementary categorisations. Static integrated SD-ABM HS can be realised in three ways (Swinerd & McNaught, 2012, p. 124):

- agents with rich internal structure: "an SD module is built within agents of an AB module"
- Stocked agents: "a level within an SD module is used to bound an aggregate measure of an AB module"
- Parameter with emerging behaviour: "an aggregate measure or observation of an AB module is used to influence a parameter within an SD module"

Agents with a rich internal structure are characterised by an ABM that describes the relationship among the agents, whose individual behaviour is determined by an SD model (see Figure 3.13a).[24] This type of integrated HS is described in a similar way in the categorisations by Borshchev & Filippov (2004) and Vincenot et al. (2011). An example of this design is used for supply chain management (Größler et al., 2003; Schieritz, 2002), in which the HS "consists of a 'master' program representing the overall [ABM] simulation environment and the internal [SD] structures of the agents" (Größler et al., 2003, p. 2). Similar

[24] The ABM module is represented as a set of agents, but all of the designs presented in this section can be modelled using different ABM typologies, including cellular automata or networks, among others (Swinerd & McNaught, 2012; Vincenot et al., 2011).

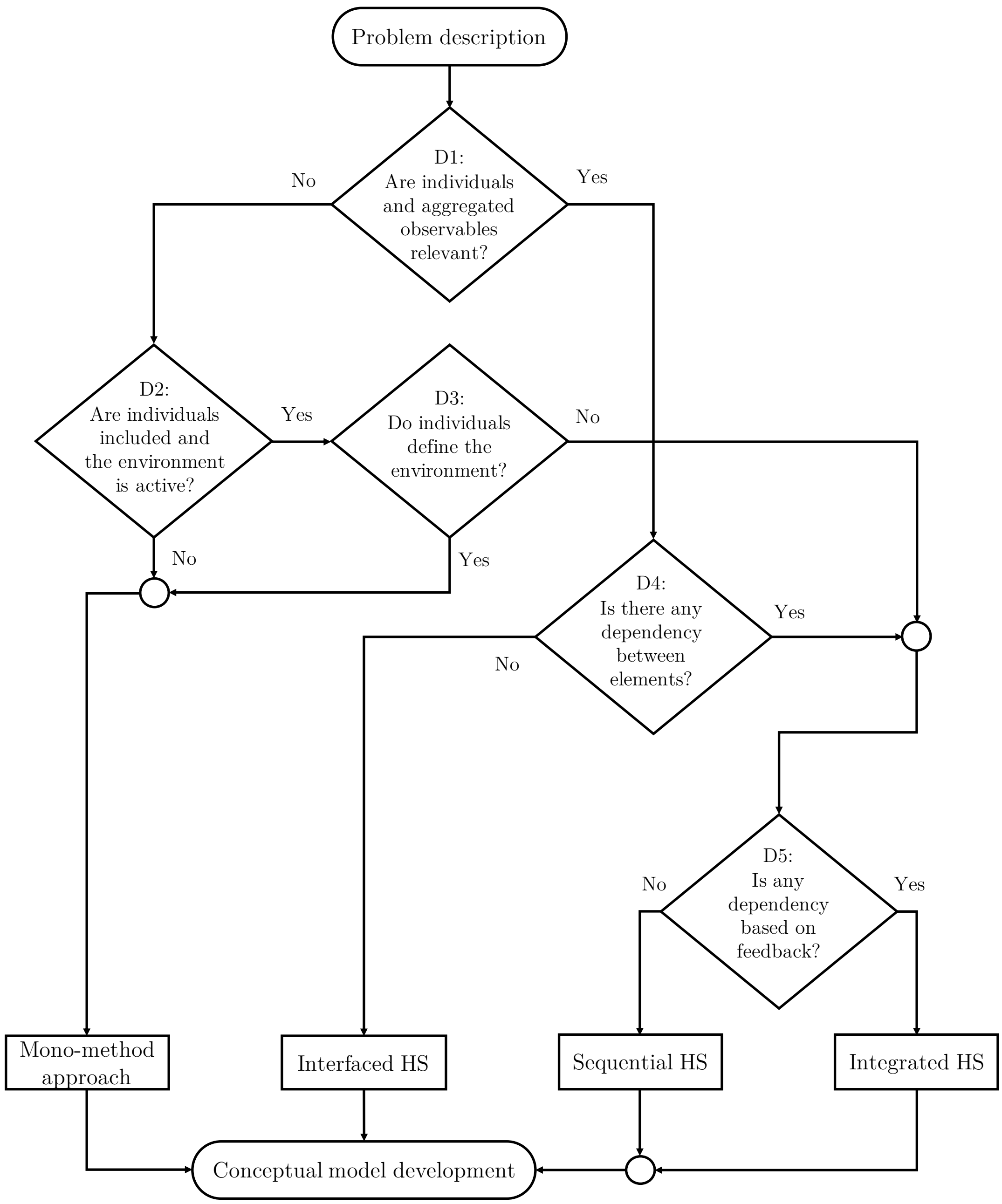
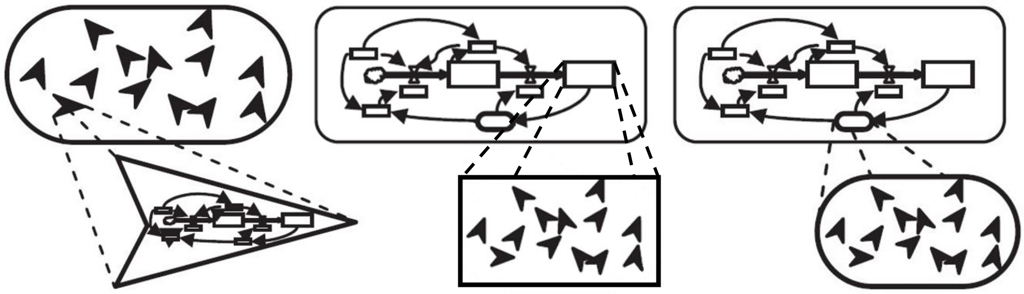


Figure 3.12: Decision process for HS design choice (adapted from Swinerd, 2014)



a) Agents with rich internal structure b) 'Stocked agents' c) Parameter with emergent behaviour

Figure 3.13: Integrated SD-ABM HS designs (Swinerd & McNaught, 2012)

designs have been used by Duggan (2008), Schieritz & Größler (2003), (Rahmandad, 2015) as well as Feola & Binder (2010) and Feola et al. (2012) in the area of ecological modelling.

Stocked agents (Figure 3.13b) and parameters with emergent properties (Figure 3.13c) are conceptually similar, as they aggregate the behaviour of individual agents into a parameter or stock, respectively (Swinerd & McNaught, 2012). Both are described by Borshchev & Filippov (2004) as agents 'living' in an environment that is modelled using SD. Vincenot et al. (2011) do not differentiate between stocked agents or emergent parameters either, but focus on the spatial aspect of hybrid SD-ABM simulations. An ABM module can either interact with a single SD module or "spatially disaggregated instances of a SD model", which are effectively multiple SD modules that have a particular spatial meaning. A detailed review of published models using either parameters with emergent behaviour or stocked agents is again provided by Swinerd & McNaught (2012). Stocked agents are e.g. used to model regional demand as an SD model that is based on the aggregation of land grids and their interactions as individual agents (Verburg & Overmars, 2009). Chaim & Streit (2008) use an ABM module for an emergent parameter within an SD model for pension funds, in which the ABM represents a heterogeneous customer base. More common are different combinations of the three possible designs to represent different scales (e.g. spatial) or levels of aggregation within the model (Swinerd & McNaught, 2012). Swinerd & McNaught (2014), for example, use a model based on a parameter with emergent phenomena, in which the agents' decision-making is based on an SD model, to make predictions about the national adoption of cell phone, fixed internet, and fixed broadband. A combination of parameters with emergent behaviour and stocked agents is applied for land use modelling (Gaube et al., 2009).

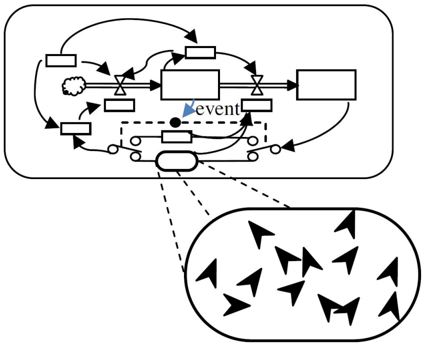


Figure 3.14: Event reconfigurable dynamic design (Swinerd & McNaught, 2012)

A dynamic HS design can be described as a "time or event driven reconfiguration of a hybrid model" (Swinerd & McNaught, 2012, p. 130). A particular part of the system is either modelled with an SD or ABM module. Dynamic SD-ABM designs are based on one or more of the static designs and could remain static if the change condition, that triggers the event, is not met throughout the simulation (Swinerd & McNaught, 2012; Vincenot et al., 2011). Figure 3.14 presents a generic illustration of a model that uses an event to switch a parameter with emergent behaviour on and off. Bobashev et al. (2007) present a model that uses a threshold as the criteria for switching between SD and ABM and advocate the efficient use of computational resources of this approach.

Wallentin & Neuwirth (2017) elaborated on the dynamic designs proposed by Swinerd & McNaught (2012) and Vincenot et al. (2011) and tested six different types of dynamic SD-ABM hybrid models. A surprising result was that a higher computational performance is not necessarily the result of a higher degree of aggregation. This has significant implications for further research in this area and contradicts the common belief that the application of ABM over SD leads to higher computational requirements *per se*.

3.6.5 Conceptual HS Framework

The previous two sections have demonstrated how integrated HS designs are particularly suited for modelling complex systems with different levels of aggregation. This section will describe the HS framework for modelling academic entrepreneurship. Understanding academic entrepreneurship based on a single university is insufficient as it does not account for the complex, evolutionary dynamics between heterogeneous universities within a region and (international) networks as discussed in Section 2.7. Academic entrepreneurship can be stimulated at different levels and the development of effective policies and adequate incentive structures requires the consideration of three levels (Grimaldi et al., 2011; Murray & Kolev, 2015):

- systemic level, including the legal framework, national and regional policies, history, and culture;
- institutional level, including internal support mechanisms and resource allocations for both universities and companies; and the
- individual academic level, including their networks, norms, and incentives.

The proposed HS framework is based on the integration of SD modules for universities (solid contour line) in an ABM module for the ecosystem with firms as agents (dashed contour line as they are not separate modules), whose decision-making is based on probabilistic rules, i.e. rules that are partially triggered by dynamic probabilities. This general structure is illustrated in Figure 3.15.

ABM provides a means to model the university ecosystem that is more natural with universities and companies as distinct entities, whose interactions can be easily observed. Heterogeneity among companies with regard to size, resources, R&D activities, and absorptive capacity, as well as their history and preferences for collaborations with universities can be represented accurately. The ABM environment can incorporate the systemic level, including legal restrictions or policy incentives, which encourage or limit agents' activities. ABM is the preferred choice here, because it does not require knowledge about the macro-level effect of these policies for which evidence is scarce.

Using an SD module, universities can be modelled at an institutional level, without the need for modelling individual academics, departments, or faculties, while still being able to represent the internal structures, processes, policies, and resulting dynamics. A separate SD module is used for every university to incorporate diversity among universities (e.g. with regard to their strategy, size, or resources) and the evolutionary dynamics that arise from the interaction of multiple universities with businesses within ecosystems. Universities, therefore, represent *agents with a rich internal structure* within the ABM (Swinerd & McNaught, 2012).

All modules are fully integrated into one model, which means that there is feedback between these modules and the entire model does not work if a module is missing. The company agents in the ABM module are affected by the aggregated state variables of the university agents. For example, reputation and prestige of universities, their organisational proximity, or resources affect companies' decision

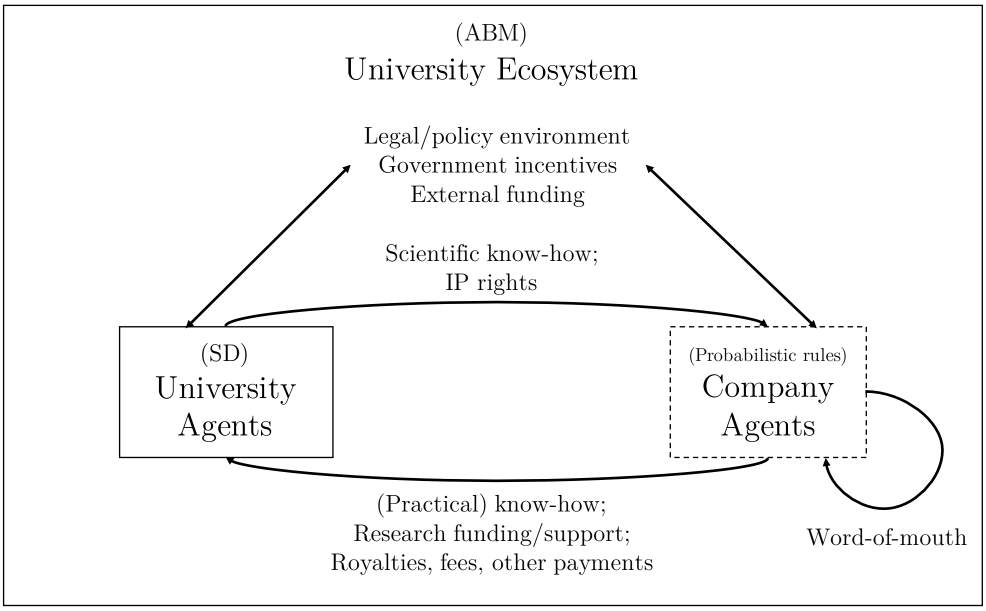


Figure 3.15: Hybrid simulation framework showing the the interaction between university agents with 'rich internal structure' (SD modules) and company agents with 'traditional' decision-making within an ABM module.

making regarding their preferred collaboration partner. However, these aggregate SD variables depend on the decisions and actions of companies, e.g. whether they will get involved in licensing, consulting or collaborative research endeavours, and if so, with which university. Interactions among company agents also lead to word-of-mouth effects and the spread of university reputations. Without knowing the detailed structure of the model, this can result in either stocked agents or SD parameters with emergent properties. This will be determined when the actual causal structure is developed.

3.6.6 Methodological Aspects

Developing HS poses additional challenges compared to a mono-method approach, including philosophical, cultural, cognitive, practical, and methodological issues (Brailsford et al., 2013; Lynch & Diallo, 2015; Mingers & Brocklesby, 1997). This thesis, and this section in particular, focuses on the methodological challenges of combining SD and ABM. Research in MS/OR should focus less on "paradigm-based theorising" and more on "promoting ontological flexibility and methodology-in-use", i.e. developing a sound theoretical basis for innovative HS development (Zhu, 2011, p. 784). Philosophical considerations build the foundation of HS and M&S studies in general and these will be discussed in detail in Chapter 4.

Methodological challenges include different time representations, bases for values, behaviours, expressions, executions, and resolutions (Lynch & Diallo, 2015, based on work by Fishwick, 1995; Sokolowski & Banks, 2010; Sulistio et al., 2004; Wooldridge & Jennings, 1994). Some of these issues have also been addressed in the literature as part of the theoretical feasibility of HS (Mingers & Brocklesby, 1997) and in general comparisons of SD and ABM (Lättilä et al., 2010; Parunak et al., 1998; Pourdehnad et al., 2002). The key differences between SD and ABM with regard to these issues are summarised in Table 3.3 and briefly discussed in the following. Contrasting modelling approaches pairwise shows the different characteristics and limitations (Martinez-Moyano & Macal, 2016).

First, different methods and models can have different time representations (Lynch & Diallo, 2015). Essentially, a model can change with the progression of time (dynamic) or be a static representation of reality (Law & Kelton, 2000). Both SD and ABM are dynamic models that are time-dependent, but the time in ABMs is often not depending on certain events and actions that agents perform within a time step. Both methods need to be synchronised by mapping the real numbers in SD to the integer numbers from the ABM.

Closely linked to the first issue are multiple bases for values, referring to discrete and continuous models (Lynch & Diallo, 2015). A key feature of SD is that the temporal variable is continuous (Forrester, 1961; Sterman, 2000). ABM is a discrete modelling approach, mapping discrete individuals and their interactions as opposed to populations being represented by continuous variables in SD (thereby representing e.g. a fraction of a person) (Parunak et al., 1998; Wilensky & Rand, 2015). For many people not trained in simulation modelling, this is easier to understand and a better comparison to real-world phenomena. There are ways to make an ABM pseudo-continuous (e.g. randomise the order in which agents are activated) (Osgood, 2007). Since computers are discrete machines, even continuous simulations like SD are not truly continuous and need to be broken down into small discrete steps, which allows the combination of the two methods by e.g. aggregating discrete events from the ABM into the SD module within these small steps.

Third, models can have stochastic or deterministic characteristics, which is one of the fundamental differences between different simulation methods (North & Macal, 2007). Deterministic models always produce the same output for a given input and, therefore, only need to be run once. SD models usually fall in this category (Sterman, 2000), but SD is sometimes criticised for this determinism (Lane, 2001). In his clarification, Lane (2001, p. 112) argues that an approach based on determinism and "the modelling of causal laws, which transcend human subjectivity, is a reasonable position because of the level of aggregation of models". Furthermore, the required characteristic of the model and whether stochastic features are important also depends on its purpose (Pidd, 2004).

ABMs are usually stochastic and randomness is a key feature because agent rules and decisions do not need to be specified deterministically but can be probabilistic in nature (North & Macal, 2007; Wilensky & Rand, 2015). This is crucial in cases in which there is insufficient knowledge about how a complex system works, which means that "the only type of model that we can build is a model with some random elements" and randomness serves as an appropriation (Wilensky & Rand, 2015, p. 34). Since stochastic models can produce different outputs for given inputs, they have to be run multiple times and statistical tools and techniques are necessary for the evaluation. But each individual simulation run can also be of value as it provides a different historical trace if the model is constructed properly (North & Macal, 2007).

Fourth, models can be executed in a parallel or serial way (Lawton Smith, 2007). Serial models are "generally executed on a single processor and the simulation execution proceeds sequentially" (Lynch & Diallo, 2015, p. 1623). Particularly large ABMs that are computationally intensive need to be executed in parallel to reduce the run time. Running a model in parallel, either over multiple processors like in a high-performance computing (HPC) environment or over multiple computers, requires synchronisation of events within the simulation so that all of them are in the right order (Fishwick, 1995; Law & Kelton, 2000). Local causality constrains must not be violated and a simulation that is run in parallel should produce exactly the same output as if the simulation were run sequentially (Fujimoto, 2000). This relates to the wider area of interoperability, i.e. sharing and using relevant information among models or model components (Diallo et al., 2010).

Fifth, different expressions refer to the notational standards and building blocks of different methods (Sokolowski & Banks, 2010). SD models are based on feedback loops, which are illustrated via causal loop diagrams and stock and flow diagrams and formally expressed by a set of differential equations that describe variables and their relationships (Fishwick, 1995; Forrester, 1961; Richardson, 1999; Sokolowski & Banks, 2010). The building blocks of ABMs are individual agents and their rules and decisions (Macal & North, 2010). These are formally expressed using logic sentences that define conditions and sequences of events (Parunak et al., 1998; Romero & Ruiz, 2014). When combining these two types of expressions, the following issues need to be addressed: event detection and location; sequences of discrete transitions; consistent semantics of formalisms; and sensitivity to initial conditions (Mosterman, 1999; Mosterman & Vangheluwe, 2004).

Lastly, the resolution characteristics refer to the level of analysis or abstraction of the model, which is "the level of detail needed to construct the model assists in the modeling process by directing focus to features of the objects within the system being modeled that are relevant to addressing the problem" (Lynch & Diallo, 2015, p. 1624, with reference to Fishwick, 1995; Zeigler, 1984). Pourdehnad et al. (2002) classify the degree of realism of ABM as high compared to a moderate score for SD. This can be supported by comparing the level of abstraction that is used by both approaches (see Figure 3.16). While SD looks at an aggregated level and uses a high level of abstraction, ABM can be applied to the whole range and provide insights at the individual and aggregate level simultaneously (Borshchev & Filippov, 2004; Gilbert, 2008; Kim & Juhn, 1997; Martinez-Moyano et al., 2007; Richardson, 2011; Sterman, 2000; Wilensky & Rand, 2015).

When combined, the information exchange and aggregation and disaggregation need to be mapped and clearly defined (Chahal et al., 2013). Inconsistencies can occur despite a valid model at each level of aggregation due to insufficient correlation between the attributes at multiple levels of the same entity (Reynolds Jr. et al., 1997, p. 368). Particularly, if any of the following questions is answered with 'no', inconsistencies can be the result (Lynch & Diallo, 2015, based on Davis & Hillestad, 1993):

- Do the assumptions and operations hold across all levels of resolution?
- Is the representation of time maintained across all resolutions?
- Are spatial representations maintained across levels of resolution?
- Are aggregation and disaggregation relationships maintained?

This section has shown that SD and ABM have different underlying assumptions and differ in many technical aspects. The development of HS is possible because approaches have been developed to address these issues. The key feature of integrated HS is unconstrained feedback between modules and, hence, different levels of aggregation (Swinerd & McNaught, 2012). This is the reason why hybrid SD-ABM simulations have a huge potential for researching and simulating complex systems and emergent behaviour. Yet, this is an under-researched area, particularly the relationship between aggregation and disaggregation and whether this is maintained throughout the simulation run. The following section will further explore this issue.

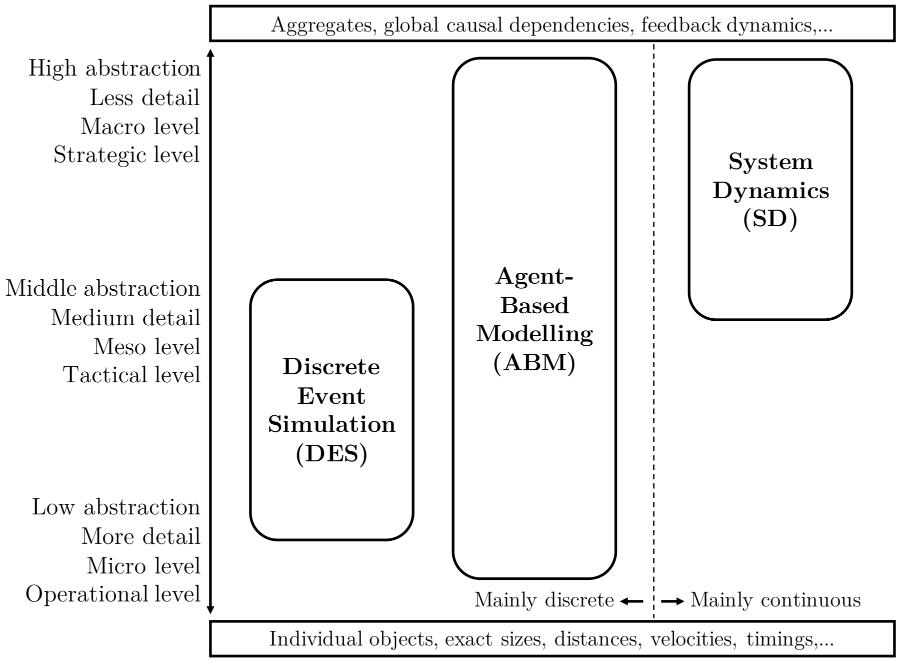


Figure 3.16: Abstraction level of simulation approaches (Borshchev & Filippov, 2004)

Table 3.3: General comparison between SD and ABM

Issue	**SD**	**ABM**	**HS Mechanisms / Problems**
Time representation	Dynamic, time-driven	Dynamic, time- or event-driven	Run HS to explore dynamic behaviour, synchronisation of events and time
Bases for values	Continuous	Discrete	SD is run on a discrete computer anyway; ABM can be made pseudo-continuous
Behaviour	Deterministic	Stochastic	Run HS many times to account for stochastic nature and create confidence intervals
Execution	Serial	Serial or parallel	Synchronization; local causality constraint; high memory requirements to run the HS
Expression	Equations	Logic sentences	Event detection and location; sequences of discrete transitions; consistent semantics of formalisms; sensitivity to initial conditions
Resolution	Aggregate state	Individual rules	Map SD and ABM and define interface; aggregation into parameters or stocks; problems with emergence

3.6.7 Feedback Between Modules

Although hybrid SD-ABM simulations receive increasing attention, the *holy grail* (Brailsford et al., 2010, p. 2293) of genuinely combining the two methodologies has not yet been found. The proposition of this thesis is that the key to finding this holy grail is the concept of feedback between modules, both how it works conceptually across module boundaries and in determining a rigorous process to develop such models. While efforts have been made to categorise HS and various combinations of SD and ABM in particular, there is not much work regarding the concept of feedback in hybrid SD-ABM simulations (Swinerd & McNaught, 2012; Vincenot et al., 2011; Wallentin & Neuwirth, 2017). Simulations are often treated as software and the relationship between the simulation and the feedback structures in the real world is often neglected and *integronsters*, i.e. "constructs that are perfectly valid as software products but ugly and useless as models" are created (Voinov & Shugart, 2013, p. 151).

SD is based on a fixed system structure and the dynamic behaviour is based on non-linear differential equations (Sterman, 2000). This non-linearity also enables learning within SD models (Richardson, 1999). In contrast, the complexity in ABMs emerges as a result of agent interaction and their learning and adaptation (Gilbert, 2008; Railsback & Grimm, 2012). While complex phenomena can emerge from simple rules of behaviour, sufficiently intelligent agents would have the opportunity to not only create emerging patterns at the aggregated level but create completely new rules and behaviours (though it can be argued that this will not be achieved without including artificial intelligence or machine learning). This could, however, potentially create discrepancies between an ABM and an SD module.

When conjoining multiple scales of a system within one simulation, feedback is the *glue* that links (spontaneous) emergence from the bottom up with higher-level structures that adapt at a much slower rate (Lichtenstein, 2014; Railsback & Grimm, 2012; Salamon, 2011; Uhl-Bien et al., 2007). In the example of population dynamics, a high-level system dynamics structure can be identified and quantified using an ABM module (Schieritz & Milling, 2009). The authors note, however, that "transfer of local policies to a system level is only possible if the local situation of the major part of the agents is comparable to the global situation" (Schieritz & Milling, 2009, p. 142). This example of the interplay between social structures and individual actions is described by Lane & Husemann (2008, p. 54):

> *[...] social structures shape behaviour by discouraging some acts and encouraging others. Human agents interpret such influences in*

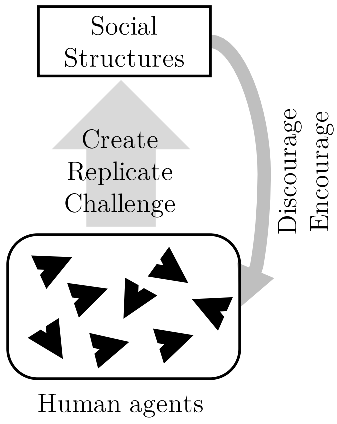
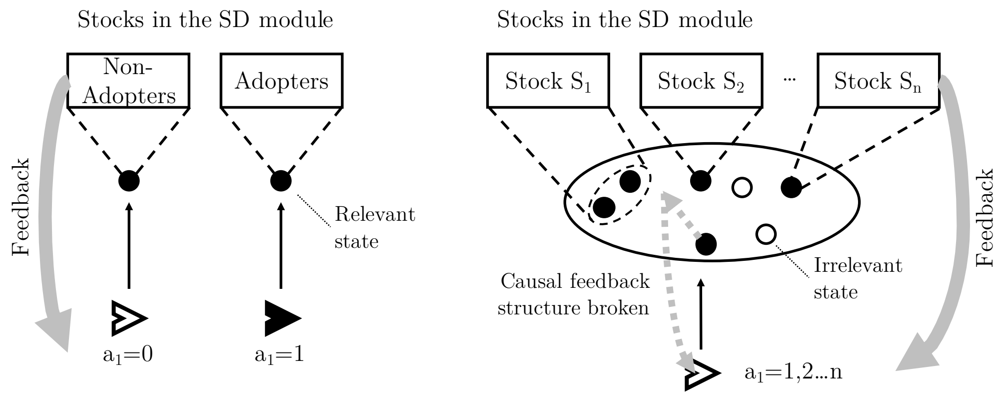


Figure 3.17: Unifying multiplicities between individuals and observables (based on Lane & Husemann, 2008; Swinerd & McNaught, 2012)

> *terms of attitudes, values and roles which become part of the mental models informing their behaviour. Such mental models are expressed as social actions which then create new structural effects, or replicate existing ones, though some acts challenge existing structural effects. From a system dynamics perspective we might view this as social acts accumulating into a stock of patterns of human behaviour.*

The basic dynamics of this example are illustrated in Figure 3.17. It shows how higher-level structure influence human agents (the same social structure can both discourage or encourage different agents with different characteristics, respectively) and vice versa. Though not explicitly shown here, the time plays an important role in this feedback mechanism. The time it takes for social structures to emerge or even change can be significantly different compared to agents adapting to those structures.

This is not an issue if "the collection of agent states at any given time in an AB model is directly linked to the set of state variables within an associated SD model", for both the stocked agents and parameters with emergent behaviour (Swinerd & McNaught, 2012, p. 124). Even for agents with a rich internal structure they are important, as the states of different agents (determined by SD stocks) trigger a certain behaviour of other agents with whom they interact. An example with an agent that can only be in two states, which are matched with two stocks in the SD structure is presented in Figure 3.18a. The relationship between aggregation and disaggregation is fully maintained in this case (Davis & Hillestad, 1993) and 'causality errors' are not an issue as long as the hybrid model architecture processes simulations events in increasing timestamp order (Mustafee, Sahnoun, et al., 2015).



a) 'Stocked agents' in a simple diffusion model

b) 'Stocked agents' with more intelligent agents and larger state space

Figure 3.18: Inconsistencies between multiple resolutions (own depiction)

The existing literature on hybrid SD-ABM simulations focused on change and transformation, rather than emergence (as discussed in Section 3.4.1). If, however, emergent behaviour is included in the ABM, maintaining the relationship between aggregation and disaggregation is not that simple. For example, how does the simulation behave if agents learn from their interactions with other agents, bounded by the social structures, and adapt their behaviour to an extent that they *overthrow* those structures? This is illustrated in Figure 3.18b. The agent can be in more than two states and one of the relevant states is not linked to a stock in the SD structure, in which case the micro-macro-micro feedback structure would break down. When simulating academic entrepreneurship and the dynamics in university ecosystems, the agents are far from being simplistic. History has shown that new modes of collaboration emerge as a result of these interactions and even the nature of individual interactions can change from ad hoc to long-term partnerships.

In order to fully leverage the benefits that such a hybrid approach promises, this issue needs to be addressed. There is no approach yet for designing integrated HS in which the SD module could cope with this, or even what the implications are of these limitations. The next section will further clearly define emergence at the SD-ABM interface and provide a possible solution for maintaining consistency among aggregation and disaggregation even in the case of emergent behaviour.

3.7 Emergence at the SD-ABM Interface

Three approaches have been presented in Section 3.6.4 to model the interface between an SD and an ABM module: agents with rich internal structure, stocked agents, and SD parameters with emergent behaviour. The last two approaches aggregate system behaviour from the ABM and integrate it into the SD module (Swinerd & McNaught, 2012) and is required for the hybrid SD-ABM simulation for academic entrepreneurship (as previously discussed in Section 3.6.5). Formally describing emergent behaviour based on interactions and characteristics at a lower level of aggregation is one of the key challenges in complexity theory and ABM (Chen et al., 2007a). It is also necessary to explain emergent behaviour and distinguish it from errors in the model structure or the code (Gore & Reynolds Jr., 2007). This section elaborates on the issue of emergence and how emergent behaviour within the ABM module can be captured and integrated into an HS. Complex events are proposed as a means to preserve the structure of emergent behaviour at the systemic level and, consequently, fully exploit the potential of the integration of SD and ABM compared to a pure SD model. Examples will be provided and the application of complex events to academic entrepreneurship will be discussed.

3.7.1 Specifying Emergent Properties

Emergence has been introduced as emerging patterns or properties that are not specified at lower levels (see Section 3.4.1). The terms emergence, emergent behaviour and emergent properties have been used interchangeably. Emergent properties can, however, be further divided into three distinct types that are particularly relevant when using ABMs. An emergent *state* is "an identifiable state at a particular level of abstraction that results from a configuration of states at lower levels of abstraction, defined atemporally" (Chen et al., 2007b, p. 971).[25] Examples in the context of academic entrepreneurship include new entrepreneurial activities such as knowledge transfer partnerships, which emerged as a result of an increased demand of more scientist involvement in knowledge exchange and a decrease in funding (Rossi et al., 2017).

An emergent *entity* can be defined as "an identifiable entity at a particular level of abstraction that is able to persist through time (has temporal extension) and which is subject to the rules operating at that level of abstraction, but whose existence is dependent on entities and/or processes at lower levels of abstraction" (Chen et al., 2007b, p. 971).[26] Technology transfer offices have emerged as new

[25]A temporal state persists in time and is linked to time, whereas an atemporal state "does not internally refer to time: e.g., being blue, [and] the description of the state itself does not include a reference to time" (Chen et al., 2007b, p. 971).

[26]This emergent entity is, by definition, always is a particular state (like every other agent/entity). This state of the emergent entity is not linked to the *emergent state* mentioned

entities at the interface of academia, industry, and government (Etzkowitz & Leydesdorff, 2000; Krücken, 2003). Another example of emergent entities are network and broker organisations such as Interface in Scotland, which aims to connect businesses and academia.[27]

Lastly, an emergent *behaviour* is "an identifiable temporally extended process at a particular level of abstraction that results from a set of processes operating at a lower level of abstraction that are related to one another temporally and/or spatially" (Chen et al., 2007b, p. 971). Establishing awards like the "Entrepreneurial University of the Year" in the UK has led universities to increasingly paying more attention to their entrepreneurial reputation and are adopting their behaviour and resource allocations accordingly. These awards are also a new criterion for companies for identifying potential academic collaborators and could lead to reinforcing feedback loops and Matthew effects for successful universities.

Another example is the shift from ad hoc interactions to long-term partnerships and the implications for companies (Section 2.6.3) and universities (Section 2.3.6). Partnerships represent a change in behaviour that is not captured by a new state or even a single state. The actual interaction between a company and a university is the same compared to an ad hoc interaction, the difference is the behaviour over time and the investment of resources into developing trust and understanding. This type of emergent pattern is the key to address the research questions in this thesis. The following section will look at how ABMs can be analysed and how emergent behaviour can be captured.

3.7.2 Capturing Emergent Behaviour in ABMs

The increased use of ABM is mainly driven by its ability to simulate emergent properties (see Section 3.4.1). There are two ways in which the system behaviour in ABMs can be tested for emergent behaviour (Chen et al., 2007b). First, *human observation* can be used to analyse the qualitative changes in a system that is modelled using ABM (see e.g. Reynolds, 1987; Wilensky & Rand, 2015). Figure 3.19 shows an example of the flocking behaviour of birds. The two snapshots show a clear trend from the birds being scattered across the space (left) towards a few larger, more concentrated crowds (right) at a later time in the simulation. However, only observing many instances over the course of the simulation will fully reveal the emergent behaviour and how the crowding happens. Human observation is capable of describing emergent behaviour and preserving the un-

above.

[27]For further information see: https://interface-online.org.uk.

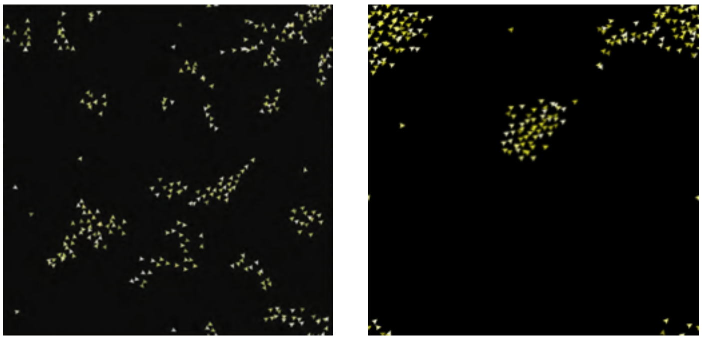


Figure 3.19: Flocking behaviour of birds modelled with ABM (Wilensky & Rand, 2015)[28]

derlying structure, but is also subjective and heavily influenced by the experience and subject matter expertise of the observer and, therefore, limited in its ability as a scientific method (Chen et al., 2007b). There are ways to quantify this kind of observation, but it is still not easily integrated into an HS (see e.g. Wright et al., 2000; Wang et al., 2016).

The second option is *state aggregation*, in which the current states of all agents at any time t are aggregated into one or more macro-variables. These variables represent changes in the macro-structure of the model and can be observed over the course of the simulation (Chen et al., 2007b). Figure 3.20 provides a schematic illustration of this traditional view on ABMs, in which the temporal dynamics of the system are broken down into individual snapshots at each time step and the macro behaviour is calculated based on the current state(s) of the individual agents. This is the common method for linking an ABM and a SD module in an HS when using stocked agents or parameters with emergent properties. Swinerd & McNaught (2014), for example, simulate the aggregate temporal diffusion of innovation in a SD module that uses an ABM module in which nations are represented by individual agents to model the spatial patterns.

Reducing the output of a simulation to a single or a small number of variables can also lead to a loss of information about the structure of the system behaviour, i.e. "which agent interactions have given rise to the behaviour, and how these interactions are related in time and space" (Chen et al., 2007b, p. 969). This can be illustrated with the following example: in an innovation diffusion model, customers are modelled as an agent population A of n individual agents that can choose between different products from m providers. All agents have an initial preference regarding how quickly they adopt and which product they prefer. During the simulation, agents are influenced by other agents (word-of-mouth) and

[28]Screenshots of the Flocking model from the standard NetLogo library, sources: left (Wilensky & Rand, 2015, p. 326) and right (http://ccl.northwestern.edu/netlogo/models/Flocking).

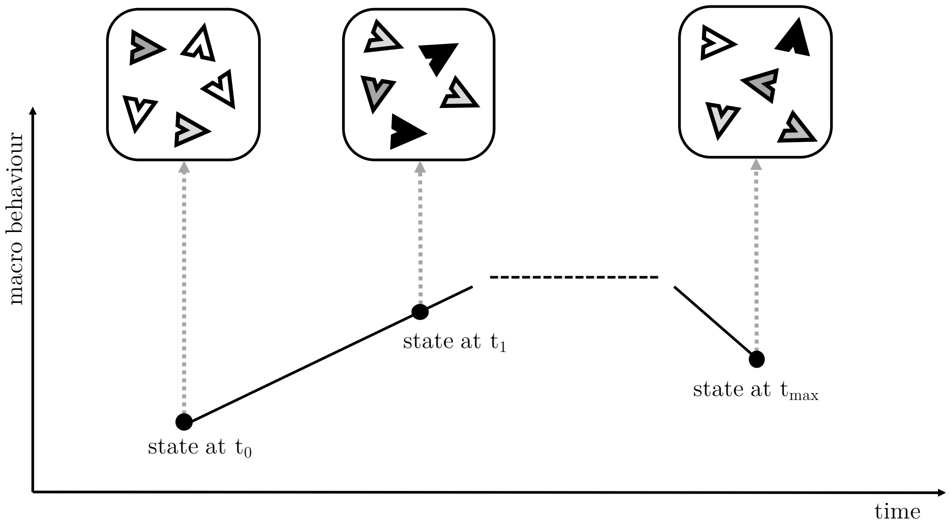


Figure 3.20: Schematic illustration of state aggregation (Chen et al., 2007b)

by marketing activities of the m providers. Using state aggregation, the state of the system can be determined at any time t by aggregating how many agents have adopted each of the products and how many are left as potential adopters. With this approach, information is lost whether agents followed their initial preference or adjusted their preference based on word-of-mouth or marketing efforts. This can also result in inconsistencies when aggregating the behaviour at lower levels, as discussed in Section 3.6.7. So the question is, how can the emergent behaviour at the aggregated level be described without the loss of information about the structure that gave rise to this behaviour?

3.7.3 Complex Events

Emergent behaviour is the result of agent interactions and the resulting adaptations in agents' behaviour as opposed to individual agents' isolated actions. Therefore, understanding emergent behaviour is increasingly important with a growing number of agents and complexity, e.g. in terms of the interconnectivity among the agents or their geographical distribution (Szabo et al., 2014). A single action of a single agent based on its rules is defined as a *simple event* (Chen et al., 2008). Simple events are explicitly specified in the model and can more formally be described as "a change in state (given by a state transition function $trans()$) that occurs in time with a non-negative duration d" (Chen et al., 2007b,

p. 971):[29]

$$SE :: (trans(x_{a_1},...x_{a_q}),\ [t_{start}, t_{end}]) \tag{3.3}$$

$$d :: t_{end} - t_{start},\ d \geq 0 \tag{3.4}$$

The $trans()$ function in equation 3.3 includes at least one but possibly q variables $x_{a_1},...x_{a_q}$ of an agent a of the total agent population A. These variables change at time t_{end} (if $t_{end} - t_{start} = d = 0$, this change is instantaneous). Each simple event, i.e. an agent-specific transition, is an instance of a general simple event type T_{SE}, which is defined by the transition function and the duration d, whereas SE is specified by a particular time of the simulation:

$$T_{SE} :: (trans(x_{a_1},...x_{a_q}),\ d) \tag{3.5}$$

A state transition rule STR is "a function that changes the values of a set of variables when a particular condition C is satisfied" (Chen et al., 2007b, p. 971):

$$STR :: (T_{SE},\ C) \tag{3.6}$$

Conditions C are a basic mechanism that enable dynamic behaviour in ABMs as they link agents to other agents and changes in the environment. For example, an event $f \in T_F$ can conditionally depend on an event $e \in T_E$, if the outcome of T_E is in any case equal to the condition for T_F as specified in the STR.

$$(C_f\ ==\ trans_e),\ \forall e \in E,\ \forall f \in F \tag{3.7}$$

The relationship between state transition rules STR, simple events T_{SE}, and the condition C is also illustrated in Figure 3.21. Three generic agents are presented at two points time t_i and t_{i+1}, with each agent's state being represented by its colour. For two agents (grey and black at time t_i), the respective condition C is met and the agents change their state for t_{i+1} (SE_1 and SE_2, respectively). The required condition C for the third agent (white in t_i) is not met and the agent stays in its current state in t_{i+1}.

Different types of complex events represent different combinations of $STRs$ (from multiple agents or a single agent) and describe the emergent behaviour in terms of how these rules interact. They provide an approach to uncover the

[29] The mathematical formulation in this section follows the definitions by Chen et al. (2007b) and Chen (2009) with only minor adjustments.

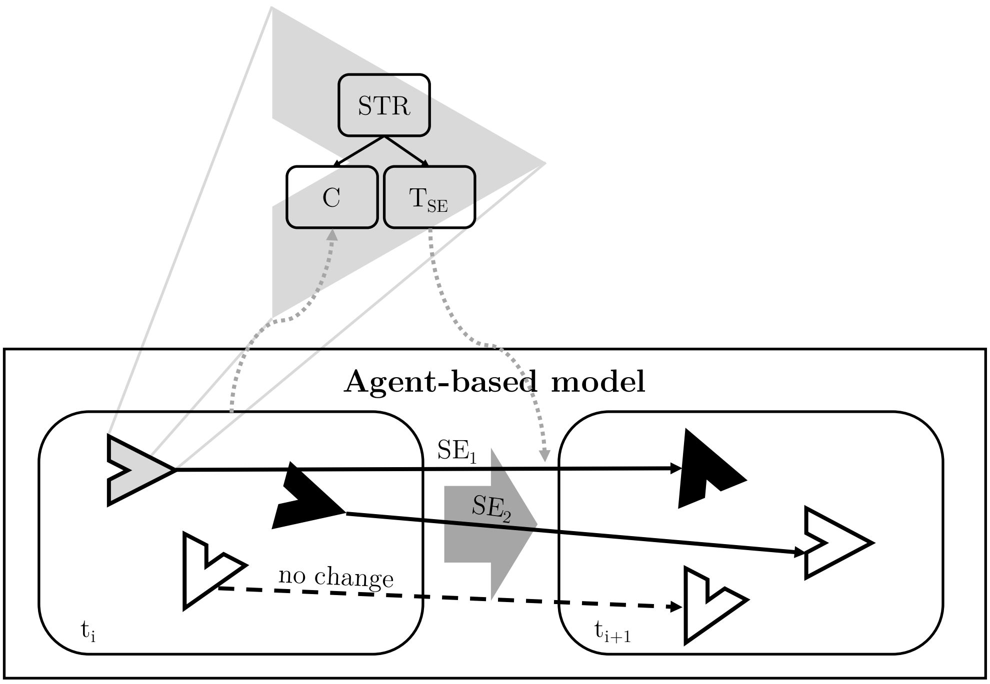


Figure 3.21: Simple events based on STRs (adapted from Chen, 2009)

mechanisms behind emergent behaviour as specified in the agents' rules (Chen et al., 2008). The concept of complex events is based on *reconstructability analysis (RA)* in discrete multi-variate modelling, which "decomposes the macro level into micro level relationships that are specified in terms of relations and distributions involving subsets of variables" (Szabo & Teo, 2012, p. 4). Another approach to test the validity of emergent behaviour is *explanation exploration*, which, combined with causal inference, "reveals the interactions of identified abstractions within the model that cause the emergent behavior" (Gore & Reynolds Jr., 2008, p. 712).

All these approaches have in common that they explain emergent behaviour that is not directly specified at lower levels of aggregation but emerge from the interactions of agents. Applying complex events is a significant advantage compared to simple state aggregation as it preserves the structure of emergent behaviour. In general, complex event types T_{CE} are defined recursively as "events that comprise one or more related constituent events (the constituent events can also be complex events)" (Chen et al., 2007b, p. 971). Essentially, a T_{CE} can be reduced to a combination of simple event types that are linked by a particular relationship $\bowtie$:

$$T_{CE} \;::\; T_{SE1} \;\bowtie\; T_{SE2} \;\bowtie \ldots \;\bowtie\; T_{SEn} \tag{3.8}$$

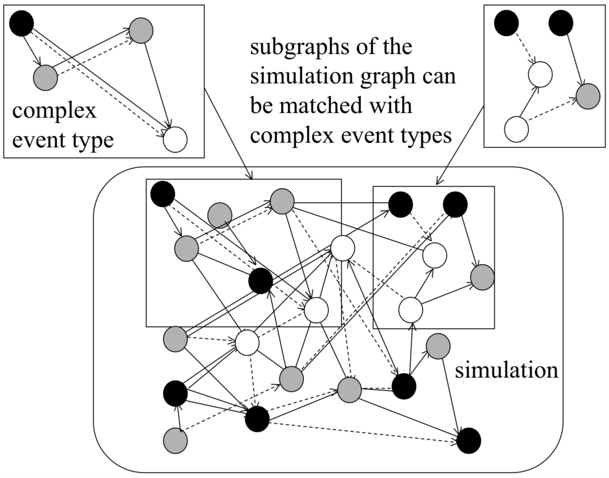


Figure 3.22: Complex events as subgraphs of the simulation (Chen et al., 2007b)

The relationship $\bowtie$ is defined as temporal operator $\otimes$ followed by optional constraints of regarding space [*space*] and other variables of the agents [*var*] (Chen et al., 2007b). This syntactic structure is defined in the following equation:

$$T_{CE} \ = \ T_{SE1} \ \bowtie \ T_{SE2} \ :: \ T_{SE1} \ \otimes [space][var] \ T_{SE2} \tag{3.9}$$

A T_{CE} can also be conceptualised by a hypergraph H_{CE}, which consists of n single events $SE_{CE} = SE_1, ..., SE_n$ represented as nodes, which are related by a hyperedge R_{CE}, i.e. an edge that can connect more than two nodes in the simulation space (Chen, 2009):

$$H_{CE} \ = \ (SE_{CE}, \ R_{CE}) \tag{3.10}$$

This notation is schematically illustrated in Figure 3.22. An ABM can be described as a directed graph (Chen et al., 2007b). Different types of simple events T_{SE} are represented by nodes of different shades and linked by directed arcs. In this example, there are two types of relationships between events, illustrated by solid and dashed arcs. An agent can be part of different subgraphs at the same time, which means that a simple event has e.g. consequences at different levels of aggregation. An instance of a complex event type can be identified if a subgraph of the simulation is identical to a specified complex events graph. Therefore, two complex event types T_{CE1} and T_{CE2} are *computationally equivalent* if they can be described by the same hypergraph (Chen, 2009).

Formalising complex events in this way is a means for specifying and computationally detecting emergent behaviour within the ABM module (Chen et al., 2008). Complex events offer many opportunities for advancing ABM in general and are trajectories for future research in their own right. But complex events can also be very useful for developing HS and lead to additional insights compared to e.g. linking SD and ABM via simple state aggregation. In particular, complex events could be integrated into HS simulation modelling via:

- Aggregation of complex events: instead of aggregating simple events (e.g. an agent purchases a new product), a stocked agents approach could aggregate complex events instead (e.g. an agent with an initial preference for product m_i purchases a new product m_j after being influenced by the marketing efforts of provider j). This requires an algorithm that searches for this particular complex event or while the simulation is running, which is also referred to as a "live analysis" (Szabo & Teo, 2012). Depending on how tightly the complex event is defined (examples that illustrate this feature are presented in the next section), the algorithm can be very flexible and potentially detect a variety of emergent behaviours. At least a few characteristics of the emergent behaviour need to be known in advance as the SD structure is defined and it needs to be clear where and how the complex event aggregation fits into this structure.

- Complex events for reconfigurable dynamic designs: particularly for rare emergent behaviour or when emergent behaviour represents a tipping point, complex events can be used to reconfigure a hybrid simulation (see Section 3.6.4). Similar to the aggregation of complex events, this requires an algorithm that searches for this particular complex event or a set of possible complex events while the simulation is running.

- Post-simulation analysis: if dynamic insights into emergent behaviour are not required, i.e. complex events are not embedded into the simulation model directly, it can still yield additional insights *post-mortem* (see e.g. Szabo & Teo, 2012, 2013). In this case, all agent activities need to be saved and a search algorithm will be used to find pre-defined complex events. Using the example of product diffusion, this post-simulation analysis can also show what led to the adoption of a new product (e.g. word-of-mouth or marketing efforts). The difference is that the model is not able to adapt to these behaviours. Furthermore, post-simulation analysis can be used as an exploratory tool. An ABM can generate a great number of different complex events and it is impossible to define all of them *a priori*. A different algorithm can be used that simply searches for recurring combinations of simple events, which can then be analysed by the modeller as to whether they show emergent behaviour.

The following section will elaborate on the applicability of complex events to academic entrepreneurship in the context of the hybrid SD-ABM framework that was developed in Section 3.6.5.

3.7.4 Entrepreneurial Activities and Complex Events

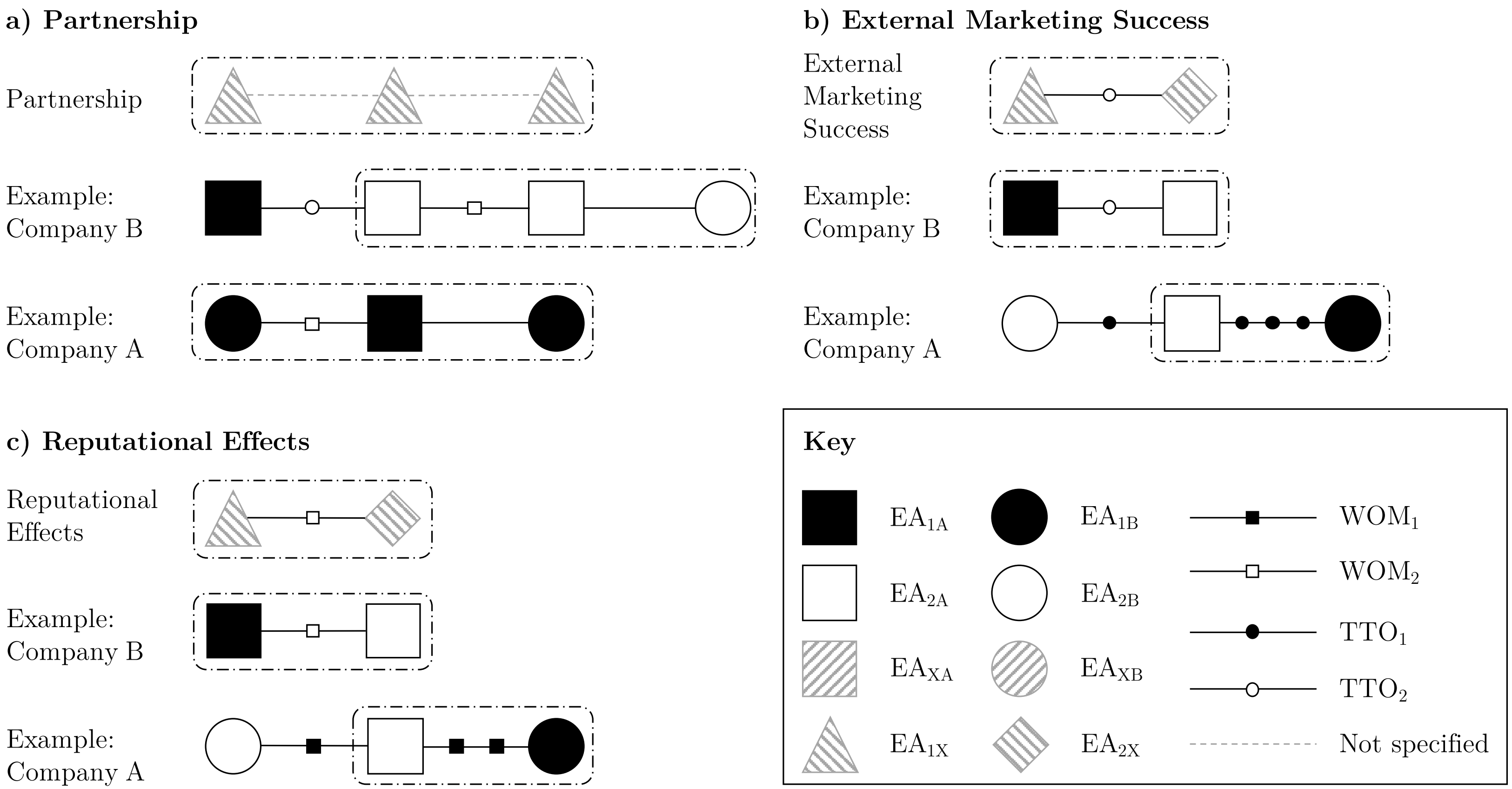
The proposed HS framework is designed to use SD for the internal resource and reputational dynamics of universities and ABM for the university ecosystem. Aggregating the type and number of entrepreneurial activities per university provides a first overview of the system behaviour. However, it does not yield to any insights regarding the relationships between universities and companies within the ecosystem. A crucial component for research question Q3 is whether universities are able to form partnerships, i.e. recurring interactions with the same company (see Section 2.8). This cannot be answered by using simple state aggregation.

A 'partnership' can be defined as a sequence of different interactions, i.e. entrepreneurial activities, between a company and the same university. The essence of a partnership is the interaction between these two agents, not the actions of the individual agent (i.e. the type of entrepreneurial activity). Furthermore, the other interactions such as external marketing activities by a TTO or word-of-mouth effects are not relevant for this complex event. A generalisation of a partnership between a company and a university is schematically depicted in Figure 3.23a.

Complex events can also be used to identify why companies chose to collaborate with a particular university. Companies have an initial preference for which university to work with. This can be based on the university's reputation, personal relationships, or geographical proximity, among others, or a combination of different factors (Laursen et al., 2011). However, these change over time and are affected by 'external marketing' efforts of the university TTO (see Figure 3.23b) or 'reputational effects' based on word-of-mouth interactions among agents (see Figure 3.23c).

Similar to the 'partnership' complex event, the type of entrepreneurial activity is not relevant for these two complex event types. Essentially, these complex events are about a change in the university partner for subsequent entrepreneurial activities of a company. This might, however, require more than interaction with the TTO or multiple interactions with other companies for a company to change its preference. This is illustrated in the examples of company A's three interactions with university 1's TTO (Figure 3.23b) and two interaction with other agents influencing its preference for university 1 (Figure 3.23c).

Crucial to understanding the dynamics of academic entrepreneurship in university ecosystems is an insight into the repeated interactions between different ecosystem actors (company agents and universities) and not simply the individual actions of individual agents. In these examples, the relationships between the simple events, denoted as $\bowtie$, are based on a temporal operator $\otimes$ and other variables such as the previous preference of academic partner $[var]$, but no spatial restriction $[space]$. The three examples presented in Figure 3.23 are based on issues from the literature review in Chapter 2. How complex events are used (e.g. aggregation, post-simulation analysis) and what their final structure looks like will be described as part of the conceptual model description in Chapter 5.



Every entrepreneurial activity (EA_{ij}) is specified by two indices; i indicates the university partner (in this example, university 1 or 2) and j indicates the type of activity (A or B, representing e.g. licensing or consulting). The university index i also denotes which technology transfer office (TTO) reached out to the company and whether word-of-mouth (WOM) from other companies changed a company's preference towards a particular university. An "X" for either i or j is a non-specified placeholder (EA_{1X} means that a company can engage in any possible activity but only with university 1).

Figure 3.23: Entrepreneurial activities as complex events (adopted from Chen et al., 2007b)

3.8 Summary

The aim of this chapter is to select the appropriate simulation method(s) and to provide a framework for developing a conceptual model. Complex systems were defined and SD and ABM presented as powerful methods to generate insights into the behaviour of dynamic system behaviour. Both have been applied to a variety of problems, including a very limited applications in academic entrepreneurship and ecosystems. Neither SD nor ABM alone is sufficiently and efficiently able to address the research questions outlined in Section 2.8. In particular, SD has its limitations with regard to ecosystem structures and the shift from ad hoc interactions to partnerships, whereas ABM is not well suited to model the internal dynamics of universities. As a conclusion, the opportunities to combine both methods in an HS should be explored.

This chapter makes two contributions to this thesis and beyond. A framework is presented for an HS that leverages the advantages of SD and ABM and models universities using SD and the university ecosystem as an ABM. The framework is based on a review of existing frameworks and approaches to combine SD and ABM. Furthermore, methodological and theoretical challenges are discussed and crucial issues are highlighted that need to be addressed when developing a simulation model. This framework, without any further simulation work, forms a basis for how universities are embedded in their ecosystem and for future research.

A key methodological challenge is the feedback across module boundaries and inconsistencies with regard to emergent phenomena from the ABM module. This chapter introduces complex events as a means to better capture emergent behaviour within hybrid simulations involving ABMs. Complex events are a crucial mechanism for the proposed HS framework to address the research questions, but they can also be applied in a wide range of areas and problems and could significantly improve the potential value of HS. They are still an under-studied and under-theorised approach for exploring emergent behaviour in both ABMs and HS involving ABM module(s) and further research is required.

Another unresolved issue is the process of how hybrid SD-ABM simulations can be developed in a scientifically rigorous way, how modellers can decompose the system and identify feedback between levels of aggregation, and develop models that can deal with potential emergent behaviour across different levels of aggregation within the simulation. The following chapter will focus on these issues and describe how the HS framework presented in this chapter is further developed into a conceptual model and eventually a simulation model for quantitative analysis.

Chapter 4

Research Design

4.1 Introduction

The previous chapters have described the problem and the existing gap in the literature with regard to a dynamic understanding of a university's engagement with its ecosystem (Chapter 2) and a hybrid SD-ABM approach that can address this problem (Chapter 3). This chapter will reflect on the overall research design of this study, which involves the "plans and procedures for research that span the decisions from broad assumptions to detailed methods of data collection and analysis" (Creswell, 2009, p. 3). The appropriate research design depends on the nature of the problem, the personal experience and expertise of the researcher, and the audience where the study is supposed to make an impact (Creswell, 2009).

There is little guidance for developing HS and combining SD and ABM in particular (Nasirzadeh et al., 2018; Swinerd & McNaught, 2012). A new 'modelling process' (MP)[30] will be presented in Section 4.2, that is based on a review of existing MPs and co-evolved with this research project. Within an MP, a variety of research methods can be applied and combined in different ways to understand the problem through collecting and analysing both qualitative and quantitative data. The aim of this chapter is to show how the previously described work fits within this process (Section 4.2), the philosophical foundation (Section 4.3), what data is collected and how it is analysed (Section 4.4), the ethics of this study (Section 4.5) and how this leads to the detailed structure of the model (Chapter 5), and eventually the simulation results (Chapter 6).

[30]This terminology reflects the concept of 'modelling as a learning process' (Pidd, 2004) and is very common in the SD literature (e.g. Forrester, 1985; Sterman, 2000, 2001).

4.2 Modelling Process

Modelling is an activity, not a means to an end, and a process of continuous learning that requires methodological rigour and documentation for reproducibility and credibility (Pidd, 2004). MPs are systematic guidelines for the development and analysis of simulation models (Hillier & Lieberman, 1995). Modellers typically refer to the method-specific MP when developing mono-method models, such as Sterman (2000) for SD, Railsback & Grimm (2012) for ABM, and Robinson (2004) for DES.[31] Modellers tend to stick to what they know and the processes that they are used to and also build HS models based on these mono-methods MPs (Brailsford et al., 2013). However, these do not provide adequate support for dealing with the additional decisions and increased complexity of HS. There can be a significant reduction in the quality of the HS model if a modeller does not have proper training and lacks experience and expertise in other methods. An appropriate MP or forming a team of modellers with complementary skills can (partially) compensate for this (Morgan et al., 2017; Tako & Robinson, 2010; Willemain, 1995). In the latter case, an MP specifically for this purpose can improve communication and coordination among team members. This section will review existing MPs for mono-method simulations and first attempts of establishing processes for HS and propose a new MP for this study.

4.2.1 Existing Modelling Processes

The three commonly-used examples of mono-method MPs by Sterman (2000), Robinson (2004), and Railsback & Grimm (2012) are not only representative for approaches in their respective method, but also do not differ significantly from each other or from a general MP in MS/OR (Hillier & Lieberman, 1995)[32] as shown in Figure 4.1. While the overall frameworks are similar, the modelling practices and processes for SD and DES are more specific and rigorous compared to ABM (Heath & Hill, 2010). This is mainly a result of the young age of the field of ABM and different forms and topologies that ABMs can take (see Section 3.9). As a conclusion from this comparison, these five or six main steps have

[31] Sterman (2000) and Robinson (2004) are representative for other MPs for SD and DES, respectively (Tako & Robinson, 2009). Sterman's work, for example, is similar the MP by Randers (1980), which is also widely used a frame of reference. Similarly, the MP for ABM by Railsback & Grimm (2012) is representative for other approaches by e.g. North & Macal (2007) and Salamon (2011).

[32] The 10th edition of this book, together with previous editions, are commonly used as a reference for modelling in the wider field of MS/OR. Other MPs that are more specific to general M&S are similar too (see e.g. Pidd, 2004).

Table 4.1: Comparison of mono-method MPs

MS/OR **Hillier & Lieberman (1995)**	SD **Sterman (2000)**	ABM **Railsback & Grimm (2012)**	DES **Robinson (2004)**
Problem definition	Problem Articulation Reference Mode Time Horizon	Formulate the question	Real world (problem)
Conceptual modelling	Dynamic Hypothesis Endogenous explanation Map system boundaries	Assemble hypothesis (Patterns) Choose model structure	Conceptual modelling Problem situation Modelling objectives Conceptual design Data
Model coding	Formulating a simulation model	Implement the model	Computer model Coding
Model validity	Testing		(Validation and verification included as links between the steps)
Model results and experimentation	Policy formulation and evaluation	Analyse the model (Patterns)	Experimentation
Implementation and learning		Communicate the model	Implementation

been proven to successfully support the modeller through the whole process and should be included in one way or another in an MP designed for hybrid SD-ABM simulations.

MPs that are designed to support HS have been developed for the combination of SD-DES (Chahal et al., 2013; Morgan et al., 2016) and SD-ABM (Martin & Schlüter, 2015; Nasirzadeh et al., 2018). Section 3.7 has highlighted the unique features of a hybrid SD-ABM simulation with regard to the conceptualisation of feedback and capturing emergent behaviour. This requires a thorough integration of the HS features into the overall MP, hereby also helping the modeller realise that in some cases an HS might not necessarily be the preferred option and show how to proceed with a mono-method approach. While the latter issue is included in the MPs by Chahal et al. (2013) and Morgan et al. (2016), a combination of SD and DES does not involve emergent behaviour as required in this study. Therefore, both approaches cannot be directly applied to model academic entrepreneurship in university ecosystems.

Martin & Schlüter (2015) and Nasirzadeh et al. (2018) incorporate decision support with regard to whether a hybrid simulation is required as well as the HS design. However, both do not provide direct guidance on developing the SD and ABM structures within the respective modules of the HS and only refer to the mono-method MPs for developing the detailed structures. Neither of the four approaches, therefore, properly guides the modeller through the whole process of understanding the basic mechanisms of the system, developing sound causal structures, conceptualising feedback across module boundaries and emergent phenomena at the module interface. This does not invalidate their legitimacy or harm their credibility, as they were designed with a particular purpose in mind and "there is not a one clear answer as there are many possibilities to create the hybrid models" (Lättilä et al., 2010, p. 7973). The research questions in this study simply require a different approach, which will also be applicable to other problems with potential emergent behaviour at the SD-ABM interface.

4.2.2 Proposed Modelling Process

Building on the previous discussions and the insights from existing MPs, a novel approach for hybrid SD-ABM simulations will be presented in this section. Essentially, the aim of this process is to address the following issues (adapted from Chahal et al., 2013):

- Is a mono-method or hybrid simulation required and why?
- How do SD and ABM interact and what is exchanged?
- How is feedback conceptualised across module boundaries?
- What emergent properties are anticipated and how does the model cope with these?

The MP that is used in this study is shown in Figure 4.1. The framework is comprehensive, which offers modellers the opportunity to leave certain aspects out as long as it can be justified why (Schmolke et al., 2010). Hence, it should provide value and guidance for modellers across the whole spectrum from mono-method beginners to experts (Chahal et al., 2013). A discussion and eventually the selection of an HS or mono-method approach is incorporated in the early

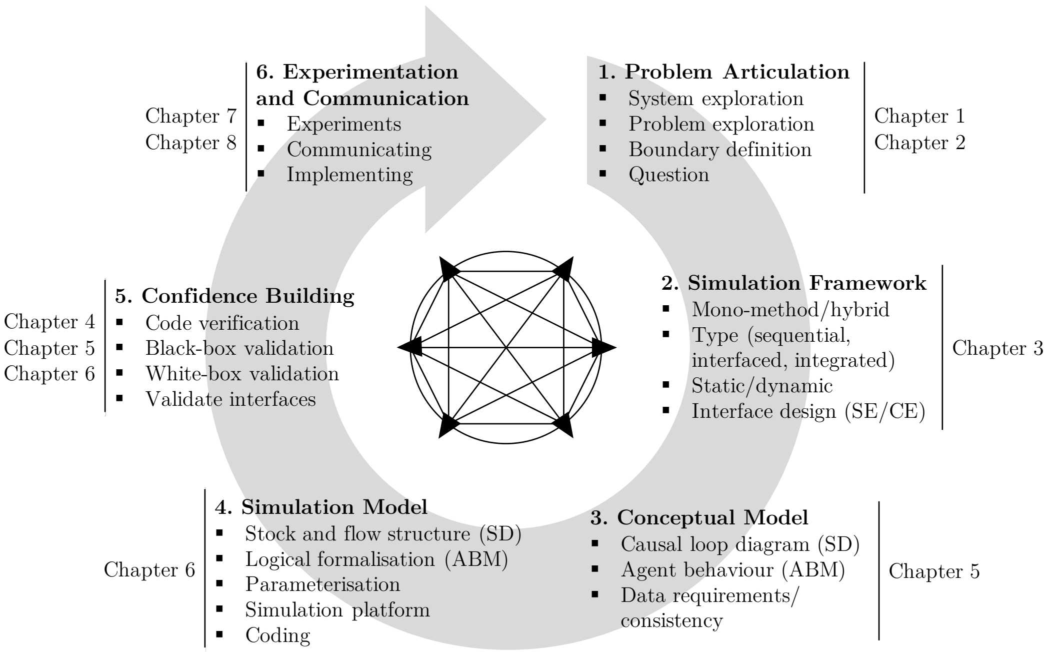


Figure 4.1: Proposed MP for hybrid SD-ABM simulations (step 1 and 3-6 are adopted from the mono-methods MPs by Sterman, 2000, Robinson, 2004, Railsback & Grimm, 2012, and Hillier & Lieberman, 1995, whereas step 2 is new based on work by Chahal et al., 2013, Swinerd & McNaught, 2012, Martin & Schlüter, 2015, and Lorenz & Jost, 2006)

stages of the process (Lorenz & Jost, 2006). Deciding to develop an HS is, however, not the end but merely the start as there are many more decisions to make that influence the model and subsequent steps of the MP (Chahal et al., 2013; Swinerd & McNaught, 2012). A separate step has been included in addition to the general ones that are adopted from the mono-method MPs to underline the implications of selecting an HS and to provide a focal point within the MP for these decisions and how they affect other steps and vice versa. A key feature of this MP is that it considers the (hybrid) model framework before developing the detailed causal structure (SD) and agent rules (ABM) for the individual modules.

4.2.3 Steps of the Modelling Process

The six steps are described in more detail in the following. While they are presented in a linear fashion and as discrete entities, it is worth highlighting the iterative nature of the MP. Iterations do not always include the full circle through all six steps but between steps (as illustrated by the arrows in the centre) or even within individual steps as well (Homer, 1996).

4.2.3.1 Step 1: Problem Articulation

The field of MS/OR is concerned with addressing problems, so the "essential first step of any OR investigation is to ensure that the 'right problem' is studied" (Curtis et al., 2006, p. 1300). This is not a trivial task and "deciding which are the problems to be tackled and trying to understand their linkages is as challenging a task as the detailed formulation and implementation of simulation models" (Pidd, 2004, pp. 32-33), particularly in *everything effects everything else*-cases such as healthcare or academic entrepreneurship in university ecosystems (Brailsford et al., 2013, p. 260). Problem articulation includes the exploration of both the system (university ecosystems) and the problem (how universities interact with other actors) (Morgan et al., 2016, 2017) and is not purely a predecessor to the modelling part but an essential component of the MP. This step does, therefore, not differ from the MS/OR literature and existing MPs.

The aim of this step is to draw the problem boundaries and to identify clear research question(s). It is important to stress that at this point, the modeller should focus on the system and the problem, not a potential simulation method or combination of more than one. Different methods recommend different tools and the modeller should use a representation that is most natural to the problem. Key variables and the time horizon of the problem can be specified at the system or component level or both, and neither is superior *per se*. Particularly in an academic setting, this stage would also include the formulation of the philosophical stance of the modeller. Model development as well as analysing and reflecting on simulation results is only possible within the boundaries of a chosen research paradigm (Mingers & Brocklesby, 1997). Lastly, it is important to identify and involve all relevant stakeholders if necessary from this point forward throughout the whole modelling process (Pidd, 2004; Robinson, 2004; Schmolke et al., 2010; Sterman, 2000). Problem articulation is described in this thesis in Chapter 1 and Chapter 2.

4.2.3.2 Step 2: Simulation Framework

Following the problem articulation, the overall *simulation framework* is developed. The term 'framework' is introduced here as this step goes beyond the selection of the 'hybrid design' (Lorenz & Jost, 2006; Swinerd & McNaught, 2012). This process is similar to the MP by Martin & Schlüter (2015), who prescribe a conceptual specification of the modules and their links prior to specifying the detailed structure within the individual modules. Other approaches develop the structure of individual modules first and subsequently the overall simulation

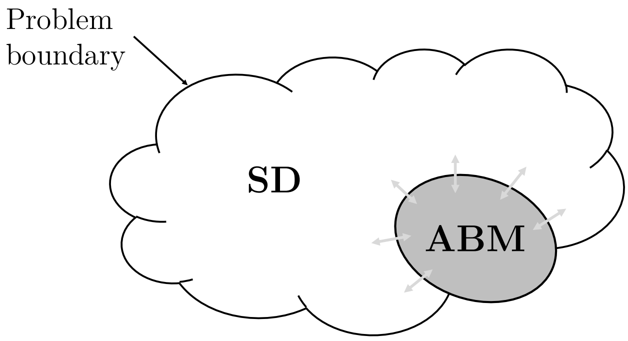


Figure 4.2: Matching the problem space to simulation methods

framework, including the interfaces between the modules (see e.g. Chahal et al., 2013). The chosen structure provides a better fit for this study as specifying the overall structure of the simulation significantly helped with subsequently developing the structures of the different modules as the interfaces between them are actually a key part of the model output.

The first question within this step is whether a mono-method approach is sufficient or an HS is required to address the research question(s). If the need for an HS has been clearly identified, a set of additional decisions has to be made in this step, otherwise the modeller can proceed to step three (Lorenz & Jost, 2006; Swinerd & McNaught, 2012). Whether or not an HS is required should be the result of the problem articulation and whether the relevant aspects of the system are characterised by a combination of aggregated behaviour and interactions of individual agents. SD provides a representation that is more natural to certain problems and systems compared to ABM. Whether either method or a combination of both is required should be a logical consequence of the work up to this point. Key indicators include whether the dynamics are driven by heterogeneous agent interactions, spatiality, or certain network structures (ABM) as opposed to the feedback structure of key variables at the system level (SD) or a combination of either of these. Similarly, it can be a first indicator that an HS is required if the problem articulation led to a decomposition of the system into multiple levels of aggregation (Homer, 1999; Schieritz & Milling, 2009; Swinerd & McNaught, 2012).

In this study, the applicability of SD (Section 3.3.5) and ABM (Section 3.4.4) as well as their limitations (Sections 3.3.6 and 3.4.5, respectively) are reviewed individually. The results are discussed in more detail in Section 3.5 and the conclusion is reached that an HS is required. This is schematically illustrated in Figure 4.2.

Reflections on the Need for HS 3.6.2

The starting point for developing an HS is the type of hybrid design based on how the different modules are linked within the model framework. This thesis has identified three potential configurations, namely sequential, interfaced or integrated HS (Swinerd & McNaught, 2012). Following from this, the interface between the two or more modules need to be specified. The interface design defines what is exchanged between the modules and how (Chahal et al., 2013). Options include stocked agents, parameters with emergent behaviour, or agents with a rich internal structure, as well as dynamic designs that e.g. turn an SD model into an HS by activating a parameter with emergent behaviour if a predefined criterion is fulfilled (Swinerd & McNaught, 2012; Wallentin & Neuwirth, 2017).

Lastly, and unique to combinations of ABM and SD, is the question of how feedback is conceptualised across module boundaries and how the model copes with potential emergent properties. This issue is under-developed and under-theorised. A first attempt was made in this thesis to use complex events (CE) as opposed to simple events (SE) to capture emergent behaviour from the ABM module. The integrated design and the use of complex events for this thesis were developed and presented in Chapter 3.

4.2.3.3 Step 3: Conceptual Model

The aim of this step is to develop the causal structure of the different modules and how they are linked in more detail. This includes a theoretical explanation or working theory of the cause of the problem (called dynamic hypothesis in SD) and the causal structure of the relevant parts of the system, hereby combining both the problem and system perspective (Martin & Schlüter, 2015; Pidd, 2004; Sterman, 2000). Focusing on the endogenous explanation is crucial for SD, ABM, and a combination of both. As Sterman (2000, p. 95) defines, "an endogenous theory generates the dynamics of a system through the interaction of the variables and agents represented in the model". Although deeply rooted in the SD literature ("system structure drives the behaviour"), an endogenous explanation is also important for most ABMs. Agent interactions do not happen in isolation, but are bound by an environment and the possible states of an agent. Self-organisation, emergence, and (top-down) feedback form an endogenous system that spans different levels of aggregation (see Section 3.4.1).

This can be further illustrated through the use of agent feedback diagrams, which can serve as "bridges between the typical logic-based depictions of agent models and feedback-oriented representations such as causal-loop or stock-and-flow diagrams characteristically used in the system dynamics approach" (Martinez-Moyano & Macal, 2013, p. 1647). Agent feedback diagrams can be a valuable tool both for designing ABMs as well as HS based on e.g. stocked agents. A more widely used tool to map the individual behaviour in ABM modules is a traditional flowchart. The typical tool for SD modules is a causal-loop diagram. However, the most appropriate tool depends on both the problem as well as the preference of the modeller. For example, one could also directly develop a stock-and-flow diagram for the SD module.

A fundamental principle of good modelling practice is that the model drives the data, not the other way around (Pidd, 2009). The model framework and the conceptual structure will guide further data collection. SD and ABM have different data requirements, most notably the level of granularity that is required. In addition, it is important that the data is consistent when exchanged between the modules and e.g. aggregated from an ABM module to an SD module. The conceptual model of this study is described in Chapter 5.

4.2.3.4 Step 4: Simulation Development

The conceptual model will now be transformed into an executable computational model. This includes the development of a stock and flow structure for the SD module(s) and the mathematical formalisation of the agent rules and characteristics for the ABM module(s). Furthermore, new algorithms might be required for a dynamic detection of emergent behaviour at the module interface between SD and ABM (as discussed in Section 3.7). Good modelling practice dictates to start small and add, i.e. simulate a small part of the model and if it is running, add further components to it (Pidd, 2004, 2009). Through the process of formalisation, this step often includes valuable insights and helps to "recognize vague concepts and resolve contradictions that went unnoticed or undiscussed during the conceptual phase" (Sterman, 2000, p. 103).

The simulation needs to be parametrised with empirical or experimental data. It might be the case that particular data is not available at all or not at the required level of aggregation/granularity. In this case, a sequential hybrid design could be used to generate the data with one simulation method (not limited to SD and ABM) that feeds into one of the modules of the simulation model as it was developed thus far (Swinerd & McNaught, 2012). This is another example of the iterative nature of the MP as the modeller has to go back to step two and refine the characteristics of the hybrid approach.

A software platform needs to be selected to eventually run the simulation.

Modellers usually have a preferred platform for mono-method simulations that they are familiar with. In case an HS is required, there are several options for the realisation of the simulation. ABMs always require a certain amount of coding, which modellers coming from an SD background should keep in mind. However, there are modern software packages that reduce the amount to a bare minimum and provide an easy step into the world of ABM. Simulation packages like AnyLogic are particularly designed to run hybrid simulations (Borshchev & Filippov, 2004). Some of the widely used mono-method packages are also capable of running hybrid SD-ABM simulations such as NetLogo (Swinerd & McNaught, 2014) or can be linked, like the combination of Vensim and RePast to run HS (Größler et al., 2003). A third option is to code the model from scratch. Particularly object-oriented programming languages such as Java or C++ have proven to be viable approaches (Lee & Tepfenhart, 2002). The simulation model, including its structure, parametrisation, and simulation platform and coding are presented in Chapter 6.

4.2.3.5 Step 5: Confidence Building

Verification and validation (V&V) are crucial parts of the MPs for all methods. The definitions for V&V vary, as do the approaches and strategies that are applied in different modelling and simulation techniques (Kleijnen, 1995b). In general, verification can be defined as "determining whether the conceptual simulation model (model assumptions) has been correctly translated into a computer 'program', i.e., debugging the simulation computer program" (Law & Kelton, 2000, p. 264). Validation covers all activities in the "process of determining whether a simulation model (as opposed to the computer program) is an accurate representation of the system, for the particular objectives of the study" (Law & Kelton, 2000, p. 265). Validation is a binary concept and since a model is a simplification of reality, it is, by definition, always wrong. Yet it can be very useful in a particular situation and for a given purpose (Forrester, 1961; Pidd, 2004; Rand & Rust, 2011; Sterman, 2002).

In the case of an HS, the validation of module interfaces is another crucial activity. Martin & Schlüter (2015) propose to verify and validate the individual SD and ABM modules individually first and then in combination with the respective other module. This includes a sensitivity analysis for those variables or parameters that are influenced by other module(s). This can significantly improve the "understanding of one-directional influences before the feedback between submodels is fully integrated [and] can be very helpful to interpret results from the fully implemented feedback" (Martin & Schlüter, 2015, p. 5).

This MP views V&V as part of confidence building, i.e. "the process by which we establish sufficient confidence in a model to be prepared to use it for some particular purpose" (Coyle & Exelby, 2000, p. 28, with reference to Coyle, 1977). Confidence building is a good example to underline the iterative nature of the MP. Confidence building should be part of each of the other five steps and includes the confidence of both the modeller and the stakeholders. There is a huge body of literature covering a variety of methods and tools to build confidence in mono-method simulation models (see e.g. Barlas, 1996; Coyle & Exelby, 2000; Kleijnen, 1995b; Liu, 2011; Rand & Rust, 2011; Roy & Mohapatra, 2003; Sargent, 2013). However, there is little guidance and not an established set of tools for building confidence in HS. This is reflected in the small number of papers that report any form of confidence-building practices (Brailsford et al., 2019).In the absence of an established HS-specific approach, this thesis draws upon methods and tools from SD and ABM that are relevant and appropriate for the specific design of this HS. A summary of all efforts to build confidence in the model is provided in Chapter 6.

4.2.3.6 Step 6: Policy experimentation and communication

In this last step, the final simulations will be run. In MS/OR, M&S studies are conducted with a particular purpose in mind and are usually a means rather than the final output of a project/intervention (Pidd, 2004). Simulations can lead to two types of insights, intangible assets in the form of an improved understanding through new knowledge and insights from the modelling process and tangible assets from the model output (Pidd, 2009). For the latter, different what-if scenarios can be specified and form the basis for experiment with the simulation model. Results from stochastic models (such as most ABMs) are harder to interpret than those from deterministic models (most SD simulations), because they essentially represent sampling experiments that need to be well-controlled for credibility and replicability (Pidd, 2004). The experimental design and the corresponding simulation results are presented in Chapter 6, discussed and put into context in Chapter 7, and key findings and limitations are presented in Chapter 8 to conclude this thesis.

4.3 Philosophical Stance

The philosophical underpinnings are not explicitly stated in many scientific publications and usually not acknowledged at all in any practitioner work. However, they do affect how the research is carried out and how results have to be analysed and understood (Creswell, 2009; Pidd, 2009). This section provides a general frame of reference and terminology of basic concepts for this thesis. In particular, critical realism is selected for this study and a functionalist and radical structuralist approach to research and their implications are discussed (Burrell & Morgan, 1979).

4.3.1 Foundations and Terminology

A research paradigm, also referred to as a researcher's worldview (Creswell, 2009; Guba, 1990), is defined as the "underlying basis that is used to construct a scientific investigation" (Krauss, 2005, p. 759) and forms a "basic belief system or world view that guides the investigation" (Guba & Lincoln, 1994, p. 105). Beyond an individual investigation, paradigms are also "universally recognized scientific achievements that for a time provide model problems and solutions to a community of practitioners" (Kuhn, 2012, p. xlii). Emphasising the basic understanding and agreement, paradigms also provide a "commonality of perspective which binds the work of a group of theorists together" (Burrell & Morgan, 1979, p. 23). Hence, paradigms "define the nature of possible research and intervention" (Mingers & Brocklesby, 1997, p. 490).

There is, however, some confusion in the literature as to what constitutes a paradigm (Crotty, 1998). The common approach is to describe paradigms in the form of different layers which form a hierarchy. Mingers & Brocklesby (1997) use the three layers ontology, epistemology, and praxiology to conceptualise paradigms. The latter can be broken down into effectiveness, ethics, and morals (Habermas, 1993) and it is argued that it is of particular importance to MS/OR due to the field's focus on intervention and action.

A similar framework is provided by (Crotty, 1998). In contrast to Mingers & Brocklesby (1997), ontology and epistemology are not separate layers because "writers in the research literature have trouble keeping [them] apart conceptually" (Crotty, 1998, p. 10). Hence, the combination of these two forms the bottom layer. Building on this foundation, Crotty (1998) refers to theoretical perspective, methodology, and method as further layers (see Figure 4.3). Although the notions of praxiology (Mingers & Brocklesby, 1997) and theoretical perspective appear to

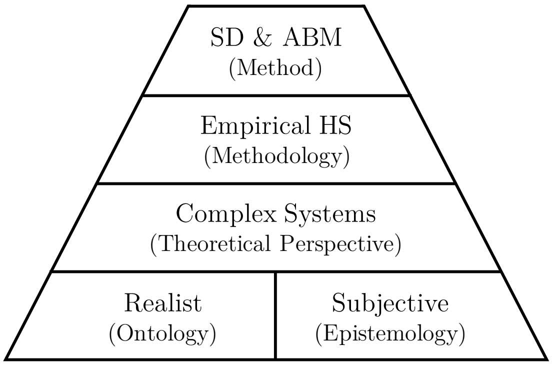


Figure 4.3: Layers of a paradigm (adapted from Crotty, 1998)

deal with different aspects, there is in fact a lot of overlap. In order to establish a consistent frame of reference, the four-layered paradigm structure by Crotty (1998) will be used throughout this thesis. The complex systems perspective that has been established in Section 3.2 represents the theoretical perspective of this study.

Ontology is concerned with the question regarding the nature of reality and truth, the question of 'what is' (Crotty, 1998). There are two ontological strands, nominalism and realism. Nominalism assumes that society and the social world are relative and that it is only real because humans construct it with their consciousness. Realism, on the other hand, assumes that there is an external real world, which exists independently from the observer's perception. This real world consists of hard structures and a social world exists in the same way as the physical world.

Epistemology deals with how knowledge can be generated and how the truth can be found, i.e. "what it means to know" (Crotty, 1998, p. 10). There are three main types, namely objectivism, constructivism and subjectivism (though there are variations of each). Realism (ontology) usually implies an objectivist epistemology, which assumes that objects have meaning regardless of any conciousness (Crotty, 1998). While highlighting this complementarity, Crotty (1998, p. 11) also shows that a realist ontology and a constructionalist epistemology are also possible, which underlines the co-emergence of ontological and epistemological issues.

4.3.2 Critical Realism and Simulation

This study takes a critical realist perspective. Critical realism (CR) is based on a realist ontology (Fleetwood, 2005). In short, this means that there is a world that exists independent of the investigator with an objective truth and it is possible for the investigator to see at least parts of this objective truth. This fits with the beliefs of the author that variables and measurement scales can be developed, but they contain both subjective and objective information. In contrast to the positivist paradigm, critical realism does not assume that knowledge is value-free. Values and cognition help constructing and understanding the objective reality and a critical realist is aware of *value-ladenness* of different research methodologies, methods, assumptions, and so on (Pruyt, 2006).

While there are different strands like critical pluralism (Pruyt, 2006) or Cambellian realism, i.e. "model-centred realism — accountable to the legacy of positivism — and evolutionary realism — accountable to the dynamics of science after relativism fell" Henrickson & McKelvey (2002, p. 7289), they share an objective (realist) ontology and a subjective epistemology. CR is therefore a "middle way between empiricism, which defines science very narrowly in terms of empirically observable and measurable events, and the many forms of conventionalism or interpretivism which highlight the limitations on our knowledge of the world and tend thereby to diminish the reality of the world itself" (Mingers, 2006, p. 203).

It is, however, more than simply a mix of these two extreme positions on a spectrum. CR distinguishes between the *real*, *actual*, and *empirical* world (Bhaskar, 2008). The real world contains durable structures and mechanisms, which generate the events (and non-events) in the actual world, some of which are observed and experienced by people in the empirical world (Mingers, 2006). With this structure, CR differs from both empiricism and interpretivism, but it does explain why "critical realists frame explanations for empirical phenomena in terms of their underlying mechanisms" (Miller, 2015, p. 179). A positivist perspective would change the aim of this study from exploring the role of universities in ecosystems to testing hypotheses about their behaviour. On the other hand, an interpretivist approach would limit the generalisability of not only the simulation results but also the ecosystem conceptualisation and even the new MP.

A general CR perspective carries implications for simulation modelling, which are not limited to ABM or SD and include implications for "specifying models, clarifying ontology, evaluating model outcomes, validating models, triangulating among methods, and identifying the limits of agent-based modeling" (Miller, 2015, p. 182). In SD, a CR approach starts with mental models as opposed to the real world in a positivist approach (Pruyt, 2006). The aim of the model is to create learning, not just from the model output but throughout the whole modelling process. This generates an increased understanding of which structure drives a particular behaviour, which forms the basis for interventions. In line with this, correlations (as in many positivist approaches) do not provide a sufficient explanation and, hence, causal relationships are explicitly modelled and are *the key* to this increased understanding (Pruyt, 2006). A direct correspondence between the model outputs and the real world, as it is assumed by positivists, is not adopted by critical realists. The model output is evaluated qualitatively (at least at first), i.e. critical realists act based on learning from the model and its output, which involves acknowledging the context and limitations, not just the raw output. As a consequence, models have to be developed by working with stakeholders and are context and time dependent (Fleetwood, 2005; Pruyt, 2006). Therefore, the appropriateness of a model depends on whether it leads to "real insight and understanding" (Pruyt, 2006, p. 14).

CR is also well-suited for the adoption and development of hybrid M&S studies and HS in MS/OR (Mingers, 2006). It accepts a variety of entities from physical objects to social structures, beliefs, and experiences, to name a few. While not all of them are experienced by everyone, they are still *real* as they form causal relationships with other entities. To address this variety, different research methods are accepted under a critical realist paradigm, which can be used in combination throughout a hybrid M&S study (Mingers, 2006).

4.3.3 Synthesising Functionalism and Structural Realism

There are different perspectives on how social reality is constructed (van den Berghe, 1963). These sociological theories can be understood and categorised in four quadrants among two axes as illustrated in Figure 4.4 (Burrell & Morgan, 1979). The x-axis describes the subjective-objective debate and the regulation-radical change is mapped on the y-axis. Each quadrant corresponds to a particular paradigm in sociology, namely the radical humanist, interpretivist, radical structuralist and functionalist paradigms. In line with the CR paradigm and its objective ontology, the functionalist and radical structuralist paradigms assume that there is a science of society and objective findings can be reached by rational investigators and are therefore suitable for this study. Though Figure 4.4 indicates four clearly distinct boxes, this is a very simplified view of reality where the boundaries are less strict and more permeable.

The functionalist paradigm has been the dominant paradigm for organisational and innovation studies as well as sociology in general (Drazin, 1990; van den Berghe, 1963). Functionalism takes a regulation-focused look at society and provides a way of theory building that recognises society as a complex system, in which its components (e.g. institutions, norms, traditions) are interrelated and

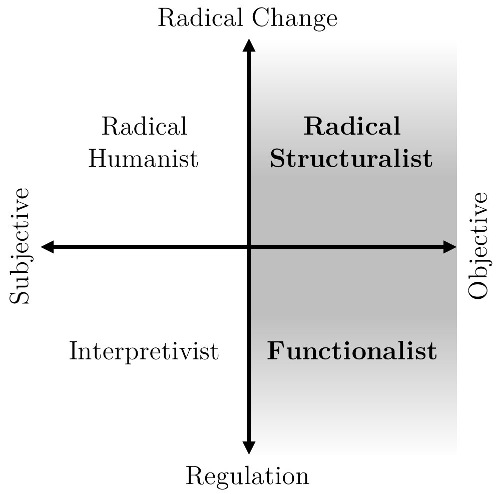


Figure 4.4: Four paradigms for social science research (Burrell & Morgan, 1979)

evolve together (Macionis & Gerber, 2011). Stability and solidarity are a result of these co-evolutionary processes. Change is, therefore, an ordered process and the system tries to reach a state of equilibrium, but may never actually reach it. This is referred to as "moving equilibrium" (Parsons, 1961) or "dynamic equilibrium" (van den Berghe, 1963). Functionalism is often criticised for being unable to account for radical change in society, structural contradictions, and conflict as well as for ignoring inequalities (e.g. race, gender, class) that cause tension and conflict (hence it is also called "consensus theory"). In particular, functionalism and a dynamic equilibrium approach are unable to incorporate the irreducible facts that (van den Berghe, 1963, pp. 697-698):

1. reaction to extra-systemic change is not always adjustive;
2. social systems can, for long periods, go through a vicious circle of ever deepening malintegration;
3. change can be revolutionary, i.e. both sudden and profound; and
4. the social structure itself generates change through internal conflicts and contradictions.

The radical structuralist paradigm is also based on a realist ontology but otherwise provides an antipode to the functionalist paradigm (Burrell & Morgan, 1979). The key ideas go back to the work by Karl Marx and are based on a non-stable society in which radical changes are possible (van den Berghe, 1963). These radical changes are endogenous to the system and based on concepts of e.g. conflict, emancipation, and domination. Opposing factors such as "values, ideologies, roles, institutions or groups" and the resulting tensions are causing change in society (van den Berghe, 1963, p. 699).

Stability and radical change are not mutually exclusive. However, showing that the two paradigms are complementary and can be applied for different aspects of society is not sufficient. There is "a unique opportunity to extend current research, and clear up contradictory empirical findings by building theories of [e.g.] innovation and professionalism that integrate both viewpoints into a logical and useful synthesis" (Drazin, 1990, pp. 259-260). The key to showing that both paradigms are reconcilable and that the boundary between them is permeable is to go beyond the metaphorical application of the complex systems concept. Complex systems are characterised by both co-evolution of interrelated parts and disruptive change, often initiated by minor perturbations or tensions in the system (Mitchell, 2011). In fact, applying a complexity perspective can provide a means to "arrive at a theory of society that achieves an adequate balance between stability and the various sources of endogenous and exogenous change, between consensus and conflict, and between equilibrium and disequilibrium" (van den Berghe, 1963, p. 695).

4.3.4 Implications

The CR paradigm as well as a combination of functionalism and radical structuralism have a number of implications for this study. Models and simulations that are based on different paradigmatic foundations have different objectives and serve different purposes (Pruyt, 2006). Hence, they cannot be used interchangeably, even if the same problem is modelled. Models that are developed under a CR paradigm are likely to be rejected by (post)positivists, such as classical economists, because the model is flawed from their perspective (Miller, 2015). Consequently, a critical realist does not see the value in the pure focus on quantitative simulations that are validated and evaluated quantitatively under the assumption that they correlate directly to the real world (Pruyt, 2006). Quantitative simulations that are performed under this paradigm have to be evaluated and interpreted qualitatively, acknowledging that they are shaped by individuals' perceptions and values. Not only does this include a subjective perception of the world, but people's experiences are limited to the empirical world. In contrast to positivist research, critical realism does not depend on deductive research and falsification of hypotheses. This allows for the inclusion of inductive and abductive approaches, i.e. the models can focus on the underlying mechanisms and explore what causes a particular phenomenon.

A CR perspective also has two major implications for studying ecosystems. First, CR enables the study of mechanisms that drive the evolution of ecosystems. Instead of working under the assumption that all ecosystem characteristics must perfectly align for progress to happen, CR shifts "attention away from the framework itself and towards identifying the specific causal mechanisms that drive particular transitions [and] the priority should be to demonstrate the necessity or contingency of specific mechanisms and events" (Sorrell, 2018, p. 1280). Second, it provides the foundation to combine both the functionalist and radical structuralist paradigm within an ecosystem framework, i.e. within a complex system.

In general, complexity economics (as the overarching theory for ecosystems) focus on how structures develop, with non-equilibrium being the predominant state of the economy while it is striving to reach equilibrium (Arthur, 1999, 2013). A key mechanism within economic development is entrepreneurship, which can be seen as a means of both creating disruptions (e.g. companies and platforms like Airbnb, Uber, or Apple) as well as creating consensus and order (e.g. tackling inequalities via social entrepreneurship). This is central to the entrepreneurship ecosystem framework, which corresponds well to regulation (Mack & Mayer, 2016; Stam, 2015; Thompson et al., 2018) and the co-evolution of its components like other systems of innovation (see e.g. the co-evolutionary dynamics in the Triple Helix, Leydesdorff, 2000), a primary goal of ecosystems is to produce transformative innovations (Coutu, 2014). This can be reconciled with a micro-functionalist approach, which applies functionalism at the individual level, hereby looking for individuals (companies) in their pursuit of homoeostasis in a constant unstable environment with no assertion of the macro-structure of society (macro-functionalism) (Alderson, 1957).[33] The macro-environment can then suddenly and profoundly be altered by transformative innovations and radical change.

This is reflected in the research objectives of this study. The aim is to explore the dynamics of academic entrepreneurship in ecosystems and the mechanisms that drive these dynamics. The simulation model acknowledges the time and context dependency (e.g. the academic landscape could be fundamentally altered by the introduction of new laws or funding policies or individual universities might change their strategies if the individuals in charge change) and not as the ultimate model for understanding academic entrepreneurship. This research is designed to provide a new perspective and the foundation for further research that adds to our understanding of university ecosystems. From a functionalist perspective,

[33]See also work on cooperation by Axelrod (1997).

this research aims to identify the dynamics within a given structure. A regulatory view does not exclude non-linearity and change in the system, which explains why it corresponds well with SD in general (Lane, 1999). Furthermore, the inclusion of the radical structuralist perspective allows to arrive at an endogenous explanation for transformative changes.

4.4 Data Collection and Analysis (Methods)

Every simulation method relies on the careful and systematic collection and analysis of data to inform model building and parametrisation. Different forms of data collection, analysis, and interpretation are defined as research methods (Creswell, 2009). This chapter will describe how different methods, namely literature review, interview, and secondary (quantitative) data analysis, were used at different stages in the MP and how their insights are triangulated to inform the conceptual and simulation model (Bryman & Bell, 2011). This involves many iterations, some of which will be described to show how the model and the MP were developed. Furthermore, the empirical context and the characteristics of Scotland and the UK are examined and how this informed data collection and the identification and evaluation of existing data sources.

4.4.1 Literature Review

The starting point for the system and problem exploration in step 1 was a literature review that combined the macro (university ecosystems) and micro level (institutional perspective on the history of academic entrepreneurship, drivers, and companies' perspectives) as described in Chapter 2. A literature review is not purely descriptive and should analyse and synthesise the existing body of knowledge. In this thesis, this has led to a novel conceptualisation of university ecosystems from an inter-organisational perspective. Furthermore, reviewing the literature is not a one-off exercise but a frequent activity throughout the modelling process. For example, a theme that emerged from the interviews was universities are trying to form long-term strategic relationships with selected companies. These partnerships are characterised by a mutual benefit and are not limited to a particular means of interaction such as licensing or contract research but a constant exchange through a variety of activities. This issue is under-represented in the literature and was not addressed in the initial literature review. Based on the insights from the interviews, the researcher was able to go back and do a more precise search around this topic and explore the significance of university-industry partnerships.

A second literature review was performed with the aim of understanding how to model complex systems and the methodologies that are commonly used in MS/OR. This review formed the basis of step 2 of the MP and the decision that an HS approach is required to address the research questions. The importance of partnerships between universities and industrial partners has revealed that these cannot be modelled through simple state aggregation as they represent a particular type of emergent behaviour. A related body of literature was then reviewed and the concept of complex events was introduced to the realm of HS modelling practice. This was, again, the result of iterations between modelling steps and different research methods.

4.4.2 Geographical Context

While the existing body of literature provided a good starting point for exploring academic entrepreneurship in university ecosystems, further information is required to add different perspectives and to explore the causal mechanism in more depth. This study will focus on the interaction of Scottish universities and the UK businesses within their ecosystems. Every country or region has its unique structure, which is further divided into subsystems and different layers of institutions, infrastructure, and networks, and also includes different configurations of university-industry interactions (Eom & Lee, 2010; Spigel, 2015). These characteristics of the environment have to be considered to develop a "contingent or context-specific perspective" (Acs et al., 2014; Eun et al., 2006).

Scotland has an ambitious goal to become a world-leading entrepreneurial and innovative country (Scottish Government, 2013). As part of these efforts, Scotland participated in the MIT Regional Entrepreneurship Acceleration Program (REAP) from 2012 to 2014 in order to develop a comprehensive strategy for innovation-driven entrepreneurship (REAP Scotland Team, 2014).[34] This strategy involves fostering regional ecosystem development, growing a supportive and ambitious culture (Scottish Government, 2013) and encouraging entrepreneurial recycling (Mason & Harrison, 2006). The strong higher education sector plays a key role in Scotland's economic development efforts (Brown, 2016; Lyall, 2007). Scotland has currently 19 higher education institutions in total, of which 15 are campus-based based universities, two art schools, one conservatoire, and one agriculture college. Five Scottish universities are among the top 200 universities and

[34] For further information see also http://reap.mit.edu/cohort/scotland/.

a total of twelve among the top five per cent in the world. Scottish universities have been at forefront of 'enhancement-led' teaching, supporting students to become innovative and entrepreneurial to increase their employability, excel at both blue-sky and applied research, and translating insights into real-world impact for society and economic development.[35]

Academic entrepreneurship and the contribution of universities to economic development as part of their Third Mission have received attention from policy and government UK-wide.[36] British universities are in a strong position to take advantage of the globalisation of R&D and the trend towards open innovation and have, consequently, taking a more active approach towards their Third Mission activities (Lambert, 2003). Overall, they have "outstanding" potential for collaboration and interaction with businesses (Wilson, 2012) and "extraordinary" potential to contribute to economic growth (Witty, 2013). Particularly research-intensive universities are the subject of a variety of policies and are expected to drive these changes (Abreu et al., 2016), although they have not yet reached their full potential in supporting their ecosystems relative to their world-class research base (Dowling, 2015).

Many of these policies still see universities as "a provider of technological knowledge, critical for innovation and economic growth" (Abreu et al., 2016, p. 2) and inflate the effect of spillovers, particularly in rural areas (Brown, 2016). This underestimates the complex role of universities for "enriching society that goes way beyond technology-transfer indicators, not least their crucial role in producing human capital and undertaking basic research" (Brown, 2016, p. 201). There is a consensus among government reports and the academic literature that UK universities should focus less on technology transfer and commercialisation and prioritise the demand-side through long-term, strategic partnerships, research collaborations, and capacity building (Brown, 2016; Cowling, 2016; Dowling, 2015; Lambert, 2003; Wilson, 2012; Witty, 2013). This is also reflected in the UK's dual public funding system for universities. Universities receive both block funding that depends on their performance (e.g. the Research Excellence Framework) and individual researchers may submit applications to funding councils for competitive research funding. This way, "funding to support the strategic role of universities has become intimately linked with the need to identify and establish impact and the pathways to impact" (Hughes & Kitson, 2012, p. 724).

[35] Further information is provided by Universities Scotland at https://www.universities-scotland.ac.uk/about-us/.

[36] See e.g. Dowling (2015, p. 11) for a timeline of government-issued reports on university-industry interaction.

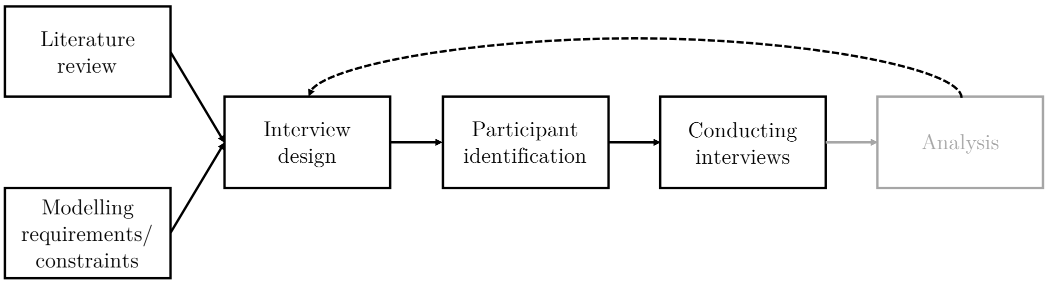


Figure 4.5: Planning and conducting interviews (adapted from Huberman & Miles, 1994)

While there are potential issues when generalising insights from single cases, the case of Scotland with a high level of attention from government and policy dedicated to innovation and (academic) entrepreneurship, a range of universities from world-class research-focused to teaching-led institutions with a regional focus, as well as both rural and urban areas provide insights that are relevant for other regions around the world.

4.4.3 Interviews

Interviews are widely recognised as the primary method for data collection in qualitative research projects (Cooper & Schindler, 2011). Depending on the structure and design, they can serve a variety of purposes from exploring a particular phenomenon to hypothesis testing (Cassell, 2015). The potential contribution of interviews as part of the modelling process has long been recognised, from exploring phenomena and eliciting agents' rules for ABMs (Polhill et al., 2010; Schenk, 2014) to constructing CLDs from interview data (Luna-Reyes & Andersen, 2003).

Interviews were planned and conducted with representatives from Scottish universities that are involved in both initiating and facilitating entrepreneurial activities as well as the university's strategic position in this area. The aim of the interviews is threefold. First, they are a means of gathering data from a strategic and operational perspective on the role of academic entrepreneurship, which would either confirm or challenge the insights from the academic literature. Second, the interviews are also explorative and a means to uncover issues or dynamics that have not been highlighted in the literature or were not part of the initial literature review. Third, the interviews are a first step to involve universities, i.e. one of the key stakeholders, in the MP and this study. A two-stage process was adopted from Huberman & Miles (1994), in which the interviews are planned and conducted in stage one (see Figure 4.5 and analysed in stage two (see Section 4.4.3.4).

4.4.3.1 Interview Design

There are three main types of interviews, namely standardised structured, semi-structured and unstructured interviews. Semi-structured and unstructured interviews are also characterised as non-standardised interview forms (Matthews & Ross, 2010). Structured interviews are designed to ask every interviewee the exact same line of questions, which includes the same order for all questions and using exactly the same words as specified in the interview guide. Eventually, this allows to aggregate the responses of the interviewees (Bryman & Bell, 2011). The questions for this type of interview are usually closed (or closed-ended), i.e. they limit the range of potential answers of the interviewee. Unstructured interviews, on the other hand, are based on open-ended questions or even one single question and the interview unfolds from here to "gain insight into an individual's lifeworld" (Cassell, 2015, p. 13).

Particularly semi-structure interviews are an effective means for developing causal structures for SD models (Sterman, 2000). Semi-structure interviews have the advantage that there are certain questions or areas that will definitely be covered, but there is also room for interviewees to focus on what they see as important and issues that the interviewer might not have known before or not regarded as relevant. The interviewer can at least to some extent prepare for the interview, while there is still room for a two-way communication and adjustments as the conversation unfolds (Cassell, 2015).

In this study, the interview was structured around the five formal entrepreneurial activities that are considered within this study (see Section 2.3.3), with two sets of additional questions regarding the personal background and experience of the interviewee as well as more holistic questions at the end of the interview (see Appendix A for the complete interview guideline). The personal questions included the current position and experience/expertise regarding the five entrepreneurial activities, how long he/she has been in this position, and whether he/she would characterise his/her role as generalist or specialist (a similar approach regarding the personal profile was used by Castillo Holley & Watson, 2017). Demographic data should be collected carefully and limited to a reasonable amount that actually contributes to the aims of the study. Asking for too much personal information can be perceived as an invasion of privacy or let the interviewee question her/his anonymity and might restrict their answers. The interview started with a short introduction to the research project and the aim of these interviews. This provides a shared understanding among all interviewees regarding their role in this study.

4.4.3.2 Participant Identification

Sampling can be defined as "the process of selecting some elements from a population to represent that population" (Cooper & Schindler, 2011, p. 727). There are two main types of sampling, probability and non-probability sampling. In general, non-probability sampling is the default approach in qualitative research as it explores a phenomenon in depth without necessarily having a representative sample of the population (Cooper & Schindler, 2011). The three common types are purposive, snowball, and convenience sampling (Cassell, 2015). Purposive sampling means that the researcher selects participants "arbitrarily for their unique characteristics, or their experiences, attitudes, or perceptions; as conceptual or theoretical categories of participants develop during the interviewing process, researchers seek new participants to challenge emerging patterns" (Cooper & Schindler, 2011, p. 167). When applying snowball sampling, the researcher relies on recommendations of participants for others, who can either differ or be similar in their views, attitudes, experiences or characteristics. Lastly, convenience sampling involves selecting whoever is available to become a participant (Cassell, 2015).

Only the 15 campus-based Scottish universities are included in this study for consistency reasons, because they share the three missions of research, teaching, and knowledge exchange (even if the priorities differ between institutions) and are subject to similar funding structures and performance measures. This still covers a variety of institutional settings, resource bases, and strategic orientations, from world-class, research-intensive to regional, teaching-led universities. The goal was to interview at least one person per institution, which is essentially a population or census study (of the institutions, not all relevant people within them) and is feasible due to the small population size (N=15).

A total of 16 Associate Principals for Knowledge Exchange[37] from 14 universities (an internet search for the other university did not identify a contact person for the other university, whereas two universities listed two persons with responsibilities in this area at the senior management level) were contacted via email with an explanation of the study and an interview request with a potential follow-up. One Associate Principal agreed to be interviewed, seven did not respond, and six either referred to or directly forwarded the request to the director of the TTO (which represents a form of snowball sampling).[38] While this is

[37] The exact title differs among universities, in addition to "knowledge exchange", terms like enterprise, commercialisation, or engagement are used as well. This standardisation is used for clarity and to protect the anonymity of the interviewees.

[38] The term "technology transfer office" will be used for all universities for the sake of clarity

unfortunate but anticipated, it still creates a buy-in from the senior university management and increases the chances of an interview with a TTO director or staff. However, this did not always work and while some TTO directors showed an interest in the study, an interview could not be arranged. When there was no response from the Associate Principal, the TTO director(s) were emailed directly with an explanation of the study and a request for an interview.

Interviewing TTO directors has proven to be insightful and formed the core of many studies in this field (Siegel, Waldman, Atwater, & Link, 2003; Siegel et al., 2004). The main reason for this is that directors are involved both in the practical day-to-day work but also work on strategic issues with the top-level university management. The final sample included one Associate Principal for Knowledge Exchange, seven TTO directors, and five members of TTO staff from seven different universities. This provides a good spread across institutions and positions, including strategic and operational responsibilities.

4.4.3.3 Conducting Interviews

A pilot study with three interviews was conducted at the researcher's own institution. The data from these interviews was then analysed with a particular focus on the usefulness of the data, i.e. whether the data is appropriate for model building and whether all relevant aspects were covered. Minor adjustments were made to the interview outline such as the inclusion of a prompt whether there is a word of mouth effect among businesses if the interviewee does not mention this aspect. These pilot interviews could therefore be used as the interview guideline remained mostly unchanged. The pilot interviews have also supported the assumption that the interview guideline with the way the questions are asked works for interviewees in different positions and that there is no need to create separate ones for TTO staff, directors, and associate principals. The reflection process did, however, not stop after the pilot study and was a constant feature of the interview process.

All interviews had to be conducted within a limited amount of time to create a snapshot of the current practices and policies within similar external conditions. Scottish universities are, like their counterparts around the world, constantly changing and adapting as conceptualised in the dynamic states model (Levie & Lichtenstein, 2010). All interviews were conducted over a period of four months between May and September 2016. Out of the thirteen interviews, eleven were

and anonymity. Furthermore, all job titles have been standardised to either "TTO director" or "TTO staff" for the same reasons.

Table 4.2: Overview of interviewees and interview content

Code[1]	Position	1.	2.	3.	4.	5.	6.	7.
A11	TTO Director	Y	Y	Y	-	-	Y	Y
A12	TTO Director	Y	Y	Y	Y	Y	Y	Y
B21	TTO Director	Y	Y	Y	Y	Y	Y	Y
B31	TTO Director	Y	Y	Y	Y	Y	Y	Y
B41	Associate Principal	Y	Y	Y	Y	Y	Y	Y
B42	TTO Staff	Y	Y	Y	Y	Y	Y	Y
B43	TTO Staff	Y	-	-	-	Y	Y	Y
B44	TTO Staff	Y	Y	-	-	-	-	Y
B45	TTO Staff	Y	Y	Y	Y	Y	Y	Y
B46	TTO Director	Y	Y	Y	Y	Y[3]	Y	Y[3]
C61[2]	TTO Staff	Y	Y	Y	Y	Y	Y	Y
C71	TTO Director	Y	Y	Y	Y	Y	Y	Y
C81	TTO Director	Y	Y	Y	Y[4]	Y[4]	Y[4]	Y

Legend:
1. personal, 2. licensing, 3. spin-offs, 4. consulting, 5. contract research,
6. collaborative research, 7. holistic perspective
Y = addressed, - = interviewee opted out
Notes:
[1] Code is based on the categorisation of universities that will be described in Section 5.3.1.
[2] Limited insights for all activities, broad overview only.
[3] Limited discussion, not all questions addressed.
[4] Limited discussion, all three activities discussed together.

done face-to-face, one over the phone, and one via Skype. The interviews lasted between 42 and 93 minutes, with an average of 71 minutes. The interviews were recorded and transcribed for further analysis. Furthermore, notes were taken by the interviewer during the interview to capture any thoughts or issues that were particularly highlighted by the interviewee and as a backup in case the recording device fails. In the introduction to the study and the aim of the interviews, all interviewees were presented with the seven areas that should be covered, giving them the opportunity to opt out of talking about a particular entrepreneurial activity if that is outside their area of expertise. Table 4.2 provides an overview of the interviewees and the areas that were covered. Codes were used to protect the interviewees anonymity and personal information such as for how long the interviewee has been in his/her role is kept confidential.

4.4.3.4 Qualitative Data Analysis

The interview data was analysed with the goal of "identifying significant relationships between data, emerging themes, and existing literature", similar to a non-simulation study in this field by Villani et al. (2017, p. 89). In a first step, the data was sorted and organised as illustrated in using NVivo 12 (Huberman & Miles, 1994). The total amount of raw interview data was divided into personal information about the interviewer, information about the processes and how the five entrepreneurial activities are organised with each university, and other rele-

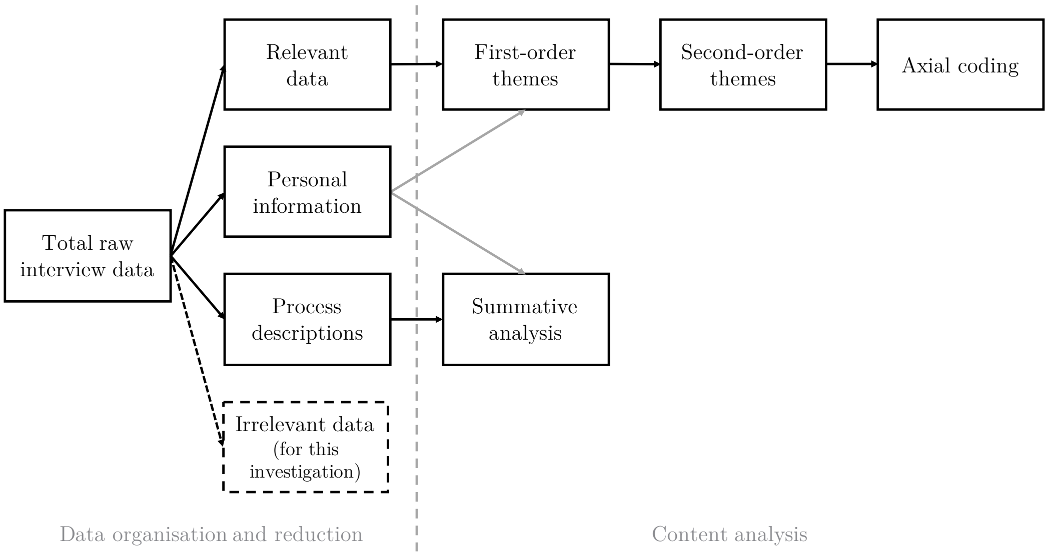


Figure 4.6: Qualitative data organisation, reduction, and analysis (adapted from Graneheim & Lundman, 2004; Huberman & Miles, 1994)

vant data (see Figure 4.6). This separation allows to use the most appropriate type of analysis for the different types of data that were collected during the interview (Hsieh & Shannon, 2005; Huberman & Miles, 1994).

Personal information helps the researcher to make sense of the data and put research findings in context. It is also important for potential replication studies or extensions to this study. In this case, the personal information was only used for comparison between the participants and controlling for experience and potential biases in their view. For example, the limited insights from C61 can be explained by the relatively short tenure of the interviewee. Furthermore, the position of the interviewees and their responsibilities can also help understand the issues that they raised. Interviews with a more senior position, for example, emphasised the importance of partnerships and continuous interactions as opposed to being overly concerned with pushing certain entrepreneurial activities. TTO staff, on the other hand, with a more operational perspective and day-to-day interactions with academics and companies, clearly stated that the means are important.

Content analysis is used to "organize and elicit meaning from the data collected and to draw realistic conclusions from it" (Bengtsson, 2016, p. 8). It includes both quantitative and qualitative approaches for analysing qualitative data (Cavanagh, 1997; Kondracki et al., 2002). Content analysis can be very time consuming and, like all methods, "requires consideration of sources of errors and bias, and care in making assertions about the meaning and generalisability of the findings" (Cavanagh, 1997, p. 15). There are three types of content analysis, name conventional content analysis, a directed approach, and a summative content analysis (Hsieh & Shannon, 2005). The type of content analysis used for a particular study depends on the problem itself as well as the researcher's worldview and theoretical perspective (Weber, 1990). In this case, summative and conventional content analysis will be used separately for different parts of the data.

Summative content analysis represents a quantitative approach for analysing qualitative data. After certain words or content of interest are identified, their use in the data is quantified "with the purpose of understanding the contextual use" (Hsieh & Shannon, 2005, p. 1283). The aim is to explore how words are used, their meaning in different contexts, as opposed to inferring meaning in the conventional content analysis (Hsieh & Shannon, 2005). A summative content analysis was used for the process descriptions to explore whether all universities have similar processes in place for the five entrepreneurial activities and whether there is a discrepancy between the descriptions in the academic literature and the practices at Scottish universities. The descriptions from the literature were used to predefine the words of interest (e.g. 'disclosures', 'patent filing/application', 'granted patent', 'negotiation' in the licensing process), but these were also adjusted during the analysis as some universities have their own terminology. The results will be presented in the description of the model in the next chapter.

Conventional content analysis, in which "coding categories are derived directly from the text data", represents a basic form of qualitative analysis and inductive reasoning (Hsieh & Shannon, 2005, p. 1277). It avoids predefined categories and codes and is most useful when knowledge and theory about a certain phenomenon is limited (Creswell, 2009; Kondracki et al., 2002). These basic concepts are shared by many qualitative methods (Hsieh & Shannon, 2005). While quantitative research requires the researcher to follow a deductive procedure that often starts with a small number of variables, qualitative researchers must "review all of the data, make sense of it, and organize it into categories or themes that cut across all of the data sources" (Creswell, 2009, p. 175). Hence, the interviewer must be a *quick study*, i.e. grasping an understanding of the main concepts without much experiences in a quick time (Cooper & Schindler, 2011, p. 168).

The process that will be applied here follows a structure that is similar to grounded theory (Glaser & Strauss, 1967; Suddaby, 2006) and incorporates the strategies by Gioia et al. (2012) for a more rigorous approach to inductive, qualitative research and grounded theory articulation. In a first step, first-order categories are generated (open coding) and further summarised into second-order themes, before they are positioned within a theoretical model (axial coding)

(Creswell, 2009, p. 184).

The first-order themes include a wide range of experiences and factors that influence certain processes with and outwith the university. Through re-reading both the codes and the whole interviews and becoming increasingly familiar with the material, these codes could be summarised and synthesised into more abstract second-order themes. In the axial coding stage, the relationship between codes is analysed and connections are uncovered. This step is important to uncover causal mechanisms, which then can be used to inform the model building process. In total, 389 nodes across all three levels of the coding process were derived from the interviews. Tables showing representative quotes and this coding structure are presented in the next chapter for the main themes that emerged from the conventional data analysis and are relevant for the conceptual model.

The analysis has shown that even a relatively small number of 13 interviews has uncovered a variety of different perspectives, opinions, and experiences. This is consistent with findings from Baker & Edwards (2012, p. 5) that it might "only take a few interviews to demonstrate that a phenomenon is more complex or varied than previously thought".

4.4.3.5 Trustworthiness

Qualitative research is often criticised for a lack of scientific rigour (Gioia et al., 2012). A key issue is that the conventional criteria for establishing rigour in quantitative analysis and associated measures such as reliability, validity, and generalisability, and objectivity cannot be directly projected onto qualitative research (Holloway & Wheeler, 2010). Qualitative research is "more than a naive technique that results in a simplistic description of the data" (Cavanagh, 1997, p. 5). Therefore, researchers must focus on e.g. building trustworthiness and establishing credibility throughout the whole process of data collection and analysis (Bengtsson, 2016; Graneheim & Lundman, 2004).

There are a number of strategies to build trustworthiness, even though the literature does not agree on all of them (Holloway & Wheeler, 2010). This study applies a number of these strategies with the goal of allowing the reader to look for alternative conclusions and interpretations (Bengtsson, 2016; Graneheim & Lundman, 2004). Triangulation of different data sources lies at the heart of this research project and highlights e.g. discrepancies between the literature and the analysis of the interviews. In these cases, discrepancies themselves are presented and not just the explanation of the author, which would allow a third person to question the presented explanation. The description of the conceptual model is very detailed and the input of the qualitative data analysis can be clearly traced back to the original quotes ("thick description", Holloway & Wheeler, 2010, p. 310). The constant reflection process was already mentioned and is used to assure comparability and that the researcher's knowledge and experience does not influence the process of data collection and analysis nor the outcome of said analysis (Bengtsson, 2016).

4.4.4 Secondary Data Analysis

In addition to the primary, qualitative data, different secondary datasets are analysed to inform the model structure and provide the basis for the parametrisation of the simulation model. The data sources that are used, including their advantages and limitations, are presented below.

4.4.4.1 University Data

Multiple secondary data sources were analysed to understand role and impact of entrepreneurial activities for universities. The primary data source is the Higher Education-Business and Community Interaction survey (HE-BCI), which is collected annually by the Higher Education Funding Council for England (HEFCE).[39] HE-BCI includes self-reported information on Third Mission activities, funding sources, and university resources. This data is available from 2008/09 to 2014/15.

This data is complemented by institutional level data from the Higher Education Statistics Agency (HESA). HESA collects data annually regarding staff and student numbers of all universities, their financial information, and other aspects of the UK higher education sector. This data provides important institution-specific characteristics that are used in the analysis to e.g. calculate the engagement in particular activities relative to staff size for a more accurate comparison of entrepreneurial intensity at different universities.

Lastly, results from the 2014 Research Excellence Framework (REF14) were used to rank universities based on their quality of research in the process of understanding university reputations and performances (see Section 5.3.1).[40] REF14 was a collaborative effort of the funding councils for England (HEFCE), Scotland (SFC), and Wales (HEFCW) as well as the Department for Employment and Learning in Northern Ireland (DEL), and replaced the former Research Excellence Assessment (RAE). It was designed as a basis for grant allocations from the

[39]For further information about the survey see http://www.hefce.ac.uk/ke/hebci/.

[40]For further information about the REF see https://www.ref.ac.uk.

funding bodies and also as a means for benchmarking performance and accountability of public support for higher education.

In a first step, longitudinal data for the five entrepreneurial activities were plotted for Scottish universities, including the volume and income generated from these activities, to understand general trends. In light of the diversity among Scottish universities with regard to size, strategic focus, and history, among other dimensions, the number of these five entrepreneurial activities and the income that they generated were broken down for each university. Furthermore, the number of academic staff involved in research from HESA was used to control for the size of the university and show the relative intensity. Inconsistencies regarding the reporting of staff numbers were detected for the University of the Highlands and Islands (UHI), which were too low and, consequently, indicators of the entrepreneurial performance per staff were too high. UHI has received university status in 2011 and the transfer of status regarding academic contracts from college to university is presumably causing these reporting issues. Therefore, UHI had to be excluded from the quantitative analysis and the simulation model.[41] The results are presented in the next chapter. Additional analyses were performed for the parametrisation of the model in a second step. Detailed information is presented in Chapter 6.

4.4.4.2 Company Data

Primary data was only collected on universities. This is due to two main reasons. First, there is a great variety among companies that it would be impossible within the time and resource constraints of a PhD study to get accurate insights. Companies differ significantly with regard to their engagement with universities and a large number of interviews would have been required. Second, this information is available from the *Cambridge Centre for Business Research Survey of Knowledge Exchange Activity by United Kingdom Businesses 2005-2009* (Hughes et al., 2010), or 'CBR Business Survey' as it will be referred to for the remainder of the thesis. The survey does not only cover the characteristics of the businesses

[41] One interviewee is based at UHI. After careful consideration, the interview was not excluded and remains in the qualitative analysis. The main reason for this is that the SD model covers general mechanisms and is not institution-specific. The interview did highlight these issues as the interviewee further explained: "For UHI-owned IP, we have a complication, because our 13 academic partners aren't UHI employees, they're individual institutions in their own right, so we can't have an IP policy for everybody, we can only have that for those researchers and academics who are UHI employed. [...] So the majority of our researchers are actually staff of their own institution and so they would all have to have their individual intellectual property policies and revenue distribution policies." Additional notes are provided throughout where this interview is relevant.

who engage with universities via different entrepreneurial activities, but, and this is the key issue for this research, who initiates these interactions, the reasons for and against working with universities, and how the companies evaluated these interactions.

The data was collected between July 2008 and February 2009 and covers the time period from July 2005 to February 2009. The sample size was 25,015 firms (one-stage stratified or systematic random sample) and the Neyman optimal allocation method was used to distribute the sample across twelve UK regions, 23 sectors and five company size classes (Hughes & Kitson, 2013). A census was used for companies of the largest size class (1000+ employees) because of the low absolute number of these firms. The survey includes responses from 2,530 businesses from across the UK, which results in an effective response rate of 10.1% (Hughes & Kitson, 2013).

The analysis of this data served two purposes. First, descriptive statistics were used to understand the behaviour and how different types of companies (size, innovativeness, absorptive capacity) work with universities, which activities they prefer as well as the drivers and constraints. The results are used for determining the relevant agent characteristics and the conceptualisation of their rules and are presented in Chapter 5. Second, further analyses and the use of regression methods in addition to descriptive statistics were used for the generation of the agent population and the parametrisation of the model. Detailed information is presented in Chapter 6.

A limitation of this study is the compatibility of the secondary data sources. There is only a limited overlap between the university data and the time period that is covered by this survey. Furthermore, this survey does not allow to link a particular business to a particular academic partner. Similarly, the secondary data on universities is also at an institutional level but does also not link universities to particular businesses. Several assumptions had to be made to overcome these limitations, which will be clearly stated throughout the description of the model (Chapter 5) and simulation (Chapter 6).

4.5 Research Ethics

Ethical issues were considered throughout the whole process of this research, from the aims and objectives of the project and the design of the research to the presentation and dissemination of the results (Bryman & Bell, 2011; Saunders et al., 2009). The *University of Strathclyde Code of Practice on Investigations*

Involving Human Beings[42] was used as a guide for this process. With regard to the aims and objectives, this research aims to contribute to knowledge and support the collaboration between universities and industry to address societal challenges, hereby honouring scientific and social responsibility.

The main issues regarding the research design were the use of primary and secondary data in line with the objectives of the study while avoiding any harm to individuals and organisations involved, adequately protecting privacy and anonymity of individuals, and data stored in a secure and confidential manner. A careful assessment of the secondary data used in this research did not find any critical issues. HE-BCI and HESA data are publicly available and were accessed through the HEIDI interface. The CBR Business Survey was accessed through the UK Data Service and is an already redacted version of the full data set held by the Centre for Business Research at the University of Cambridge Judge Business School. While some descriptive statistics of individual universities based on the publicly available data are reported, the majority of data is not reported at the individual organisations' level.

For the collection of primary data, ethical approval for conducting interviews both face-to-face and over the phone as well as the storage and use of this data was granted by the Departmental of Management Science Ethics Committee in line with the university guidelines. The details with regard to how the interviews were conducted and the measures taken for ensuring confidentiality and privacy are outlined in the *Ethics Application Form* in Appendix B.

The results, both findings from the analysis of the primary and secondary data and the simulation output, will be presented in an objective and non-biased way, avoiding misleading or exaggerated information. In addition to the transparent reporting of results, it is worth highlighting that the results are also based on 'generic' universities that represent groups of Scottish universities and not individual, 'real' universities.

4.6 Summary

This chapter has presented a new MP for hybrid SD-ABM simulations. It was created based on a review of existing MPs for mono-method approaches and HS as well as with the specific characteristics of this study in mind. This process should be viewed as a proposal at this point and needs to be tested in practice (beyond

[42]For further information see https://www.strath.ac.uk/ethics/ and access the Cope of Practice here https://www.strath.ac.uk/media/ps/rkes/Code_of_Practice_eighth_Feb17.pdf

the application in this thesis). After all, developing a modelling process is as much of an iterative process as developing a (hybrid) simulation and a standard for development should be tested and refined through various projects (Schmolke et al., 2010).

Critical realism is presented as the philosophical foundation of this study, which carries important implications for modelling and how the results can be evaluated. Furthermore, the complex systems perspective is used to combine the functionalist and radical structuralist approach to social science research, which allows the university ecosystem concepts to synthesise change as well as the co-evolutionary dynamics.

Building on this foundation, this chapter then provided an overview of the methods used to collect and analyse both primary and secondary data. The iterative nature of the MP and how these methods influence modelling at different stages as well each other are highlighted. The following chapter presents the conceptual model as a result of the triangulation of data as described in this chapter.

Chapter 5

Conceptual Model

5.1 Introduction

This chapter describes step 3 of the MP and ties together the work and insights from the previous chapters. By triangulating information from the literature, interviews, and secondary data, the conceptual design of the model is described in the following sections. The chapter is divided into three parts. The starting point is adding further details to the HS framework and applying it to the context of Scottish universities (Section 5.2). The following two sections will focus on the SD and the ABM modules, respectively. In particular, Section 5.3 describes the development of three 'generic' universities based on empirical data from Scotland, followed by the causal structure of internal resource allocation and entrepreneurial activities. Section 5.4 will then describe company agents, including their characteristics and decision-making. By providing a detailed account of the different parts of the model, this chapter provides the basis for the simulation as well as contributes to structural (white-box) validation.

5.2 Hybrid Simulation Framework

5.2.1 Operationalisation of the University Ecosystem Concept

Ecosystems have been used predominantly metaphorically or as a means for conceptualising a systemic perspective around the entrepreneurial activities of universities or regions. Empirical data is usually fitted to this construct, e.g. using the framework by Stam (2015) as a frame of reference for the different elements, in order to perform *a posteriori* analyses of how these elements correlate with

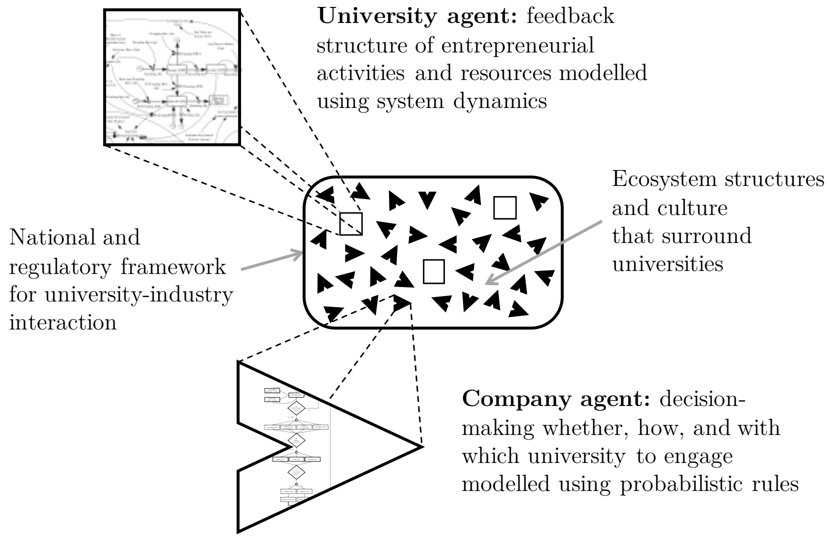


Figure 5.1: Hybrid simulation framework (adapted from Swinerd & McNaught, 2012)

certain outputs. In most cases, this is also limited to a particular level of analysis (e.g. regional performance). As a result, there is a lack of operationalisation of the ecosystem concept to support policy making and governing ecosystems beyond ‘post-mortem’ policy evaluation.

This thesis addresses this issue by operationalising the university ecosystem concept (Figure 2.1) through the intermediate generic SD-ABM HS framework (Figure 3.15). The result is illustrated in Figure 5.1 and includes the key features of the university ecosystem conceptualisation as well as further refines the HS framework. The model incorporates the systemic and institutional levels, whereas individual-level factors (including their networks, norms, and incentives) are considered at the institutional level but not modelled explicitly (as discussed in Section 3.6.5). It also combines the university (supply) and industry (demand) side (Cosh & Hughes, 2010). The majority of studies on university-industry interaction has focused exclusively on the supply side, assuming that an increased supply of opportunities for collaboration and knowledge exchange will lead to an increase in interaction between universities and firms.

Ecosystems are characterised by the interaction of a heterogeneous set of actors within a defined environment, such as a geographical area for entrepreneurial ecosystems (Stam, 2015) or around platform/technology for innovation ecosystems (Adner & Kapoor, 2010). University ecosystems, from an inter-organisational perspective, are no exception. The overarching architecture is an ABM simulation, in which two types of agents interact: universities and companies. The vast majority of existing studies have only considered either a single university or one ‘average’ university. However, looking at individual universities as role models does not account for many of the underlying dynamics and the interplay of heterogeneous universities within a changing academic landscape and dynamic ecosystems. Based on a (quasi-)evolutionary approach, the search for role models and *what works* has to consider systems with multiple universities interacting with multiple companies (Krücken, 2003).

This evolutionary aspect corresponds to *panarchy*, which is the "hierarchical structure in which systems of nature [...], and humans [...], as well as combined human-nature systems [...] and socio-ecological systems, are interlinked in never-ending adaptive cycles of growth, accumulation, restructuring, and renewal" (Holling, 2001, p. 392). Panarchy also aligns with the philosophical foundation of this research project, CR with its focus on mechanisms and the interaction of the functionalist (structure) and radical structuralist (agency) perspective that enable these cycles (Section 4.3.4).

5.2.2 Proximity and the ABM Environment

Guided by the principles of good modelling practice, including *modelling a problem, not a system* (see e.g. Pidd, 2009; Sterman, 2000), this model focuses on organisational proximity and social capital to describe the relationships between universities and industry. Following the discussion in Section 2.4, other proximity dimensions such as geographical or technological proximity are not modelled explicitly.

Geographical proximity becomes more of a factor if there is a supply of high-quality academic research within the country of the firm, meaning that firms source knowledge within their country if possible. This effect is weakened for firms with higher R&D activities (Arundel & Geuna, 2004). Scotland is home to world-leading universities, including two universities among the top 100 and an additional two among the top 200 of the Times Higher Education (THE) World Rankings 2020[43] as well as some of the best modern universities with three universities currently in the top 200 of the THE Young Universities Ranking 2019[44] and Heriot-Watt University, the University of Stirling and Strathclyde previously consistently among the top 100 of this ranking. Scottish universities also perform well against the rest of the UK (Universities Scotland, 2016):

- 77% of research conducted by Scottish universities was ranked as 'world-leading' or 'internationally excellent' based on the Research Excellence

[43]https://www.timeshighereducation.com/world-university-rankings/2020/world-ranking
[44]https://www.timeshighereducation.com/world-university-rankings/2019/young-university-rankings

Framework 2014 (REF14), compared to the UK average of 76%.

- 86% of Scottish research submitted to the REF14 had 'outstanding' or 'very considerable' impact, compared to the UK average of 84%.

This justifies the absence of geographical proximity when modelling the interaction of Scottish universities with UK businesses. In terms of the practicalities of developing the model, this is realised through an aspatial 'soup' model, in which all agents are stored in one container, which, in this case, is the ecosystem (Macal & North, 2010). In this setting, agents have no specified location and are selected randomly or based on a defined probability distribution for interaction with other agents. A soup model can allow path-dependent behaviour if these preferences are not uniformly distributed and agents adapt them throughout the course of the simulation. For example, the likelihood of a company being selected for a future interaction with a university can be increased after the company had a successful interaction with a university. A key aspect of ecosystems is social capital and trust among different actors that enable knowledge sharing and collaboration. While soup models do not contain deterministic links to other actors like a network structure, these links can be modelled stochastically with higher probabilities for working with a particular partner (to the point of a deterministic choice if the probability equals one). However, a network structure or a spatial component (e.g. grid/Euclidean space or GIS) can be easily added for future extensions of the model and when additional data becomes available. These environment designs can also be used to model a knowledge space (technological or cognitive proximity).

5.2.3 Regulatory and Policy Environment

Government, policy, and funding bodies are not represented explicitly in this model. However, the model is based on the regulatory and policy environment in the UK and Scotland in particular. This has a number of implications for constructing the model as well as interpreting the results. There is a shared vision among Scottish universities to be a world-leading collective across all three missions and to be "core part of Scotland's identity as a prosperous, inclusive and outward-looking nation".[45] This is, however, not only motivated by universities' own visions but also a result of the external environment in which the universities operate.

[45] https://www.universities-scotland.ac.uk/wp-content/uploads/2019/06/HE-Vision-2030-v-1.0.pdf

In Scotland, public funding is provided through a dual system that includes (1) block grants from the Scottish Funding Council (SFC) and (2) grants from UK Research Councils based on competitive application processes. With the SFC as its main mechanism, the Scottish Government is the second largest individual contributor to research funding for Scottish universities after tuition fees, accounting for 30% and 32% of the university sector's budget, respectively.[46] The SFC is set out to support "the competitiveness of Scotland's research base through a range of investments, as well as the training and development of postgraduate teaching and research students".[47] SFC funding is tied to outcome agreements, which specify the deliverables of universities for the funding they receive. Therefore, universities align their priorities to those of the SFC and, by extension, the Scottish Government.

The Scottish Government further aims to support the internationalisation of Scottish universities[48] and Innovator Centres that bring together academic research and businesses for the benefit of the economy and society.[49] This is in line with other national government funding programmes, including science parks (Zou & Zhao, 2014), entrepreneurship education (Rasmussen & Sørheim, 2006), innovation awards (Eesley et al., 2016), and engineering research centres (Boardman & Corley, 2008). Particularly the Innovation Centres have a direct impact on how universities engage with industry through collaborative research. Research has also recommended that national support programmes should be supplemented by e.g. tax benefits to assist spin-off firms (Henrekson & Rosenberg, 2001; Patzelt & Shepherd, 2009) and a reduction in regulation and excessive bureaucracy (Henrekson & Rosenberg, 2001; Zou & Zhao, 2014), particularly national regulation reform initiatives are complementary to entrepreneurship efforts (Klofsten & Jones-Evans, 2000; Goldfarb & Henrekson, 2003).

In addition to direct government funding, the policies, regulations, and priorities from UK-based funding councils such as the Engineering and Physical Sciences Research Council (EPSRC) or the Economic and Social Research Council (ESCR) as well as international funding bodies and programmes such as the EU Horizon 2020 programme shape the strategies and priorities of universities. With a focus on the entrepreneurial activities of universities, the most significant implications arise from regulations regarding collaborative research and e.g. the

[46] Audit Scotland, Finances of Scottish Universities, available at https://www.audit-scotland.gov.uk/uploads/docs/report/2019/nr_190919_finances_universities.pdf

[47] https://www.gov.scot/policies/science-and-research/university-research/

[48] https://www.gov.scot/policies/universities/university-internationalisation/

[49] https://www.innovationcentres.scot

required contributions of both the academic and non-academic partners. These can both enable and restrict different types of collaborations and also favour research and collaboration on certain fields.

Other important aspects are IP and antitrust laws, which have a significant impact on how universities engage with industrial partners. The most widely studied policy is the Bayh-Dole Act in the U.S. (e.g. Mowery et al., 2001; Kenney & Patton, 2009; Grimaldi et al., 2011). In the UK, IP generated by academics is assigned to the university as opposed to what is often called 'professor's privilege', which means that academics retain the rights to their IP. National IP regulations still vary significantly among countries in Europe (Grimaldi et al., 2011), though a number of countries such as Finland (Ejermo & Toivanen, 2018), Norway (So et al., 2008; Mervis, 2016), and Germany (So et al., 2008; Czarnitzki et al., 2017) have abandoned the professor's privilege in recent years and moved to a model that is similar to the UK. While some of these studies demonstrate changes in academics' propensity to patent IP based on the changing IP landscape, there is no data available that links e.g. changes in IP rights to changes in the demand of firms for licensing or acquiring patents from universities. Therefore, the model should be interpreted against the current UK policies and laws.

Many inventions with university input are patented by other institutions, even though universities could legally claim ownership (Grimaldi et al., 2011). This has been observed in a variety of countries, including Italy (Balconi et al., 2004), Finland (Meyer, 2003), and Belgium (Saragossi & van Pottelsberghe de la Potterie, 2003). However, many universities are becoming increasingly aggressive in claiming IP ownership through their TTOs, which goes as far as litigation against prestigious employees (Grimaldi et al., 2011). Some of these issues arise from a different understanding of the role of IP in knowledge exchange activities. This is summarised by one interviewee:

> "[...] there are people in Scotland, who really believe that actually we should give away, universities should give away all their IP to Scottish companies. Of course that would be illegal under European Union law and national competition law. So that's not something that's going to happen. But it also seems to me that that is based on a fundamental misperception about the way you drive innovation forward, which is that it's good to have academic-industry collaboration, because even if you have a patent, that doesn't bring you all the know-how and the other things around them. It gives you the ownership but not the understanding." – B41

Within this environment, universities must manage different and, in many cases, opposing objectives, including balancing contract and collaborative research and independent research; keeping and supporting the personal development of researchers but also allowing and supporting mobility; generating income from grants, industry, and government block funding (Intarakumnerd & Goto, 2018). This requires universities to demonstrate relevance to different audiences and constantly adapt to the changing external landscape (see also Appendix D.1 for further emerging themes from the interviews).

5.2.4 Main Assumptions of the Model

All models are simplifications of reality and are, therefore, based on a number of assumptions (see Section 3.2.2). Before describing the specific characteristics and the structure of the model in more detail, this section will outline the main assumptions that provide the basis for this HS and include:

1. The model is based on Scotland and the UK environment for both universities and companies (as described in Section 5.2.3). Both the structure and the simulation output need to be evaluated in this context.

2. Interactions between industry and universities are voluntary (Mindruta, 2013).

3. Only dyadic relationships are included in the model.

4. Licensing, collaborative and contract research, and consulting are initiated exclusively by companies.

5. Only these four mechanisms plus spin-off creation are modelled explicitly. However, the initial preference list that every company has, represents existing ties e.g. based on prior interaction or other activities such as student placements. Furthermore, this also accounts for the fact that not all universities have equal networks or resource bases (Laursen et al., 2011).

6. The number of interactions that a company can have is restricted (Mindruta, 2013) and also has an inverted U-shape relationship to innovation outputs (Audretsch & Belitski, 2019; Kobarg et al., 2019). In this case to one activity at a time.

7. Each company agent has a separate university preference ranking for each of the four activities.

8. Same decision-making process for all companies, even though there is heterogeneity with regard to the information used for partner selection (Knoben et al., 2019).

9. Companies' preferences are based on past interactions, which are categorised using a binary 'successful' or 'non-successful' value (Giuliani & Arza, 2009; Villani et al., 2017) and are updated after every interaction with a university.

10. This model treats all activities equally and does not differentiate between different objectives for engaging in a particular activity, which can change the nature of the knowledge that is exchanged (Villani et al., 2017).

11. In line with this, no market competition or further modelling of the firms' commercialisation efforts or how they influence a firm's performance (Min et al., 2019).

The following sections will describe the internal structures of each module from the framework in Figure 5.1, starting with the SD module and the university agents in Section 5.3 and followed by the company agents as part of the ABM module in Section 5.4.

5.3 University Agents

University agents are modelled using SD mainly due to its ability to model capabilities and resources from an institutional (aggregated) perspective (Q1), to reflect historical development in the current system structure and parametrisation for different universities (Q2), and to model reputational effects as accumulating stocks and evolutionary dynamics through feedback (Q4). A fixed system structure for universities that still allows non-linear dynamics within this structure does also correspond to the pace of change within such universities and the organisational inertia. Krücken (2003, p. 333) notes that "[i]n universities, the pace of change is considerably slower than at the level of current higher education and science policy talk. Though one can witness far-reaching changes on the discursive level, institutional structures and practices display a much lower volatility" (see Section 3.5 for the full discussion).

A descriptive analysis offers insights into the overall development of academic entrepreneurship among Scottish universities. Figure 5.2 shows the accumulated volume of four out of the five activities that are the subject of this study (no

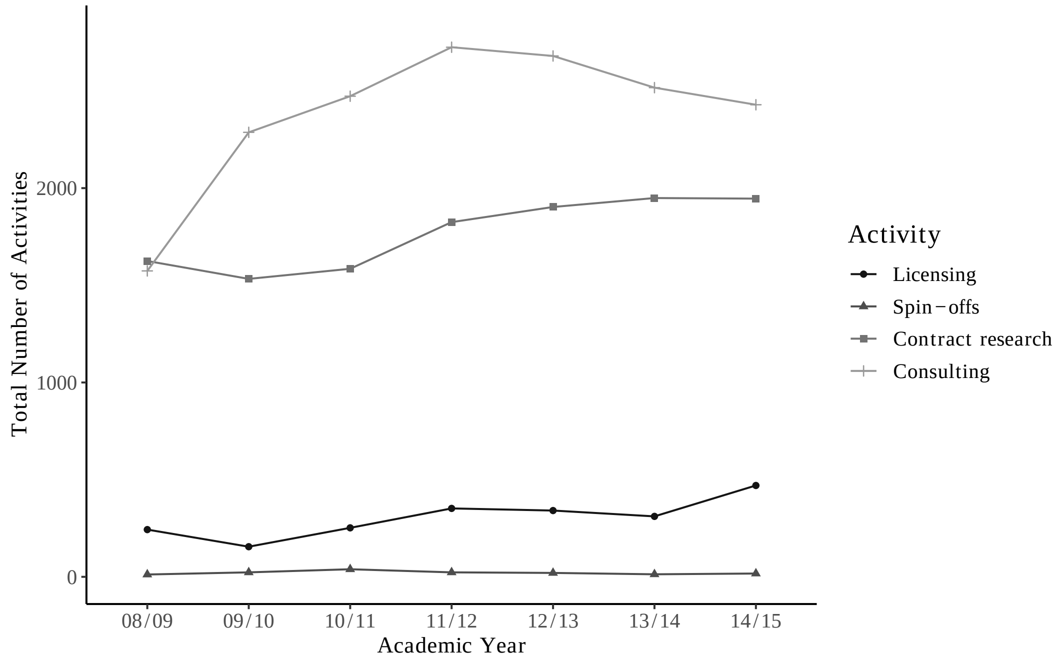


Figure 5.2: Total number of entrepreneurial activities for all Scottish universities between 2008/09 and 2014/15, showing the importance of consulting and contract research compared to commercialisation activities (source: HE-BCI B).

number of projects is reported for collaborative research). Cumulative data at the institutional level for Scottish universities is consistent with findings in the existing literature that academics engage more frequently in activities such as consulting, contract and collaborative research, compared to licensing and spin-off creation (D'Este & Patel, 2007; Harrison & Leitch, 2010; Abreu & Grinevich, 2013). Similarly, income generated from these entrepreneurial activities is dominated by contract and collaborative research (see Figure 5.3). The perceived importance of these entrepreneurial activities is also similar among industry and university (Bekkers & Bodas Freitas, 2008).

Much of the literature and policy practice is based on a 'one-size-fits-all' model of universities, which has led to "mischaracterizations concerning the role of universities and their contribution to society" (Sánchez Barrioluengo, 2014, p. 1760). Therefore, the simulation must include different types of universities with different resource bases and strategic foci.

5.3.1 Developing Generic Universities

A defining aspect of this study is the inclusion of multiple universities with partially overlapping ecosystems in the same model in order to understand the dynamics of academic entrepreneurship. Heterogeneity in terms of their research

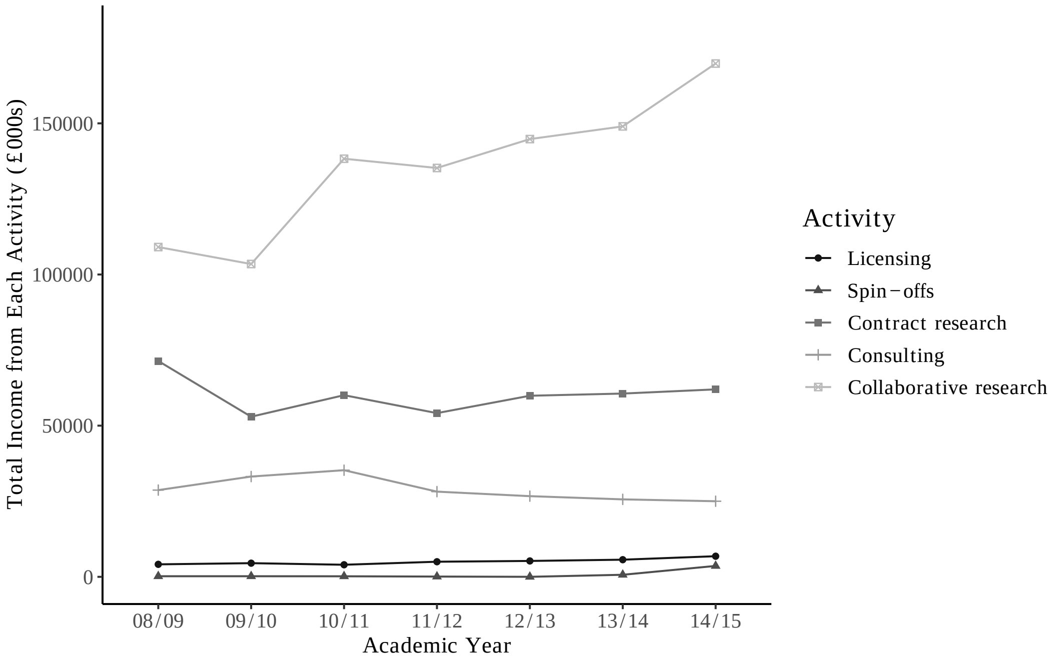


Figure 5.3: Total income per entrepreneurial activity for all Scottish universities between 2008/09 and 2014/15, highlighting the reliance on collaborative research as a crucial means for research funding and the marginal contribution of commercialisation activities (source: HE-BCI B).

base, resources, prestige and reputation influences the breadth and depth of universities' entrepreneurial activities (see e.g. Abreu et al., 2016; Mustar et al., 2006). These different 'starting points' need to be taken into consideration when investigating universities' entrepreneurial strategies and their internal resource allocation (Siegel & Wright, 2015a). However, to (1) reduce the number of reference modes the simulation needs to match and therefore the amount of parametrisation required and to (2) increase the generalisability of the model, the remaining fourteen Scottish universities[50] are grouped into *generic* universities.

Universities are commonly categorised based on their focus on either of the first two missions, i.e. research-intensive and teaching led institutions. Going beyond this binary distinction, Laursen et al. (2011), for example, used data from the 2001 RAE and divided UK universities into three tiers by calculating the percentage of staff located in departments that receive 5 or 5* in the RAE and assigned the top 10% to tier one (St Andrews), the following 40% to tier two (Edinburgh, Glasgow, Stirling, Dundee, Strathclyde, Aberdeen, Heriot-Watt), and the bottom 50% to tier three (the remaining). However, this categorisation is purely based on research metrics and does not account for entrepreneurial activities.

[50]University of the Highlands and Islands has been excluded, see Section 4.4.4.1.

By recognising excellence in teaching and research, the Russell Group of "self-proclaimed 'leading' universities" (Boliver, 2015, p. 608) arose, but a cluster analysis based on research activity, teaching quality, economic resources, academic selectivity, and socio-economic student mix shows that the Universities of Oxford and Cambridge form a distinctive cluster for themselves. The remaining Russell Group universities (including Edinburgh and Glasgow from Scotland) do not differ significantly from most other pre-1992 universities and together form the second cluster. A cluster analysis by Geuna (1998) based on the number of researchers, students, how often the university was involved in EU R&D projects, number of publications, as well as the ratios between researchers/students and publications/researchers has identified three categories. These include research-oriented, high-prestige, (mostly) pre-war universities; younger universities and a few postsecondary institutions that are more focused on applied research; and, lastly, universities with a primary focus on teaching.

Studies that go beyond research and teaching when trying to classify universities are rare. The challenge is that an accurate representation of entrepreneurial activities and performance indicators must include "a variety of knowledge transfer activities, reflect a variety of impacts, allow comparability between institutions, and avoid the creation of perverse behavioural incentives" (Rossi & Rosli, 2013, p. 2). For example, using income from entrepreneurial activities as the only measure is flawed because it is influenced by size of the university and other characteristics. When looking at multiple factors, different entrepreneurial profiles emerge. An example is a subsequent study by Rossi & Rosli (2015) that applies a clustering approach based on the 'knowledge transfer objectives' of UK universities and derives a categorisation that is very similar to the findings from Geuna (1998).

The small number of universities in this study limits the applicability for a quantitative cluster analysis, particularly with regard to the robustness of the results. To overcome this issue, a manual qualitative cluster analysis is performed. In a first step, the 14 universities were sorted according to their research performance by using their overall REF14 ranking (using REF/RAE as a proxy for research quality has been used by e.g. D'Este & Patel, 2007). For each university, the number of the five entrepreneurial activities that are considered in this study and the income that each activity generated were plotted for all years between 2008/09 and 2014/15. Both measures, count measure and income generated, were normalised by the size of university (proxied by the number of academic staff in-

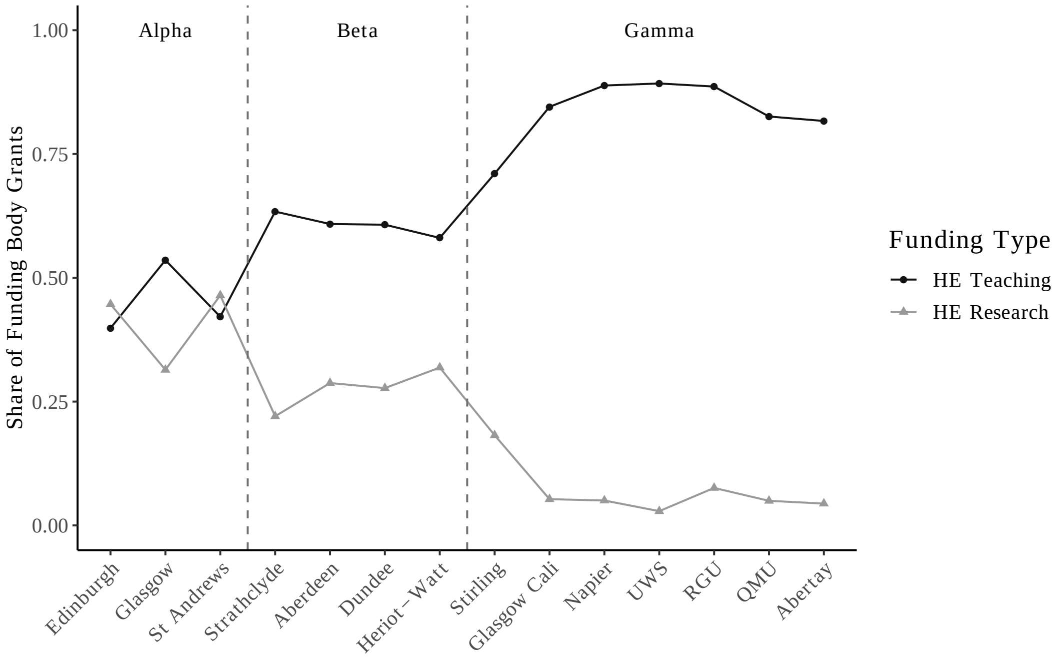


Figure 5.4: Distribution of funding body grants (source: HESA Financial Returns)

volved in research) to show the relative intensity (see Appendix C).[51] This allows taking into account the diversity among Scottish universities with regard to size, strategic focus, and history as these differences have manifested over decades and even centuries. From this analysis, the following three generic universities are established:

1. *Alpha*, constructed from the University of Edinburgh, the University of Glasgow, and the University of St Andrews;

2. *Beta*, constructed from the University of Aberdeen, the University of Dundee, Heriot-Watt University, and the University of Strathclyde; and

3. *Gamma*, constructed from the University of Abertay Dundee, Edinburgh Napier University, Glasgow Caledonian University, Queen Margaret University Edinburgh, Robert Gordon University, the University of Stirling, and the University of the West of Scotland.

Differences between the universities that form the basis of each generic university can also be observed when comparing the relative share of research and teaching grants from the UK funding bodies (see Figure 5.4).

[51] The number of collaborative research projects is not reported, only the income generated for each university.

Table 5.1: Characteristics of the three generic universities, showing median values for year when the university was established, staff and student numbers (median of the averages for 2008/09-2014/15), and absolute number for the prevalence of medical schools.

	Alpha	**Beta**	**Gamma**	**Source**
Established (year)	1451	1851	1888	University websites
Students FTE	21,975	12,075	9,588	HESA Students
Academic staff FTE	2,240	1,263	526	HESA Staff
- teaching only	206	136	32	HESA Staff
- research only	903	490	44	HESA Staff
- research & teaching	1,131	636	450	HESA Staff
TTO staff FTE[1]	13.5	32.0	11.2	HESA Staff
Medical school	all (3/3)	some (2/4)	none (0/7)	University websites

Notes:
[1] Data only available for 2008/09-2012/13.

5.3.2 University Characteristics

The three generic universities derived from all Scottish universities have distinct characteristics and resource bases. The main characteristics based on the median values of the respective universities, averaged over the academic years 2008/09 to 2014/15, are compared in Table 5.1. The aim of this table is to give a general impression of what these three generic universities look like, which is important to consider when interpreting the simulation results but also when looking at the entrepreneurial activities of these universities and how they are embedded in the bigger picture.

These difference in the organisational configurations and resource bases influence the Third Mission of these three generic universities, as demonstrated by the similar findings from different clustering analyses by Geuna (1998) and Rossi & Rosli (2015). Research-intensive universities, i.e. the Alpha-type universities, are more likely to be active nationally and even globally, whereas Gamma is predominantly engaging with local and regional actors (Abreu et al., 2016). The former generally also show higher levels of income from entrepreneurial activities, particularly from 'harder' activities that involve the transfer of codified IP such as licensing and spin-offs, whereas Beta and Gamma are focused more on 'softer' activities (Sánchez Barrioluengo et al., 2016). For example, Gamma, i.e. teaching-led universities, take more "proactive leadership in regional capacity building and networking, rather than on 'pushing' innovations via the formal knowledge-commercialisation routes" (Abreu et al., 2016, p. 2).

The differences with regard to how often Alpha, Beta, and Gamma have actually engaged in one of the five entrepreneurial activities and the income generated from each activity are plotted in Figures 5.5 and 5.6, respectively. These figures are based on the median values for the respective universities for each year and are normalised by the size of the research base of the university as measured in the number of research-active staff. In contrast to the absolute numbers, Alpha no longer dominates when the size of the university is taken into consideration. This is, however, not necessarily a weakness of the three Scottish Alpha universities but due to the strength and dedication of the four Beta universities. These universities are strategically trying to grow entrepreneurial activities as a means to create impact but also to grow their research base.

Having established the three universities that will be explicitly represented in the simulation, the internal structure that give rise to these behaviours and outcomes will be explored in the following.

5.3.3 University Structures and Processes

This section will now describe the internal structures of universities using CLDs. This feedback structure is based on the existing literature and the interviews and is the same for all three generic universities. Different institutional characteristics of the university influence its engagement with industry (Chapple et al., 2005; Bercovitz et al., 2001). Size of the university (Van Looy et al., 2011; Horta et al., 2016) and whether the university is located in a region with a high concentration of high-tech firms (Friedman & Silberman, 2003) are usually correlated with an increased amount of entrepreneurial activity. Private universities are more efficient at licensing patents compared to public universities (Thursby & Kemp, 2002). While the existence of a medical school is found to increase entrepreneurial activity (Mowery et al., 2001; Feldman et al., 2002), universities with medical school are also less efficient in terms of licensing than those without (Thursby & Kemp, 2002). The relevant differences will be implemented when parametrising the simulation model in Chapter 6. In the following, the model will be presented in incremental steps and rationales for the variables and links are described accordingly. For the sake of clarity, the "+" label for all positive links is left out and only negative links are labelled with a "-".

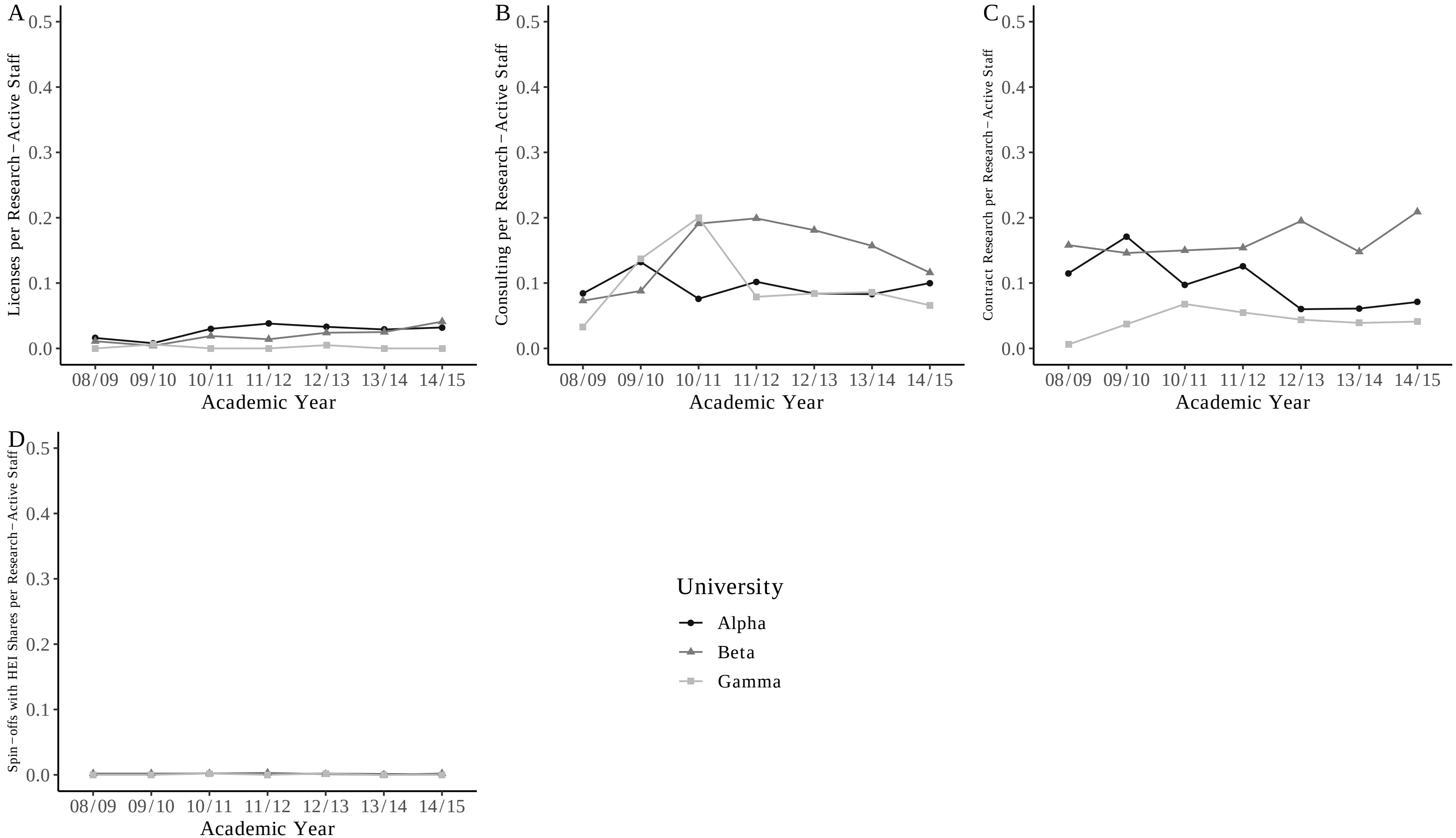


Figure 5.5: Number of entrepreneurial activities per research-active staff for licensing (A), consulting (B), contract research (C), and spin-offs (D) based on the median for the respective universities that constitute Alpha, Beta, and Gamma, respectively, for each year (source: HE-BCI B; no data available for collaborative research)

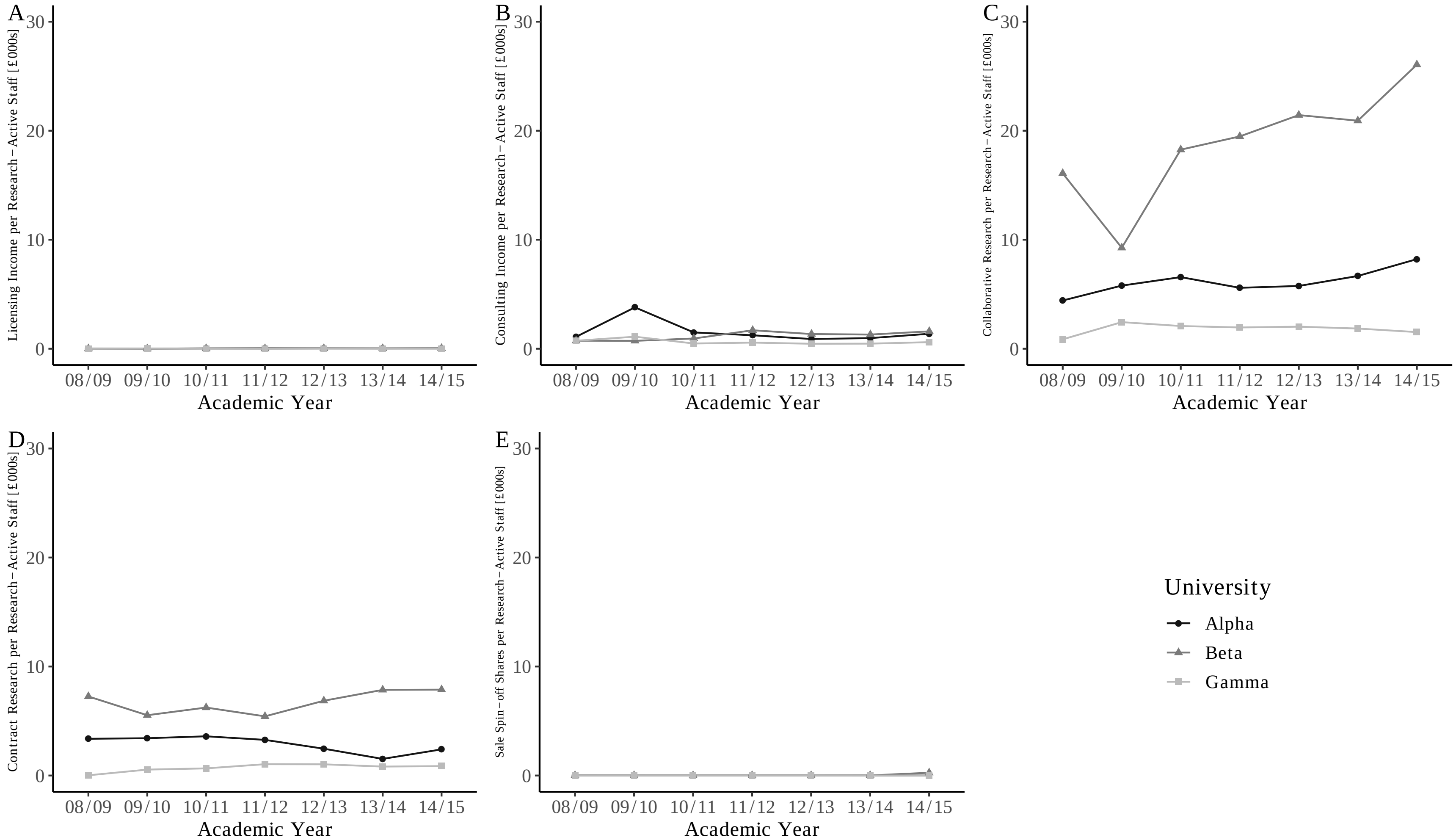


Figure 5.6: Income from entrepreneurial activities per research-active staff licensing (A), consulting (B), collaborative research (C), contract research (D) and spin-offs (E) based on the median for the respective universities that constitute Alpha, Beta, and Gamma, respectively, for each year (source: HE-BCI B)

5.3.3.1 Research

All entrepreneurial activities are related to total university R&D expenditures and the quality of research (Algieri et al., 2013; Davey et al., 2016; Link & Scott, 2005; Markman et al., 2004; Meoli & Vismara, 2016; O'Shea et al., 2005). A key aspect is the notion of 'independent research', which distinguishes universities from non-academic (contract) research organisations (Norn, 2016). Research performance strengthens entrepreneurial performance over time, which, in turn, supports research "through positive mediation between past and future research" (Sengupta & Ray, 2017, p. 881). The relative effect of research on entrepreneurial performance declines with an increase in research quality, i.e. the relative gains for Beta and Gamma are higher if they were to increase their research (Sengupta & Ray, 2017). Representatives from universities that form the basis for each of the three generic universities have highlighted the importance of their research and how this attracts companies. However, for Beta and Gamma it was more about research prestige in certain areas, whereas for Alpha it was the overall, institutional prestige based on the research excellence.

This study neither distinguishes between basic and applied research nor looks at distinct scientific disciplines. A binary distinction between basic and applied research is hard to establish both conceptually and empirically and would also neglect feedback between more basic and more applied types of research (Hughes & Kitson, 2013; Rosenberg, 1994; Mokyr, 2002). Furthermore, the share of basic research is higher for Alpha compared to Beta, and Gamma is even lower, but the available data does not allow for such a fine-grained analysis on a national level that includes all universities. In line with this, there is also no distinction between scientific fields (and, consequently, industries on the companies' side - see Section 5.4.1) due to a lack of available data and ambiguity even within the disciplines. This level of detail is also not required to answer the research questions. Therefore, the only distinction is between industry-(co-)funded and independent (non-industry-funded) research, as the former usually includes IP agreements and prevent further licensing or spin-off opportunities. In the model, 'research' is represented by the number of FTE staff involved in research activities because (1) research and the five entrepreneurial activities are inherently based on 'people' and (2) the model looks at what academics actually do, i.e. in terms of their salary costs a 'pure' researcher and an academic who engages with industry look the same, yet they perform different activities.

5.3.3.2 Patenting and Licensing

Licensing, the traditional technology transfer process, has been the starting point and locus of attention for decades with regard to university-industry interactions (Friedman & Silberman, 2003; Siegel, Waldman, & Link, 2003). The general process of invention disclosure, patenting, licensing, and collecting financial returns is well documented in the literature (see e.g. Siegel, Waldman, Atwater, & Link, 2003; Bradley et al., 2013) and is illustrated in the CLD in Figure 5.7. Summative content analysis of the interviews shows that all eleven participants, who were asked about licensing, have confirmed this licensing process within their institutions.

The patenting process and any subsequent commercialisation processes formally start with an invention disclosure by the academic. An invention disclosure is "the document filed by a faculty member when she believes that she has a commercializable invention" (Thursby & Thursby, 2011, p. 1077) and are usually filed at a very early stage in the R&D process when the technology is still in a very embryonic state (Thursby et al., 2001).

All invention disclosures are then reviewed by TTO staff and typically discussed with the academic with regard to their aspirations, the potential of the technology and how quickly it could be commercialised, prior engagement with industry, among others (Goldhor & Lund, 1983; Litan et al., 2007; Thursby & Thursby, 2002, also confirmed by interviewees). They will also search patent databases for any prior work or conflicts before making a decision regarding the patentability of a particular disclosure. Patenting comes at a high cost to the TTO (Meyer-Krahmer & Schmoch, 1998; Shane, 2004b), which have a limited budget for IP protection and must therefore scrutinise all opportunities to use their budget optimally. All interviewees stated they scan the commercial potential and also look for initial interest from industry. Some interviewees indicated they only patent if there is a clear demand and a licensing opportunity on the horizon due to the high costs for patenting, whereas a few universities are able to take chances with some inventions and patent even in the absence of current demand from industry. These insights confirm previous academic research on the necessity of concrete licensing opportunities before filing a patent application (Hsu & Bernstein, 1997; Jensen & Thursby, 2001; Mowery & Ziedonis, 2002; Shane, 2004b; Siegel & Phan, 2005; Siegel, Waldman, & Link, 2003).

The main challenge for licensing is identifying potential licensees. A lack of interest from industry caused by the uncertainty around the commercial potential or the embryonic nature of the invention, among others, does often lead to the formation of a spin-off (Etzkowitz & Goktepe, 2005). During the licensing negotiations and even at the point of finalising a licensing deal, the majority of inventions are still at an early stage of development (Thursby et al., 2001). This lack of technological readiness and the relatively low number of potential licensees make this process very time consuming (Shane, 2004b) and requires extensive interaction between the involved parties (Hsu & Bernstein, 1997; Shane, 2004b; Thursby et al., 2001). A crucial factor is the involvement of the academic (Poyago-Theotoky et al., 2002; Thursby et al., 2001).

The royalty income from licensing is typically split among the academic inventors, their department or faculty, and the university. The majority of the profit after all costs have been accounted for (e.g. patenting, external legal support) get re-invested in research (Siegel & Wright, 2015a). In this model, the split among these parties is not included. The faculty will use the income to e.g. provide academics with a budget for travelling or equipment, academics typically keep the money in their university accounts for research support; while this money is not necessarily used to hire new staff, it does support their research and might even free up some of their time because they are able to hire assistants. The relative income from licensing is marginal compared to general staff budget, which makes it a reasonable simplification to model this increase in additional research time and research support as additional staff.

A common theme in the literature and among businesses is that universities overvalue the importance and monetary value of their patents (Karnani, 2013) or are, in general, too expensive to work with. Much of this dispute is caused by asymmetric information (Macho-Stadler et al., 1996, 2007). Typically, firms cannot assess properly the quality of the invention ex ante, whereas researchers and even TTOs may find it difficult to assess the commercial profitability of their inventions. Due to a combination of limited commercial experience on the side of the TTO and their aggressiveness, in part because they are incentivised to maximise income generation, potential buyers and licensees are unwilling to meet the high valuation because of the uncertainty of generating future income streams from it (Clarysse et al., 2007). Larger TTOs may also have an incentive to shelve some projects, in order to build a reputation for only delivering high-quality projects, thus raising buyers' beliefs of expected quality (and less licenses in total but a higher return per license) (Macho-Stadler et al., 2007). Similarly, there is often a lack of understanding among companies regarding the costs of R&D, which leads to the belief that universities over-charge for certain services.

The interviews have demonstrated that this is the subject of many negotiations, but all universities stated they usually try to make collaborations and deals work as opposed to trying to maximise income. The general tone was that once a discussion reaches the issue of money, they will typically find a solution, which means the terms do not directly impact the demand as long as they are within reasonable bounds. Licensing terms as well as the terms and conditions for any other activity are, therefore, not included in the CLD.

5.3.3.3 Spin-offs

University spin-offs are diverse across a variety of characteristics (Hayter et al., 2018), including their business models (Druilhe & Garnsey, 2004; Mustar et al., 2006; Clausen & Rasmussen, 2013) and activities such as technical services, consulting, and technical manufacturing (Walter et al., 2006); the resources they require and employ (Heirman & Clarysse, 2004; Mustar et al., 2006); or their ambition, ranging from venture capital-backed high-growth to lifestyle companies (Wright et al., 2007). Universities are diverse and produce different ventures based on "their strengths, historical contexts and external environments" (Marzocchi et al., 2019, p. 184). As a result, there are different ways spin-offs can contribute to economic development and knowledge valorisation (Schillo, 2018), but also different types of support they require from the university ecosystem. When designing spin-off policies, differentiation must be made between promoting spin-off creation and enabling spin-off success (across different outcome measures such as survival, development, and performance) (Hayter et al., 2018).

The typical process for spin-off generation is similar to the licensing process and follows an invention disclosure, patenting, and then license that patent to a spin-off, usually in exchange for equity (Shane, 2004a). All twelve interviewees who were asked about spin-offs described this process of spin-off creation within their respective university in a similar way. Recent studies have, however, shown that this is not how the majority of spin-offs and staff start-ups are formed. The share varies between only 33.3% of all new businesses are based on disclosed and patented inventions (Fini et al., 2010) and 45% using codified knowledge from the parent university (Karnani, 2013). Spin-offs that are not based on codified knowledge are widely spread across all disciplines. In many universities, academics still need to file an invention disclosure, which is then reviewed by the TTO and appropriate support is provided, regardless of whether or not there is codified IP involved.

These routes are included in this model in three ways as illustrated in Figure 5.7, which reflects the definition of spin-offs used for this thesis (see Section

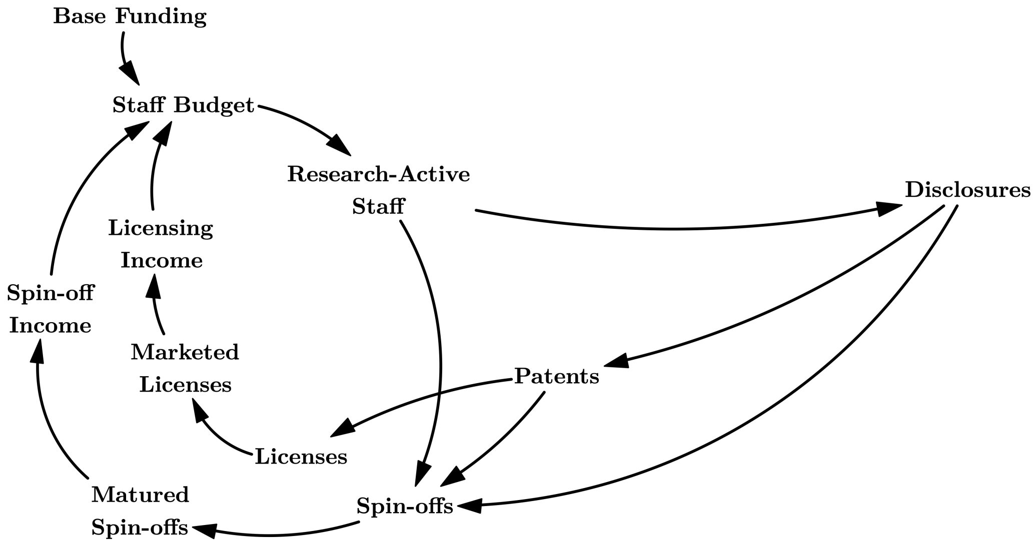


Figure 5.7: CLD 1: licensing and spin-offs

2.3.3.2) and the data collection by HESA. Spin-offs can be based on patents (corresponding to formal spin-off with partial university ownership in the HESA data), disclosures (other formal spin-offs), or academics (staff start-ups). Spin-offs will then also be represented as a new company agent (the details will be provided in Section 5.4). These agents will, if they are successful and get to market, eventually create revenues for the university.

5.3.3.4 Consulting

Academics can apply their knowledge and skills via consultancy and contract research without having to acquire additional skills and taking on the burden of creating spin-off company, yet still generate further income either personally or for their research (Klofsten & Jones-Evans, 2000). This also leads to complementarities between teaching, research, and consulting (Mitchell & Rebne, 1995). Consulting has been described by different interviewees as an effective means for scoping out the potential larger collaborations between universities and businesses due to the clearly defined goals, the relatively short duration, and, by extension, the lower financial commitment. Nevertheless, continuous and (even occasional) close interactions, for instance in the form of joint research, contract research and consulting, are likely to have a lasting impact on both parties involved (Hottenrott & Lawson, 2014).

Consulting, like licensing and any other activity considered in this model, is initiated by a company from the agent population. Since this is outwith the module boundaries, consulting is included as a 'free-standing' variable, i.e. without being influenced by any other variable, at this point in the CLD in Figure 5.8.

5.3.3.5 Contract Research

Contract research for individual firms as well as consulting are the most frequently used types of university-industry interaction and typically involve working on a targeted research project (Santoro & Chakrabarti, 2002). Entrepreneurial companies are less likely compared to established companies to engage in contract research, most likely because their problems are typically not well-defined and therefore less suitable for this type of interaction (Shane, 2002a). Similar to licensing and spin-offs, Alpha and Beta are more likely to be involved in contract research and other 'problem-solving' activities compared to Gamma (Abreu et al., 2016). Additional factors include TTO characteristics and the university's location (Berbegal-Mirabent, Sánchez García, & Ribeiro-Soriano, 2015). While industry-funding can impose restrictions on academics with regard to publishing and secrecy, which can interfere with building an academic reputation (Florida, 1999), academics involved in industry-funded research are at least as academically productive as those who are not (Blumenthal et al., 1996; Van Looy et al., 2004). However, they do restrict their communication with peers, which can harm the university culture and hinder progress in a scientific field in general (Blumenthal et al., 1996). Similar to consulting, contract research is seen as an appropriate activity for initial engagement among new partners, particularly if public support through e.g. innovation vouchers can be leveraged to lower the costs for the companies (see also Appendix D.1).

The interviews have confirmed that income from contract research is treated as regular research income and is typically used for equipment and staff costs. In particular, contract and collaborative research depend on the availability of research assistants and (depending on the field) technicians to operate the equipment. While a small percentage might be used to buy out time of the leading academic, this is neglected for the simplicity of the model in light of the marginal gains in accuracy. Contract research, like consulting, is represented as a 'free-standing' variable (see Figure 5.8).

5.3.3.6 Collaborative Research

Engaging in collaborative research has a number of potential benefits, including increasing research funding (Lee, 2000; Grimaldi & von Tunzelmann, 2002); new and valuable insights for the involved academics as well as opportunities for testing the practical applicability of their work (Lee, 2000); access to equipment owned by industry; and the adoption of new standards (Grimaldi & von Tunzelmann, 2002). The interviews have highlighted that collaborative research is seen as more intellectually stimulating by academics compared to contract research and consulting, which is consistent with previous studies (Meyer-Krahmer & Schmoch, 1998). Many of these projects are considered 'pre-competitive' and they are typically supported by additional public funding (Perkmann, King, & Pavelin, 2011). In contrast to contract research they are usually multi-actor collaborations and of a much larger financial volume.

This model only includes dyadic relationships and focuses on the way that interactions between industry and academia emerge. This is purely a simplification to reduce the computational effort and model complexity without compromising the insights the model presents for answering the research questions. Consequently, consulting, contract and collaborative research are implemented in the same way in the model (see Figure 5.8). The only difference is that consulting income goes towards the general staff budget, whereas contract and collaborative research allow hiring project-based staff such as research assistants.

In line with the definitions set out at the beginning of this thesis (see Section 2.3.3), the sum of these five entrepreneurial activities is the total amount of 'academic entrepreneurship' that the university is involved in at any point in time.

5.3.3.7 Entrepreneurial Academics and Capacity

Entrepreneurial academics are defined as "academic faculty members who adopt an entrepreneurial outlook, seeking opportunities to support their research objectives by engaging with commercial partners in a range of formal and less formal modes of engagement" (adopted from Miller, Alexander, et al., 2018).[52] There is usually a small number of academics who are involved in a large number of activities (Agrawal & Henderson, 2002; Balconi et al., 2004; Markman, Gianiodis, et al., 2005). On the one hand, this is due to the limitations that some scientific fields pose with regard to their relevance for companies and most universities only have a very limited number of research outcomes that have commercial potential (Grimaldi et al., 2011). The intensity of academics involved in entrepreneurial activities is a result of the "commercial orientation" of the university research (Di Gregorio & Shane, 2003). On the other hand, academic rationales are con-

[52]Miller, Alexander, et al. (2018) distinguish between entrepreneurial academics (with a focus on informal activities, based on the distinction made in this thesis) and academic entrepreneurs (with a focus on formal activities). Here, *entrepreneurial* refers to all activities involving commercial partners.

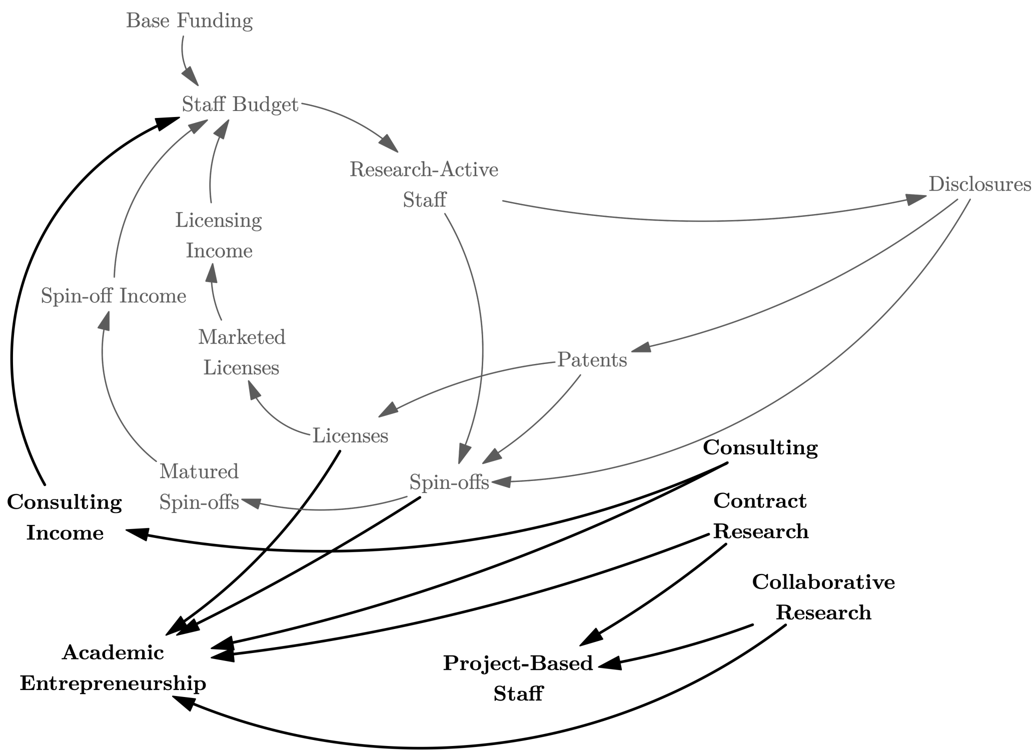


Figure 5.8: CLD 2: consulting, collaborative and contract research (the added variables and links are shown in black, the previously developed CLD is shown in grey)

flicting with entrepreneurial motivations (Perkmann & Walsh, 2008; Welsh et al., 2008; Toole & Czarnitzki, 2009; Huyghe, Knockaert, Piva, & Wright, 2016), particularly the 'publish-or-perish' culture in academia (Bennis & O'Toole, 2005) and the restriction that these activities put on the communication with peers (e.g. problems for 'open science', academic networks, publications) (Blumenthal et al., 1996; Welsh et al., 2008).

Academics must balance where they direct their attention to in line with their contracts and their university's priorities (Johnson et al., 2017). This "lack of time to fulfil all university roles" is the most substantial constraint to working with external organisations in Scotland as named by 51.7% of all academics (more prominent for Gamma-type universities with 62.7% compared to Beta 51.7% and Alpha 45.8%) (Hughes et al., 2016). In the US, for example, academics spend on average 3.1% of their time collaborating with researchers in industry (9% on average when excluding those with no industry engagement at all) (Ponomariov & Boardman, 2008).

The small number of entrepreneurial academics can have potential diminishing effects on research and teaching and can result in an 'demand overload' for universities (Clark, 1998; Poyago-Theotoky et al., 2002, see also Section 2.3.5).

However, existing studies have also not found a decline in basic research due to increased amount of entrepreneurial activities (Welsh et al., 2008; Thursby & Thursby, 2011; Siegel & Wright, 2015b) and even identified complementarities between entrepreneurial and scientific activities (Carayol, 2003; Owen-Smith, 2003; Van Looy et al., 2006; Landry et al., 2010) as well as an interplay between entrepreneurial and scientific passion (Huyghe, Knockaert, & Obschonka, 2016). Nevertheless, if universities want to grow their entrepreneurial activity and industry engagement, they have to increase the number of entrepreneurial academics. The importance of entrepreneurial academics as well as their characteristics and motivations are also an emerging theme from the interviews (see Appendix D.3). Entrepreneurial academics are important for fostering individual networks, which has been highlighted by the interviewees and also discussed in Section 2.5.3.

For the model, it is therefore not the amount of research-active staff but the entrepreneurial share of research active staff who are disclosing inventions and get involved in entrepreneurial activities in general. The total number of entrepreneurial academics and the workload allocation for these activities and research at their respective institutions define the entrepreneurial capacity of each university. If the amount of academic entrepreneurship exceeds this capacity, there are potential detrimental effects on independent research, which will also be noticed by industry, as the interviews have indicated. Furthermore, consulting, contract and collaborative research opportunities cannot be pursued due to time constraints of the available academics. This is represented in the CLD in Figure 5.9.

5.3.3.8 Entrepreneurial Reputation

The literature has traditionally focused on the overall university reputation and its 'halo effect' on entrepreneurial activities in general (Mansfield & Lee, 1996; Tornquist & Kallsen, 1994) as well as particular activities such as collaborative research (Schartinger et al., 2001) or licensing (Sine et al., 2003, see also Section 2.5.1). Research excellence, either at the institutional level (mainly for Alpha) or in specific scientific areas or even individual labs (mostly for Beta and Gamma) are an important criterion for companies before approaching a particular university. This has been extensively highlighted throughout the interviews (see Appendix D.6).

In addition to the research prestige, companies also consider the entrepreneurial reputation of a university (see Section 2.5.2). Particularly Alpha is very aware of its (global) reputation, whereas interviewees from Beta and Gamma focused more

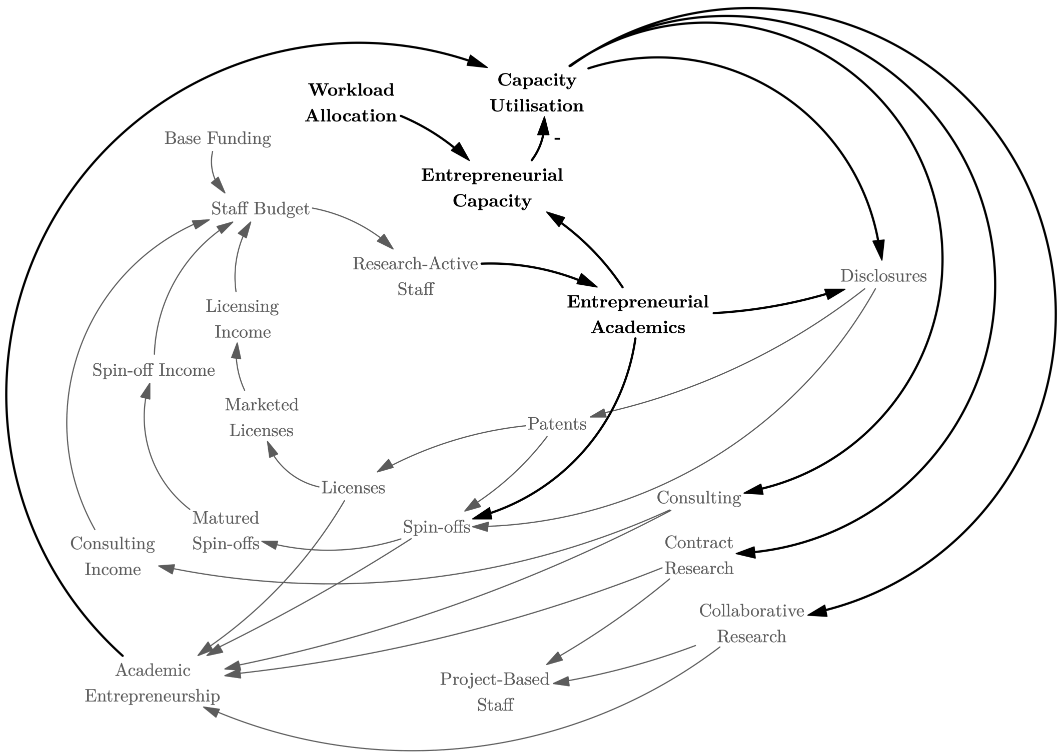


Figure 5.9: CLD 3: entrepreneurial academics and capacity

on this type of reputation and how the university is strategically trying to use it to complement its research reputation in particular areas to attract companies.

Cultivating an entrepreneurial reputation can contribute to a 'pull' from the ecosystem, i.e. increased industry demand (see Section 2.5.7). The demand for engaging with a particular university can essentially be defined as:

$$Demand = f(Need\ for\ Input,\ Reputation\ of\ the\ University). \tag{5.1}$$

The entrepreneurial reputation will not necessarily influence the need for external input among companies, but their preference with which university they want to work. It is mainly influenced by past experiences of working with a particular university and the word-of-mouth effect among companies. The interviews have highlighted that most universities are well aware of these effects and try to actively influence their reputation to the best of their ability. Other factors that were considered relevant include the signalling effects from awards such as 'Entrepreneurial University of the Year' or ranking such as most innovative universities.

Entrepreneurial reputation and industry demand are shown in the CLD in

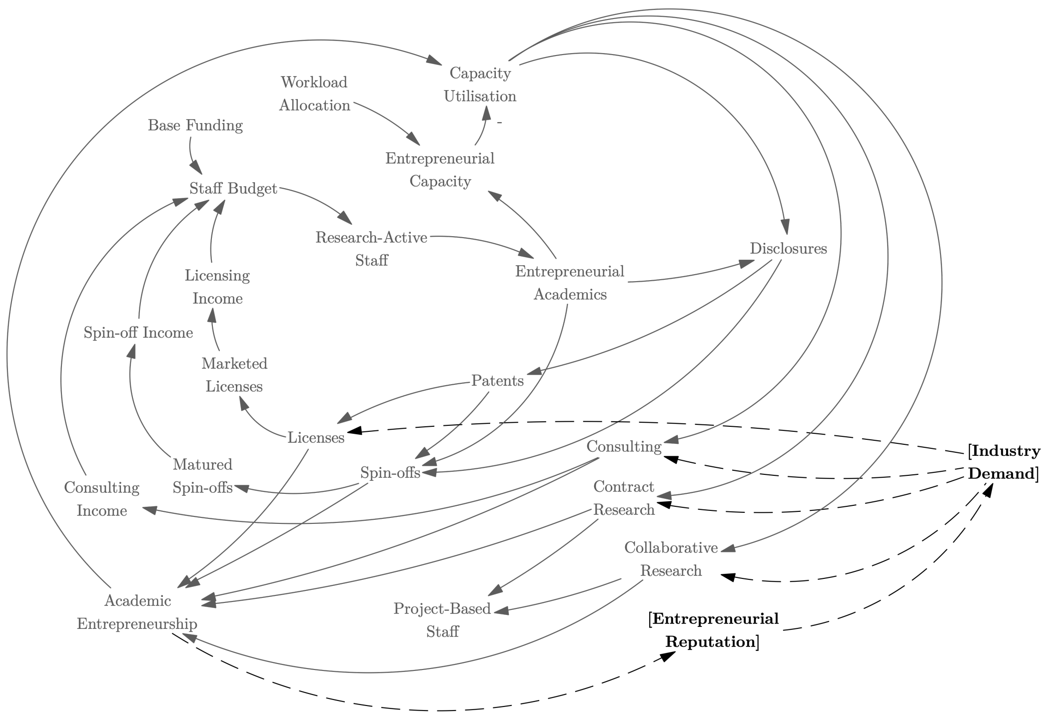


Figure 5.10: CLD 4: entrepreneurial reputation and industry demand

Figure 5.10 to illustrate the feedback effects, but they are not actually modelled in the SD modules. The crossing of the module boundaries within the HS is highlighted by the dashed lines and variables within squared brackets are modelled in the ABM module and not part of the SD module.

5.3.3.9 Internal Marketing (Supply Stimulation)

Three other main themes emerged from the interviews, namely internal marketing (Appendix D.4), external marketing (Appendix D.5), and the importance of partnerships as opposed to *ad hoc* interactions with companies (Appendix D.7). Internal marketing considers any efforts by the university to increase the number of entrepreneurial academics through a mix of incentives, developing skills, awareness and appetite, and the right hiring policies, to name a few of the mechanisms that emerged from the interviews. It is, by extension, therefore a tool for stimulating the supply side of academic entrepreneurship.

Before exploring internal marketing in more depth, it should be noted that the TTO is not represented explicitly in this model, yet its influence is included in multiple ways. TTOs are involved in different ways in all five activities that are included in this model, from handling IP issues and serving as a first point of contact for firms to negotiating terms and finalising agreements (Comacchio et al., 2012; Bradley et al., 2013; Brescia et al., 2016; Huyghe, Knockaert, & Obschonka, 2016; Huyghe, Knockaert, Piva, & Wright, 2016). This is, however, recognised in the model despite not being explicitly represented. For example, disclosure or patenting rates are influenced by the number of TTO staff and their resources. The parameters presented in the next chapter are based on the current TTO characteristics and need to be interpreted in this context. An increase on TTO resources would influence the support for academic internally but also finding licensees and other externally-facing activities (e.g. Caldera & Debande, 2010; Berbegal-Mirabent, Sánchez García, & Ribeiro-Soriano, 2015). However, this is not a relevant aspect for addressing the research questions. Instead of representing the TTO explicitly, the activities that the TTO is involved in such as internal and external marketing will be included in the model.

Growing entrepreneurial activities requires increasing the number of academics that are involved as most interviewees have stated there are a few academics who are heavily engaged in entrepreneurial activities, but this is only a small percentage of the total academic population. However, growing academic entrepreneurship represents a paradox in itself. Entrepreneurial activities depend on the availability of and interest from entrepreneurial academics, yet these academics chose academia in the first place instead of working for private companies or in other non-academic jobs (Grimaldi et al., 2011). For example, an academic who pursues basic research might not disclose an invention regardless of its commercial potential (Thursby & Thursby, 2002). Therefore, not every academic can be or should be encouraged to become more entrepreneurial.

The model does not differentiate between different ways of incentivising academics or raising their awareness. Internal marketing is the combination of a reinforcing (increased rate of academics becoming more entrepreneurial due to peer effects and active marketing) and a balancing loop (it gets increasingly hard to recruit academics the smaller the percentage of non-entrepreneurial academics) as shown in Figure 5.11.

5.3.3.10 External Marketing (Demand Stimulation)

External marketing involves all means to increase the demand from industry. This includes both stimulating the need for input among companies as well as increasing the likelihood to be the preferred academic partner for companies, i.e. both factors of 'industry demand' from Equation 5.1. While universities might have an intrinsic motivation to pursue external marketing to grow their academic entrepreneurship, there have previously also been calls for more incentivisation of this behaviour and to re-focus and increase the Higher Education Innovation

Funding (Witty, 2013). Means for external marketing include, sorted by their prevalence among American universities, personal interactions of TTO staff with industry and building relationships; exploring, expanding and intensifying relationships of the inventors; direct communication/approaching potential partners; as well as websites, meetings, and attending trade shows and industry conferences (Thursby et al., 2001). These efforts are most important in scientific or technological areas in which there are either no links at all between the university and industry or the links are weak (Colyvas et al., 2002). Particularly non-top-tier institutions, i.e. Beta and Gamma in this case, must be more proactive in external marketing (Siegel et al., 2004). In this study, the focus is on individual universities demonstrating that they in particular are the most suitable partner for collaboration, highlighting their industry-friendliness and experience in working with businesses, i.e. increasing the likelihood if being the preferred partner without increasing the general need for input.

There are no studies available in the context of university-industry interaction, but given the time constraints of academics with regard to entrepreneurial activities, there is most likely a ‘sales lead black hole’ based on the contacts that a more externally engaged TTO might imitate. In many industries, up to 70% of all leads that are initiated are not followed up (Sabnis et al., 2013) and this number would probably be at least as high among academics. A suggestion that came through in the interviews was to pair commercial business developers with academics in the first place and try to engage with businesses collaboratively, attend conferences, etc.

External marketing, while an activity performed by university staff, is implemented via the ABM module because the preferred university partner is a characteristic of each individual agent. Due to the lack of reliable data and the magnitude of opportunities in how external marketing can be realised, there will be no costs or resources attached to it within the SD module. How the external marketing works at the firm level will be described in Section 5.4.2.9 and the effects of both internal and external marketing as well as a combination of both will be explored in different scenarios in the next chapter.

The interviews have also highlighted the benefits of combining external marketing efforts from TTO staff and academics, e.g. when attending conferences together (see Appendix D.5). Particularly for developing organisational proximity, engaging with businesses with the aim of generating new interactions should be seen as a “partnership between academics and professional services” (B45). In addition to co-attending conferences, Scottish universities have hosted a series of

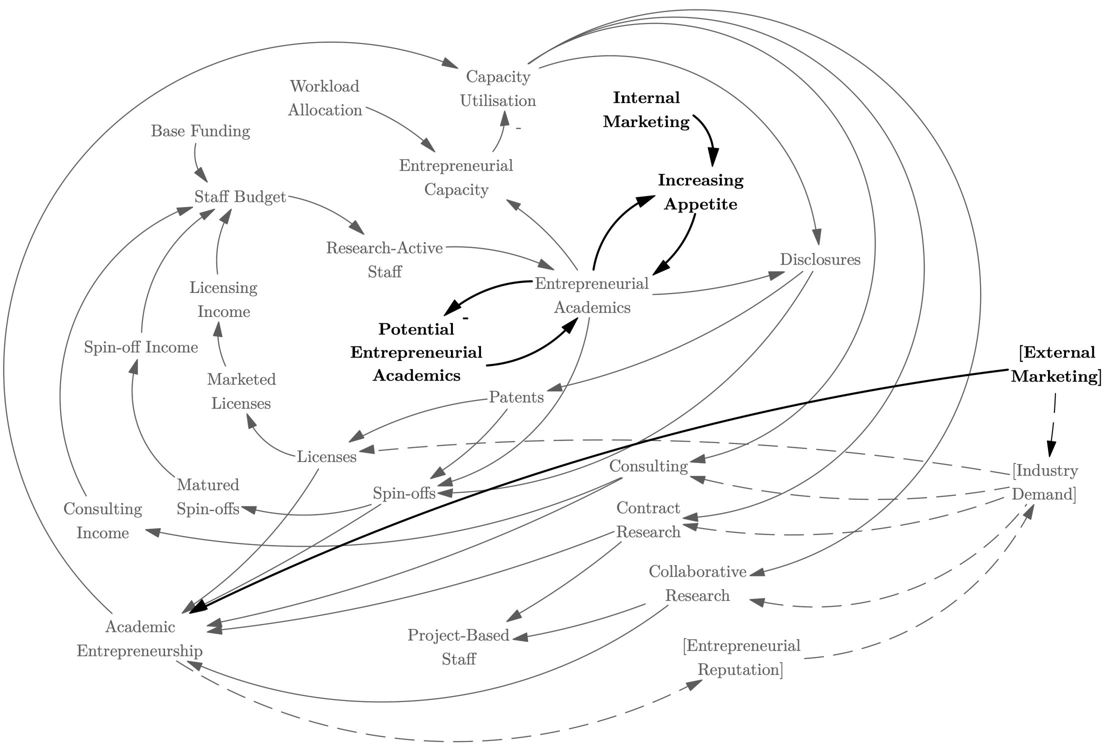


Figure 5.11: CLD 5: internal and external marketing

engagement events (B41) and invited companies to 'problem-solving days' (B21) or workshops for industry and academia within a certain sector or focused on a specific problem (A12).

5.3.3.11 Partnerships

The third main theme that emerged are partnerships, which have already been briefly introduced when applying the complex events concept to entrepreneurial universities (Section 3.7.4). A few studies have highlighted the importance of repeated interactions with the local ecosystem to foster an 'entrepreneurial spirit' (see e.g. Bramwell & Wolfe, 2008), but this is still an underdeveloped concept in the literature (Belderbos et al., 2015). Universities engage in many rather superficial activities with different partners as a search mechanism to identify those companies that they want to form long-term relationships with (Dahlander & McFarland, 2013). The most common examples are consulting and contract research, as previously described, but essentially all collaborations with universities improve performance once firms have been persistently engaged with universities (Belderbos et al., 2018). This is summarised by one interviewee:

> "So the fact that they are more likely to come here and knock on the door is one thing that follows from the institutional reputation.

> Once they started the project, they would continue and they will expand, that depends obviously on the performance of the individuals and their relationship they build up with those individual academics alongside the continued institutional support. Again, there's some nice cycles there." – B41

Company agents interacting with one of the universities will develop organisational proximity with that university, particularly if the interaction was considered a success, which encourages companies to adapt. This will, in turn, increase their likelihood of working again with this university on the future. This model, hereby, follows a similar pattern to other computational models of trust and reputation, which are based on a virtuous cycle involving reputation, trust, and reciprocity (Mui et al., 2002).

Partnerships cannot be represented explicitly in this CLD. SD provides a high-level perspective of the system and is based on aggregated values, which does not allow tracking individual agents through the system. Partnerships are the essence of research question Q3 and are, hereby, part of the rationale for the HS in the first place. They are conceptualised through complex events and will be implemented in the ABM module.

5.4 Company Agents

This section considers the second type of agent modelled explicitly in the ecosystem: companies. ABM has been selected for this part of the HS mainly in response to research questions Q3 (modelling heterogeneity and individual interactions that can be tracked easily) and Q4 (evolutionary dynamics and the interactions among different actors in an ecosystem). While ABM could potentially be used to address Q1 and Q2 as well, it would be very inefficient and both labour-intensive to construct the model as well as compute-intensive to run it (the full discussion is provided in Section 3.5).

ABMs contain a finite number of agents, in this case m company agents a_i. Company agents cannot die (i.e. companies going out of business), nor are new independent agents created throughout a simulation run (i.e. new start-ups). The only exception to this is the creation of spin-off agents (as previously described in Section 5.3.3.3) and them potentially maturing (details about their behaviour are provided in Section 5.4.2.2). In evolutionary models, firms are usually subject to a fitness function, which determines their health and affects their behaviour (see e.g. Dosi & Nelson, 1994). However, this requires the simulation of market

Table 5.2: Characteristics and rules of company agents

Company agent
Characteristics: - Size - Spin-off - Innovativeness - Propensity for collaboration - University preference - Experience
Rules: - Select entrepreneurial activity - Select university partner - Evaluate success - Update university preference - Update need for collaboration - Marketing - Networking

dynamics, which is beyond the scope of this work. The total company agent population A is defined as:

$$A = \{a_0, a_1, a_2, ...a_{m-1}\}. \tag{5.2}$$

Company agents are defined by their characteristics and their rules. A general overview of the agent design is provided in Table 5.2. The remainder of this section is divided into two parts, which describe the agents' characteristics (Section 5.4.1) and their rules and behaviour (Section 5.4.2).

5.4.1 Company Characteristics

Each agent has six characteristics, namely size; whether or not it is a university spin-off; innovativeness; propensity for collaboration; university preference; and experience. Values for all of these are generated when the agent is initiated. Firm size; whether or not it is a spin-off; and innovativeness are static characteristics that remain constant throughout the simulation. The other three are dynamic, changing as a result of interactions with universities or other agents. The six characteristics, their rationale, influence, and measurement will be described in the following subsections.

There are also other factors that influence the collaboration patterns of companies. For example, existing research has demonstrated that there are clear differences between industries in terms of the engagement with universities. Pharmaceuticals, for example, is a particularly significant case due to the huge emphasis on basic research (see e.g. Jaffe, 1989; Cohen et al., 2002). In this study, differences between industries will not be considered. First, the ecosystem concept emphasises inter-industry learning and there is learning within the university structure that cuts across industry boundaries. Second, the university data does not include any information about the scientific field or the industry of the collaborating partner and the disciplinary origin of the knowledge is not considered in the SD model of the universities. Therefore, including industry as an additional characteristic would lead to an increase in the number of assumptions without providing additional benefits for this study.

Similarly, whether the firm is part of a group, either domestically or foreign-owned; the regulatory environment and standard-setting issues; customers' responsiveness to innovation; economic or financial risk of innovation; lack of information on technologies and/or markets affects their propensity to engage with universities (Tether, 2002, p. 955-956). Network structures are not included in this model, which make the inclusion of parent organisations and their impact harder to implement. The remaining issues are mostly industry-specific and are therefore not modelled explicitly. As the model is parametrised based on data from UK companies who operate across all industries, some of these issues are reflected in the data and the parameters of the simulation.

5.4.1.1 Firm Size

A key characteristic of all agents is their size. In addition to industry classification, size is the other widely-used variable in the study of innovation (Tether, 2002). A variety of studies across different settings and industries have demonstrated that size is related to the number and particular patterns of innovative activities in general (e.g. Andrade Rojas et al., 2018; Teirlinck, 2017; Tether, 2002) as well as learning effects in interacting with universities in particular (e.g. Hewitt-Dundas et al., 2019; Santoro & Chakrabarti, 2002; Segarra-Blasco & Arauzo-Carod, 2008). Large firms (1000+ employees) are much more likely to engage in collaborative research (Fontana et al., 2006, see also Laursen & Salter, 2004; Cohen et al., 2002; Mohnen & Hoareau, 2003).[53] However, the data that is used for many studies is not representative and biased towards larger firms (and also those working in tech-related fields) (Tether, 2002). As a result, the proportion of innovative activity and collaboration is usually too high.

This issue is addressed in this model. Firm size is introduced as a categorical variable based on the number of employees. The number of employees, as opposed to e.g. revenue, is used because all activities that are considered in this thesis are based on human interactions. When using employees as the basis for

[53] Some studies have found size (and R&D intensity) not to be significant (see e.g. Eom & Lee, 2010; García-Aracil & Fernández de Lucio, 2008).

describing firm size, common approaches are (1) using the logarithm of the number of employees (Andrade Rojas et al., 2018) and (2) categorising firms based on the number of employees or the logarithm (Hewitt-Dundas et al., 2019). In line with how the government categorises businesses by size (Rhodes, 2015) and how data for the CBR Business Survey[54] are collected, the size S_i of an agent a_i is defined as:

$$S_i = \begin{cases} 1, & \text{for 5-9 employees;} \\ 2, & \text{for 10-49 employees;} \\ 3, & \text{for 50-249 employees;} \\ 4, & \text{for 250+ employees.} \end{cases} \tag{5.3}$$

5.4.1.2 Spin-off

Spin-offs from the three universities are the only means of altering the agent population in this model. In this study, spin-offs include both new companies based on licensing intellectual property from the university as well as those founded by staff based on tacit knowledge (as defined in Section 2.3.3.2). Those based on university intellectual property are 'disproportionately successful' compared to other start-ups (Di Gregorio & Shane, 2003), despite facing additional challenges (e.g. Shane, 2004a; Vohora et al., 2004; Lockett & Wright, 2005; Clarysse et al., 2007; Soetanto & van Geenhuizen, 2015). However, even those companies founded by university staff in the absence of codified university IP typically rely on a high level of human capital. Involvement of the founding academic is, therefore, a key success factor for all spin-offs, which means that at least informal engagement is highly likely.

While large firms benefit the most from public R&D, start-ups benefit more than other SMEs (Cohen et al., 2002). The authors suggest that spin-offs, as part of the start-up population, are already linked to the parent university and are involved in collaboration. In general, innovative spin-offs rely on external knowledge and collaboration as much as any comparable start-up with non-academic founders. In the absence of reliable empirical evidence, it can still be assumed that spin-offs "on average interact on a comparable level, and probably on a higher level given their geographical, cognitive and social proximity" (Zomer et al., 2010, p. 343).[55]

[54]The CBR Business Survey distinguishes between large companies with 250-999 and 1000+ employees, which are combined into one group of large companies of 250+ employees.

[55]An example of the activities and intensity of the interaction between spin-offs and universities based on exploratory case study research is provided by Zomer et al. (2010).

Spin-offs are part of the parent university's ecosystem when they are founded and continue to do so, relying on different actors for their survival (Soetanto & van Geenhuizen, 2015; Prokop et al., 2019). The majority of UK spin-offs has never been part of an incubator, neither a university nor a non-university one, which suggests they are already directly involved in the ecosystem (Hewitt-Dundas, 2015). In this role, spin-offs have also a signalling function and act as an advocate for their parent university. Therefore, whether an agent a_i is a spin-off of one of the three universities is an important characteristic and, in this study, formalised as:

$$O_i = \begin{cases} 0, & \text{not a university spin-off;} \\ 1, & \text{Alpa spin-off;} \\ 2, & \text{Beta spin-off;} \\ 3, & \text{Gamma spin-off.} \end{cases} \tag{5.4}$$

5.4.1.3 Innovativeness

A third principal characteristic of firms that engage with universities is their involvement in R&D activities and the introduction of innovations that are new to their industry (Tether, 2002). Particularly these disruptive, i.e. *new-to-industry* innovations are typically not the result of purely internal R&D but depend on external collaborations (Stringer, 2000). In the UK, innovative activities are "widely dispersed and randomly distributed across firms of all sizes, ages, and industry sectors" (Cowling, 2016, p. 576). For this study, innovation is defined as a holistic term with no differentiation between different types of innovation such as process, product, market, or organisational (see e.g. Andrade Rojas et al., 2018; De Fuentes & Dutrénit, 2012). On this basis, a three-tier measure for the innovativeness I_i of each firm a_i is constructed:

$$I_i = \begin{cases} 0, & \text{if no new innovation introduced (low);} \\ 1, & \text{if introduced innovation new-to-firm (medium);} \\ 2, & \text{if introduced innovation new-to-industry (high).} \end{cases} \tag{5.5}$$

This innovativeness indicator represents an 'output-oriented' measure of R&D activities and is closely related to 'input-oriented' measures, which are commonly associated with a firm's absorptive capacity. The influence of absorptive capacity has been discussed in Section 2.6.1, which has highlighted that the internal R&D efforts of the firm determine its openness (Fey & Birkinshaw, 2005); how much knowledge can be absorbed and translated into innovation, which cannot be ex-

Table 5.3: Innovativeness I_i of firms and absorptive capacity

I_i	N	Mean[1]	STD[2]	Min[1]	Max[1]
1	605	0.40	2.11	0.00	24.67
2	290	1.16	3.60	0.00	28.24
3	326	3.29	7.83	0.00	65.00
All	1,221	1.35	4.80	0.00	65.00

Notes:
[1] Absorptive capacity measured in R&D spending per employee [£000/person].
[2] Standard deviation, as *SD* is used for system dynamics.

plained purely by geographical proximity to universities (Beise & Stahl, 1999); and, therefore, mediates the positive relationship between entrepreneurial firms' performance and their collaboration with universities (Link & Sarala, 2019). This has also been highlighted by interviewees, as this quote demonstrates:

> "I think there's two kinds of dimensions, which determine how we engage with companies, [...] the size and the level of absorptive capacity or, I mean absorptive capacity is probably almost the wrong term because you can have absorptive capacity without actually being able to successfully absorb it if you like." – B41

There are distinct patterns and relationships between 'input-oriented' measures of absorptive capacity and 'output-oriented' measures of innovativeness, as shown in Table 5.3. Based on the data from the CBR Business Survey, absorptive capacity is measured in the R&D expenditures per employee. This is a similar measure to e.g. the share of staff that are involved in R&D (Vedovello, 1997) or normalising R&D expenditures by sales (Andrade Rojas et al., 2018; Cohen & Levinthal, 1990). These metrics have in common that they allow a comparison of firms of different sizes. Other approaches include a binary distinction of R&D-active or non-R&D-active companies (Kogut & Zander, 1992) or composite indicators (Andrade Rojas et al., 2018). There are distinct differences between the three tiers of innovativeness with regard to their relative R&D expenditures, which, by extension, means the proposed company characteristic I_i provides a good description of a company's activities.

5.4.1.4 Propensity for Collaboration

Engaging with a university is a strategic decision (Mindruta, 2013), the details of which have been discussed in Section 2.6.2. The level of engagement with universities varies considerably across firms, with small firms typically seeking support for core technologies through more short-term, 'problem solving'-type activities whereas large firms usually use university collaborations to strengthen non-core technologies through constant formal and informal interaction (Santoro & Chakrabarti, 2002). The latter is enabled by the greater resource base of larger firms and is also consistent with findings in the strategy literature that show that large firms rarely outsource key R&D activities in core areas (Prahalad & Hamel, 1990; Prahalad, 1993). Nevertheless, small and young firms typically have the greatest need for input from universities but neither have the resources to facilitate these interactions and the absorptive capacity to make them successful (e.g. Tether, 2002).

This is reflected in each agent a_i's propensity for engaging in one of the entrepreneurial activities N_i, which is independent of the preferred university partner but contains individual values $n_{i,k}$ for each of the four activities that are modelled in this study, namely licensing (k=1), collaborative (k=2) and contract research (k=3), and consulting (k=4):

$$N_i = \{n_{i,k=1}, n_{i,k=2}, n_{i,k=3}, n_{i,k=4}\}, \quad n_{i,k} \in [0,1] \quad \forall \quad i, k. \tag{5.6}$$

Innovativeness (or R&D intensity and absorptive capacity), firm size and the industrial environment are important factors in explaining the propensity of firms to use universities in their innovative activities (Laursen & Salter, 2004). Therefore, the propensity to collaborate N_i for every agent a_i depends on its size S_i, innovativeness I_i, and whether it is a spin-off from one of the three universities O_i:

$$N_i = f(S_i, I_i, O_i). \tag{5.7}$$

5.4.1.5 University Preference

Companies have, in addition to varying preferences for different entrepreneurial activities, different preferences for their collaborating university (see also Section 2.6.2). Selection criteria include research prestige, i.e. approaching (non-local) top-tier research universities (Laursen et al., 2011) and the search for 'star scientists' (Zucker et al., 2002), although there is no empirical basis that the latter leads to more successful or innovative collaborations (Baba et al., 2009). While companies with higher innovativeness (and, therefore absorptive capacity) can manage relationships with these universities regardless of geographical proximity, smaller and less innovative firms do not have the resources or the capacity to successfully absorb knowledge without face-to-face interactions and rely on their local university (Laursen et al., 2011).

This evaluation is, however, not always objective as companies have limited information about universities. In reality, some universities might dominate the 'market' and get approached first even though they might not be the optimal partner for some companies. Reasons for this include the signalling effect of awards and prizes such as 'Entrepreneurial University of the Year' and the entrepreneurial reputation (Section 2.5.2); research prestige and the halo effect, which is also expressed in (usually research-dominated) rankings (Section 2.5.1); or individual networks and personal relationships (Section 2.5.3). Lastly, companies might want to connect with a certain university to form a strategic partnership, despite another university being potentially a superior partner for the knowledge exchange opportunity at hand. The reason might be one of the previously mentioned issues or perceived network externalities, i.e. the more engaged a university is with external partners, the more valuable a connection to that university is perceived to be. Universities can act as gatekeepers and connect local companies globally due to their own global involvement and the links they have through various innovation ecosystems (as discussed in Section 2.2.3).

There are also many other ways beyond the five entrepreneurial activities that are considered in this thesis in which universities and companies are connected; many of these are not even recognised in traditional metrics (Hughes & Kitson, 2013). The model accounts for this and the objective and subjective evaluation through pre-defined preferences that companies have from the beginning. Formally, every company agent a_i has a separate preference distribution $P_{i,k}$ for each activity k:

$$\begin{aligned} P_{i,k} &= \{p_{i,k,\alpha}, p_{i,k,\beta}, p_{i,k,\gamma}\}, \quad p_{i,k,\alpha}, p_{i,k,\beta}, p_{i,k,\gamma} \in [0,1], \\ & p_{i,k,\alpha} + p_{i,k,\beta} + p_{i,k,\gamma} = 1 \quad \forall \quad i,k. \end{aligned} \tag{5.8}$$

This university preference $P_{i,k}$ for every agent a_i depends on its size S_i, innovativeness I_i, and whether it is a spin-off from one of the three universities O_i:

$$P_{i,k} \;=\; f(S_i, I_i, O_i). \tag{5.9}$$

These partner preferences change over time. Start-ups' networks, for example, "evolve in order to adapt to the firm's changing resource needs and resource challenges" (Hite & Hesterly, 2001, p. 275). For university spin-offs, this means they are usually tied to and collaborate with the 'mother' university in their early stages, which is reflected in a high preference to work with this university, but then start to make more strategic decisions when growing and this preference might change. The preferences of firms are the key to forming partnerships as repeated interactions with the same university build trust, adjust processes and increase organisational proximity, and, as a result, lead to more efficient knowledge exchange (Gulati, 1995; Gilsing & Nooteboom, 2006). However, firms are generally also prone to changing their collaboration partners as opposed to repeating collaborations with the same partner to get novel insights (Cantner et al., 2017). When and how these preferences are adjusted will be shown when describing the rules in Section 5.4.2.

5.4.1.6 Experience

Continuous collaboration with the same university, i.e. an emerging partnership, builds trust and organisational proximity between the two actors (Gulati, 1995). This simplifies future interactions and enables future knowledge exchange and learning and is, by extension, "positively related to the achievement of higher innovative outcomes" (Petruzzelli, 2011, p. 309). However, even interacting with different universities improves a company's ability to work with and absorb knowledge from universities in general and, therefore, affects future interactions (Villani et al., 2017). In particular, previous experiences of working with universities "may improve partner selection and management routines, reduce transaction costs, and enable firms to more effectively capture the knowledge flows from external collaborators thus, increasing the chances of successful innovation outcome" (Hewitt-Dundas et al., 2019, p.1312). An agent a_i's experience E_i is defined as the total number of interactions with all universities:

$$E_i \in \mathbb{N}^0 = \{0, 1, 2, ...\}. \tag{5.10}$$

It is calculated as a simple count measure of all individual interactions e_{ijk} of types k between firm a_i and all universities j:

$$E_i = \sum_{\substack{k=1 \\ j=1}}^{\substack{j=3 \\ k=4}} e_{ijk}. \tag{5.11}$$

5.4.2 Company Behaviour and Decision Rules

All company agents follow the same set of rules, which determines their behaviour. The basic structure is adapted from the two-level decision-making process by Laursen et al. (2011), in which companies first identify the need for external input and subsequently select the appropriate university. The decision-making process for this simulation is illustrated in the flowchart in Figure 5.12.

The decision-making at points D1, D2, and D3 as well as whether an agent enters one of the other possible states, namely *networking* or *marketing*, is governed by probabilistic rules. In general, agent decision-making can be realised with a variety of approaches that range from simple if/else-statements to more complex neural networks. Probabilistic rules, which incorporate uncertainty compared to if/else-statements, are widely used for social interactions in populations in ecological studies (DeAngelis & Diaz, 2019). In this case, random numbers are generated and trigger actions if they meet an agent's thresholds, i.e. its individual characteristics. In this way, every firm follows a "unique, irregular path" (Wilensky & Rand, 2015, p. 34), which also means that the behaviour of the whole system is unique even though its components are not unique.

A comprehensive discussion about probabilistic rules in the context of an ant model is provided by Wilensky & Rand (2015) and their main rationales for using probabilistic rules apply in this case as well. First, firms are affected by a variety of external and internal influences. Developing a model that accounts for all of these aspects leads to a model that is very specific to a particular empirical setting but is also very hard and cumbersome to both develop and communicate. Furthermore, this increase in detail does not automatically increase the explanatory power of the model or its accuracy. Using probabilistic rules is a way of including the required details as determined by e.g. interviews or secondary data analysis without completely ignoring all other influences. Second, in many cases, like the interaction of universities and businesses, there is not enough knowledge about the system to fully understand its complexity and build a completely deterministic model, which makes random features a requirement. Third, further specifications can easily be added to the model if deemed relevant for future analyses. This way, approximations through probabilistic rules can be reduced by adding deterministic components and details (all points adapted from Wilensky & Rand, 2015). The individual probabilistic rules that govern the agents' behaviour for all states and decision points will be specified in the following sections.

5.4.2.1 Working

In their default state, all agents are *working*, i.e. each agent is in idle regarding engaging with universities. An agent in this state is receptive for networking from other company agents or marketing activities from universities, but otherwise

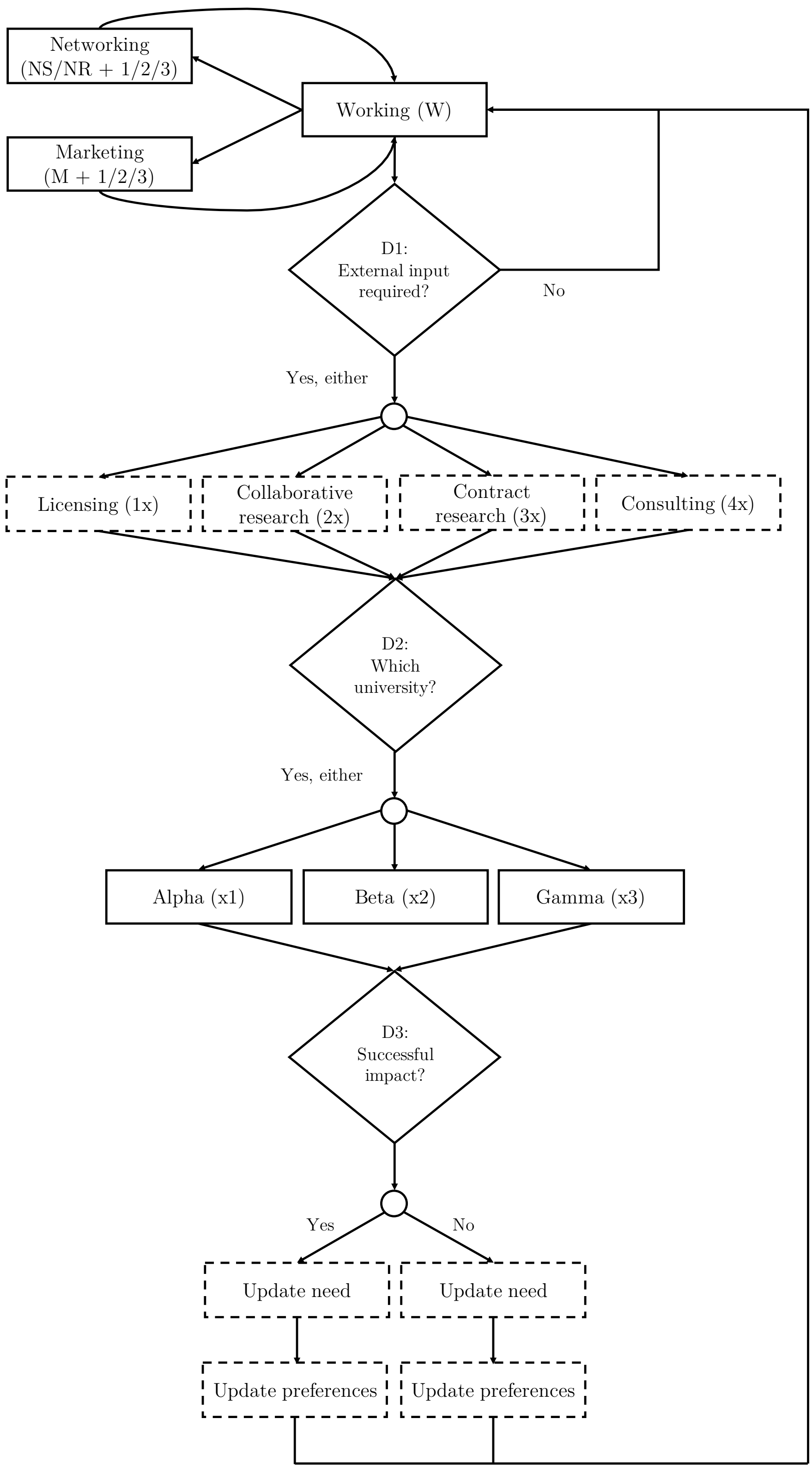


Figure 5.12: Flowchart of agent behaviour with permanent states (solid line rectangles), temporary states (dashed line rectangles), and decision points D1, D2, and D3 (diamonds).

there is no further modelling of the firm's activities or any market competition, which is in line with the basic assumptions of the model (Min et al., 2019).

> **Working rule R_{WORK}:** If the thresholds for *need for input* or *networking* are not met and the agent is not approached by a university for *marketing*, the agent remains in the working state **W**.

5.4.2.2 Maturing Spin-offs

Spin-offs have different characteristics and go through one additional step within the first t_m time steps (see Figure 5.13). Within this time frame, there is a uniformly distributed possibility of survival m_s. A random number $m_{i,f}$ is generated for every agent a_i at every time step and if its value is below the threshold m_s, the spin-off survives. In this case, the remaining behaviour is identical to all other company agents. Once the spin-off survives this initial period and becomes a 'mature spin-off', this step will be skipped and the behaviour is completely identical to all other companies.

> **Maturing rule R_{MAT}:** For the first t_m time steps (during which the spin-off can engage with universities), the maturity threshold $m_{i,f}$ must be met for the spin-off a_i to survive. If the threshold is not met, the agent will enter state **C** and no longer be activated during the simulation. If the spin-off survives, it 'matures', i.e. be in state **M**, and not be available for engaging with universities in this time step.

5.4.2.3 Need for Input

The first step in engaging with universities for a company is to identify a need or an opportunity to benefit from external knowledge (see Figure 5.12). The decision to approach a university is made after an evaluation of the company's current knowledge base and future 'knowledge needs' (Bekkers & Bodas Freitas, 2008). A number of categorisations have been developed to distinguish these needs. They range from binary distinction between companies focusing on collaboration and research partnerships for 'interdependent knowledge' (e.g. often used in biomedical science and computer science) and those relying on codified knowledge for 'systemic knowledge' (e.g. material sciences and chemical engineering) (Bekkers & Bodas Freitas, 2008) to categorisations that further differentiate companies' strategies. An example is the distinction between 'collegial players', i.e. large companies engaging in research partnerships with (top tier) universities

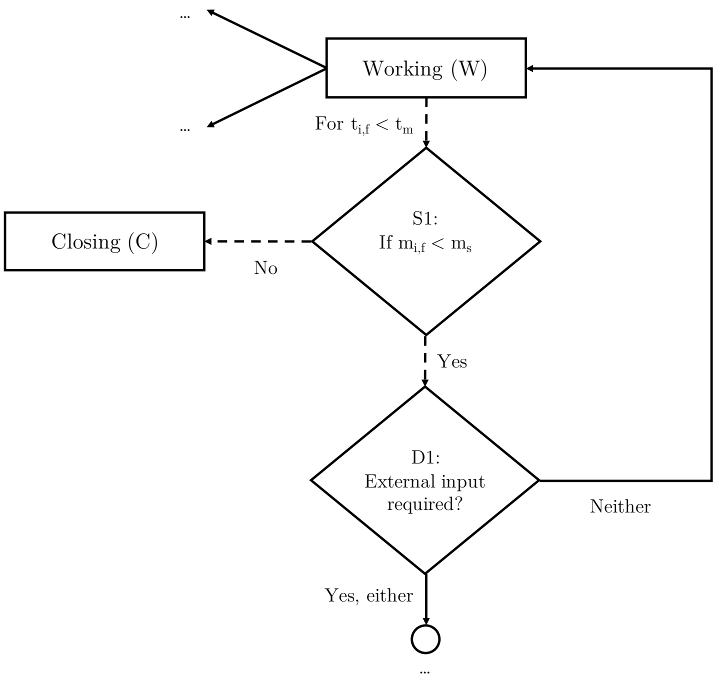


Figure 5.13: Flowchart of spin-off maturing process showing the additional probabilistic decision point

for long-term value rather than short-term commercialisation, 'aggressive players', i.e. companies of varying size that engage with universities with a focus on products and services that can be commercialised, and 'targeted players', i.e. typically smaller companies that engage with universities with the aim of solving a particular problem (Santoro & Chakrabarti, 2001).

This model does not constrain companies to a particular strategy. Rather, there are individual probabilities $n_{i,k} \in N_i$ assigned to each activity k for every agent a_i. This also implicitly models the fact that firms potentially have previous engagements with universities and need to engage with universities informally through personal contacts and students as well as engaging with scientific publications (Bekkers & Bodas Freitas, 2008).

> **External input rule R_{NEED}:** If the threshold for one of the activities $k \in [1; 2; 3; 4]$ is met, the agent will subsequently identify an academic partner and its temporary state is set to $\mathbf{k*}$[56], based on which of the four activities k the agent engages in.

This can be formalised using a piecewise-defined function, which determines which activity k is selected by agent a_i based on the value of a randomly generated

[56]The state will be finalised once the agent has selected a university j in the next step, for which the place holder $*$ is currently used.

number x and the agent's thresholds N_i:

$$\text{Activity} = \begin{cases} k = 1 & \text{if } x < n_{i,1}; \\ k = 2 & \text{if } n_{i,1} < x \leq n_{i,1} + n_{i,2}; \\ k = 3 & \text{if } n_{i,1} + n_{i,2} < x \leq n_{i,1} + n_{i,2} + n_{i,3}; \\ k = 4 & \text{if } n_{i,1} + n_{i,2} + n_{i,3} < x \leq n_{i,1} + n_{i,2} + n_{i,3} + n_{i,4}; \\ \text{`W'} & \text{if } n_{i,1} + n_{i,2} + n_{i,3} + n_{i,4} < x. \end{cases} \tag{5.12}$$

5.4.2.4 Partner Selection

Once a company has identified the need for external input and the type of entrepreneurial activity, the next step in the agent decision making process is to identify the academic partner (see Figure 5.12). Firms rely on a variety of information sources for evaluating potential partners and eventually selecting the academic collaborator, but there remains ambiguity regarding whether the university is a good fit and reliable (Knoben et al., 2019). This uncertainty is based on "the realism, comprehensiveness, and specificity of [the university's] knowledge [and] appears to be judged at an individual rather than institutional level" (Johnston & Huggins, 2018, p. 15). Particularly larger firms are at an advantage here due to their resources and capabilities for 'in-depth screening activities' (Fontana et al., 2006). However, every agent in this simulation must select an academic partner and approach them. The main assumptions of this model state that all activities are initiated by companies (which according to the CBR Business Survey is the most prominent way in which interactions emerge) and that universities do not reject an opportunity when approached by a company to engage in a particular activity.

> **Selection rule** R_{UNI}: Once an agent a_i has identified the need to engage in activity k, it selects an academic partner j based on the individual probabilities P_i and will enter the permanent state **kj**.

This can be formalised using a piecewise-defined function, which determines which university j is selected by agent a_i based on the value of a randomly generated number x and the agent's thresholds P_i:

$$\text{University} = \begin{cases} j = 1 & \text{if } 0 \leq x < p_\alpha; \\ j = 2 & \text{if } p_\alpha \leq x < p_\beta; \\ j = 3 & \text{if } p_\alpha + p_\beta \leq x \leq 1. \end{cases} \tag{5.13}$$

These probabilities also serve as an implicit account for the combination of technology readiness (more basic research at Alpha, which often does not go beyond the conceptual stage, compared to Beta and Gamma with more applied R&D) and demand readiness levels (highly innovative firms can integrate capabilities whereas those with less absorptive capacity have particular needs that need to be outsourced) (Liu et al., 2020).

5.4.2.5 Evaluation

The evaluation of the engagement with the respective university is realised through another probabilistic rule, because the high-level focus of this simulation would not allow for an individual assessment of each interaction. This would require including the firm's confidence in the academics and its perception of the usefulness of the interaction as well as how well the company is able to integrate the insights and outcomes from the interaction into their value chain (Barbolla & Corredera, 2009).

> **Evaluation rule R_{EVAL}:** If the threshold value for success ts_i is met, agent a_i will see the interaction with the academic partner as a success, which then subsequently impacts the probability of changing a_i propensity for collaboration N_i and the university preference P_i.

The evaluation of the interaction between agent a_i and a university is formalised by calculating the temporary variable U_i (i.e. it will not be saved and is only relevant for the next two temporary states) in the following way:

$$U_i = \begin{cases} 0, & \text{if threshold } ts_i \text{ is not met;} \\ 1, & \text{if threshold } ts_i \text{ is met.} \end{cases} \tag{5.14}$$

5.4.2.6 Update Need

Entrepreneurial activities are initiated voluntarily and universities and companies alike expect to benefit from these interactions (Mindruta, 2013). Firms are, however, constrained by their resources and are reluctant to engage with universities or support research that has no or only a small chance of contributing to the firm's objectives (Stephan, 1996). Particularly smaller firms are less likely to engage in activities that are less promising (see also Section 2.6.1). However, past collaboration experience and the learning from the interactions increase the likelihood of companies engaging in inter-organisational collaboration in general (e.g. Marino et al., 2008) as well as engaging with universities across different activities. The latter increased by 22% over a three-year period on average for companies of all sizes (Hewitt-Dundas et al., 2019, p. 1318).

This also implicitly reflects systemic learning for universities (since only companies initiate interactions in this simulation, this has to be reflected in the agent's propensity for engaging with the respective university). While universities are influenced by government targets and sector-wide evaluation criteria (e.g. REF), many interviewees have expressed a 'can do'-attitude and the desire to make collaborations work if possible, regardless of how the arrangement is structured and coined.

> **Update rule R_{UPNEED}:** If the threshold value, which is dependent on U_i, is met, the future propensity $n_{i,k}$ of agent a_i engaging in either of the four activities $k \in [1; 2; 3; 4]$ is increased by ni_i.

The process of whether or not an agent a_i increases the likelihood of engaging again in one of the four activities $n_{i,k}$ is illustrated in Figure 5.14. The main idea is that the success of a past interaction of type k is not the only determinant of whether or not a_i is more likely to engage in the same activity again in the future. Even an unsuccessful interaction can lead to lessons learned and both parties can realise, that this type of interaction can be beneficial in the future if e.g. managed differently or supported by more resources to make the most of it. It can also lead to the realisation, that it was not the right type of interaction and a different one should be pursued in the future. On the other hand, a successful interaction does not necessarily mean that a company is more likely to engage in the same activity (or any other activity) again in the future. This is supported by both data from the CBR Business Survey as well as the interviewees. The following quote summarises this issue:

> "You need to make sure that you're learning lessons where you've been successful also where you've not been successful and that you're adapting accordingly." – B45

The interview analysis has demonstrated that there is a great variety in the temporal order of entrepreneurial activities between partners (see the temporal order of activities within partnerships in Appendix D.7). In the absence of any secondary data at this level of granularity, one activity will be picked at random with equal probabilities for all four activities and the agent's propensity to engage in this activity in the future will be increased.

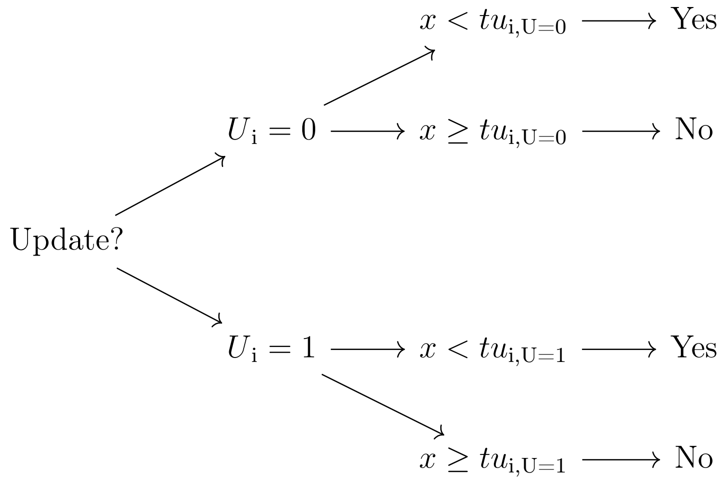


Figure 5.14: Decision tree for updating the agent a_i's thresholds for engaging with universities

This can be formalised in the following way. Assuming that a university and company a_i have completed activity k at time t and the threshold for increasing the propensity for future collaboration is met, the propensity n_{i,k^*} with $k^* \in [1; 2; 3; 4]$, which is randomly determined, at time $t + 1$ will be adjusted by ni_i:

$$n_{i,k^*,t+1} \;=\; n_{i,k*,t} * (1 + ni_i). \tag{5.15}$$

5.4.2.7 Update Preferences

Partnerships are both a crucial ingredient for successful knowledge exchange between universities and companies (Section 2.6.3) but also an emerging property of the system and, therefore, an outcome (Section 3.7.4). The former is attributed to aligning organisational practices and increasing organisational proximity over time as well as building trust and understanding among partners (Belderbos et al., 2018; Gulati, 1995). Despite the widespread belief that IP or cultural issues are the main constraints of university-industry interaction, it is actually the firm's capability and resources for initiating and fostering the relationships with universities that constrain firms the most (Hughes & Kitson, 2013). Increasing organisational proximity significantly reduces the effort required to maintain and grow these relationships. Partnerships in inter-organisational collaboration in general and university-industry interactions in particular have proven to be valuable for the parties involved (e.g. Rezaei et al., 2015; Wynarczyk & Watson, 2005). Well-functioning partnerships are also negatively correlated to non-compliance and opportunistic behaviour, but positively correlated to meeting financial goals

(Weaver & Dickson, 1998). This can lead to a reinforcing cycle, in which interactions between the same partners become more efficient and, therefore, incentivise the partners to interact again in the future, when the interactions are even more efficient.

There are no secondary data on the likelihood of companies working again with the same university (in contrast to the propensity for engaging with universities as described above). This leaves two options: the first is to increase the likelihood of working again with the same university every time when the past interaction was successful ($U_i = 1$) or, secondly, using the same decision tree with the same probabilities and update the university preference $P_{i,k}$ whenever updating the propensity N_i. In this model, the latter is used because (1) firms learn from both successful and unsuccessful interactions and increase e.g. organisational proximity to this university and (2) not every positive interaction automatically leads to an increase probability to work with the same partner again in the future.

> **Update rule R_{UPPREF}:** If the threshold value $tu_{i,U}$ is met, the agent a_i will increase the likelihood of working again with this particular university and adjust $P_{i,k}$ for one randomly selected activity k.

Therefore, if the threshold for updating is met (see Figure 5.14) and the propensity N_i has been updated according to update rule R_{UPNEED}, the university preference $P_{i,k}$ will be updated as well. In the following example, a_i interacted with Alpha at time t. The new preference for interacting with Alpha $p_{i,\alpha}$ at time $t+1$ is calculated as:

$$p_{i,k,\alpha,t+1} = \frac{p_{i,k,\alpha,t} + 1}{2}. \tag{5.16}$$

In a second step, the change in a_i's preference for Alpha is calculated:

$$\Delta p_{i,k,\alpha} = p_{i,k,\alpha,t+1} - p_{i,k,\alpha,t}. \tag{5.17}$$

Lastly, $\Delta p_{i,k,\alpha}$ needs to be discounted from a_i's preference for both Beta and Gamma as $p_{i,k,\alpha,t+1} + p_{i,k,\beta,t+1} + p_{i,k,\gamma,t+1}$ must equal one. The amount deducted is proportional to the preferences $p_{i,k,\beta,t}$ and $p_{i,k,\gamma,t}$:

$$p_{i,k,\beta,t+1} = p_{i,k,\beta,t} - \left(\frac{p_{i,k,\beta,t}}{p_{i,k,\beta,t} + p_{i,k,\gamma,t}} * \Delta p_{i,k,\alpha} \right). \tag{5.18}$$

$$p_{i,k,\gamma,t+1} = p_{i,k,\gamma,t} - \left(\frac{p_{i,k,\gamma,t}}{p_{i,k,\beta,t} + p_{i,k,\gamma,t}} * \Delta p_{i,k,\alpha} \right). \tag{5.19}$$

5.4.2.8 Networking

Technological innovation emerges from scientific and technological breakthroughs based on new ideas or the re-combination of existing ideas and knowledge (Powell et al., 1996). To this point, the focus has been on different types of interactions with universities as part of a firm's innovation activities (see Section 2.6.1). However, firms also interact with other companies in different sorts of relationships along their value chain, not limited to their own industrial sector (Jacobides & Billinger, 2006). The result is a network with multiple layers, including inter- and intra-industry ties. Much of the existing research has focused on the centrality of a company within these networks (Andrade Rojas et al., 2018). Centrality is beneficial because it allows firms to access a wider range of knowledge and resources (Jensen & Roy, 2008).

These relationships are important for firms to maximise their innovative performance with limited internal resources (Mitchell & Singh, 1996). In this case, the existence of these networks serves as a rationale for the existence of word-of-mouth (WOM) effects on a firm's university interactions and their partner selection. A distinction must be made here between contractual arrangements and actual WOM effects. The former refers to cases in which e.g. firms require their suppliers to work with the same academic partner(s) or platform technologies that are linked to a particular university. Particularly larger companies play a key role for these contractual arrangements.

All companies a_i have a more or less positive opinion about each of the three universities, which is summarised in their preferences $P_{i,k}$. This preference $P_{i,k}$ is based on previous experience and the current evaluation of universities as potential collaboration partners. Companies also interact with each other through formal (e.g. inter-firm collaboration, participation in standard-setting bodies) and informal channels (e.g. employee mobility, informal contacts, conferences) and share their experiences and opinions about universities. This information exchange also influences their preferences $P_{i,k}$, which results in opinion dynamics (Urbig, 2003). The existence of these opinion dynamics and word-of-mouth effects among companies is confirmed through the interviews.

> "I think, inevitably, there would be those [companies] that have a great experience with working with us hopefully, and which will be willing to recommend us on to others. [...] but certainly, word-of-mouth is always a powerful tool and that's why we would be keen to be positive partners in relationships [...]" – C61

Informal networks and interactions, one of the key elements of an ecosystem (Radziwon & Bogers, 2019), is modelled via the random interactions of agents. In this study, only dyadic interactions are considered as opposed to group dynamics. This simulation does not take into consideration limited verbalisation capabilities, limited comprehension capabilities, or any loss of information during the exchange (e.g. Urbig, 2003) or directed weighted network position and social capital of agents, which could be proxied by E_i based on the assumption that interactions between companies and universities are proportional to the number of interactions among companies (e.g. Li et al., 2019).

> **Networking rule R_{NETW}:** When two agents a_x and a_y meet, the more experienced agent will influence the university preference for one random activity k of the less experienced agent. The former will be in state **NS+1/2/3+**k and the latter in state **NR+1/2/3+**k, with the respective number corresponding to the university that is the focus of this interaction, i.e. Alpha, Beta, or Gamma, and the activity k that is affected.

This example of agents a_x and a_y interacting is used in the following to illustrate how the opinion dynamics and the changes in the agent's preferences work. When looking at this interaction from the perspective of a_x, there are three possible outcomes:

$$P_{x,k,t+1} = \begin{cases} P_{x,k,t}, & \text{if} \quad E_x \geq E_y; \\ P^*_{x,k,t+1}, & \text{if} \quad E_x < E_y. \end{cases} \tag{5.20}$$

The relevant case is the second, when E_x is smaller than E_y which means that the preferences of a_x will be influenced by a_y:

$$P^*_{x,k,t+1} \;=\; \{p_{x,k,\alpha,t+1}, p_{x,k,\beta,t+1}, p_{x,k,\gamma,t+1}\}. \tag{5.21}$$

To calculate $P^*_{x,k,t+1}$, the preferred university of a_y needs to be identified. For the purpose of this demonstration, Alpha is selected as a_y's preferred university (this is the only relevant assumption here, the exact values and whether Beta or Gamma is the second choice does not need to be specified). In addition to the requirement of $E_x < E_y$, there is a second condition that has to be met. This condition is that $p_{x,k,\alpha,t} < p_{y,k,\alpha,t}$, because a_y's opinion would have no effect on a_x otherwise. For this demonstration, this condition is assumed to be met. In a first step, the new value for $p_{x,k,\alpha,t+1}$ will be calculated as the mean value of

$p_{x,k,\alpha,t}$ and $p_{y,k,\alpha,t}$:

$$p_{x,k,\alpha,t+1} = \frac{p_{x,k,\alpha} + p_{y,k,\alpha}}{2}. \tag{5.22}$$

There are many ways of how these opinion dynamics can be realised, the simplest being a_x simply adopting the preference distribution $P_{y,k,t}$ from a_y without any changes. However, the approach presented here strikes a balance between the influence of a_y and a_x's own experience and history. In a second step, the change in a_x's preference for Alpha is calculated:

$$\Delta p_{x,k,\alpha} = p_{x,k,\alpha,t+1} - p_{x,k,\alpha,t}. \tag{5.23}$$

Lastly, $\Delta p_{x,k,\alpha}$ needs to be discounted from a_x's preference for both Beta and Gamma as $p_{x,k,\alpha,t+1} + p_{x,k,\beta,t+1} + p_{x,k,\gamma,t+1}$ must equal one. The amount deducted is proportional to the preferences $p_{x,k,\beta,t}$ and $p_{x,k,\gamma,t}$:

$$p_{x,k,\beta,t+1} = p_{x,k,\beta,t} - \left(\frac{p_{x,k,\beta,t}}{p_{x,k,\beta,t} + p_{x,k,\gamma,t}} * \Delta p_{x,k,\alpha}\right) \tag{5.24}$$

$$p_{x,k,\gamma,t+1} = p_{x,k,\gamma,t} - \left(\frac{p_{x,k,\gamma,t}}{p_{x,k,\beta,t} + p_{x,k,\gamma,t}} * \Delta p_{x,k,\alpha}\right) \tag{5.25}$$

5.4.2.9 Marketing

Company agents are subject to 'marketing' activities and informal engagement initiated by the universities (as described in Section 5.3.3.10 from the university's perspective). This triggers opinion dynamics that are similar to the networking interactions among companies. Two different marketing rules R_{MKT1} and R_{MKT2} are described in the following, depending on whether the company get approached by TTO staff alone or in combination with academics, accordingly.

> **Marketing rule R_{MKT1}:** When an agent a_i is approached by a university through their TTO staff, its preference towards that university for one activity k is altered. The agent will be in state **M+1/2/3**+k, depending on the university that approached the agent and activity k that is affected.

> **Marketing rule R_{MKT2}:** When an agent a_i is approached by a university through their TTO and academic staff, all four preferences towards that university are altered. The agent will be in state **M+1/2/3**, depending on the university that approached the agent.

For simplicity, this rule is demonstrated for Alpha's TTO staff approaching agent a_x, hereby triggering rule R_{MKT1} for a random activity k. In case R_{MKT2} is triggered, the following algorithm would be repeated for all four activities. In a first step, the new value for $p_{x,k,\alpha,t+1}$ will be calculated as the mean value of $p_{x,k,\alpha,t}$ and 1, which would correspond to the most extreme case in which Alpha would be the only possible partner for a_x. Similar to the networking opinion dynamics, there are other ways to model this effect, but the approach presented here strikes a balance between the influence of Alpha and a_x's own experience and history:

$$p_{x,k,\alpha,t+1} = \frac{p_{x,k,\alpha,t} + 1}{2}. \tag{5.26}$$

In a second step, the change in a_x's preference for Alpha is calculated:

$$\Delta p_{x,k,\alpha} = p_{x,k,\alpha,t+1} - p_{x,k,\alpha,t}. \tag{5.27}$$

Lastly, $\Delta p_{x,k,\alpha}$ needs to be discounted from a_x's preference for both Beta and Gamma as $p_{x,k,\alpha,t+1} + p_{x,k,\beta,t+1} + p_{x,k,\gamma,t+1}$ must equal one. The amount deducted is proportional to the preferences $p_{x,k,\beta,t}$ and $p_{x,k,\gamma,t}$:

$$p_{x,k,\beta,t+1} = p_{x,k,\beta,t} - \left(\frac{p_{x,k,\beta,t}}{p_{x,k,\beta,t} + p_{x,k,\gamma,t}} * \Delta p_{x,k,\alpha}\right) \tag{5.28}$$

$$p_{x,k,\gamma,t+1} = p_{x,k,\gamma,t} - \left(\frac{p_{x,k,\gamma,t}}{p_{x,k,\beta,t} + p_{x,k,\gamma,t}} * \Delta p_{x,k,\alpha}\right) \tag{5.29}$$

5.5 Summary

This chapter has applied the initial framework to the case of Scotland and provided further details, including the internal structures for each module through a triangulation of the existing literature, interviews, and secondary data. Three generic university agents were created based on data from all Scottish universities. The causal structure of these SD modules, which is the same for all three universities, was subsequently described. For the company agents, relevant characteristics have been identified from the literature and secondary data as well as the relevant rules and how these are affected by the agent's characteristics. The next chapter will use this conceptual model and describes the transformation into a simulation model and subsequently the simulation results.

Chapter 6

Simulation Model and Results

6.1 Introduction

Having identified the internal structure of each module in the previous chapter, this chapter describes the simulation model (step 4 of the MP), including the simulation model structures (Section 6.2), parametrisation (Section 6.3), and the simulation platform and realisation (Section 6.4). Bringing these three parts together, the baseline simulation results are presented (Section 6.5). While confidence building (step 5 of the MP) is an ongoing process throughout the MP, key efforts are summarised following the results, including code verification, black- and white-box validation, and sensitivity analyses (Section 6.6). Lastly, policy experiments (step 6 of the MP) are conducted by simulating alternative scenarios (Section 6.7).

6.2 Simulation Model

The first step is to transform the conceptual model as presented in the previous chapter into a simulation model. For the SD modules, this encompasses transforming the CLDs into SFDs and formalising the relationships using differential equations. The rules of the agents within the ABM module have already been formalised, but further specifications are required in terms of how the module is run and how the agents are activated. Lastly, the SD-ABM interface will be described, including the interaction points between the SD and ABM modules and how complex events can be observed from the model.

The unit of time for the simulation is weeks, with a $DT = 1$ (the solution interval for the differential equations of the SD module). In line with Nyquist's theorem, DT should be less than the smallest time constant for first-order delays of the system (Sterman, 2000). While DT (even if set to 1) is required in integral calculus and SD, there is neither a real-world equivalent nor one in ABMs. While crucial for SD, there is no equivalent of DT for ABM. Despite the importance, there is no particular guidance on selecting an appropriate DT for hybrid simulations involving SD and ABMs. Most publications that are based on this type of HS do not even share the value of DT or any explanation.

Swinerd & McNaught (2014) provide the most detailed rationale for their choice of the value for DT. Data for their diffusion model was collected annually and the unit of time was, accordingly, set to years with $DT = 0.25$. Similarly, the HE-BCI and HESA data that are used in this thesis are only reported annually by universities, the CBR Business Survey covers a three-year time span. In contrast to Swinerd & McNaught (2014), the unit of time for this model is set to weeks with a $DT = 1$, which allows for (1) sufficient iteration and time steps that are one-forth of the smallest time constant and (2) makes the model easier to understand because the model uses delays and generates numbers that correspond to people's experience. In this case, there are certain actions that company agents can do within a week and certain behaviours that this causes for university agents.

6.2.1 University Agents (SD)

The CLD of the university agents highlighted the feedback structure of the SD modules, but did not explicitly model the stocks and flows of the system. Stocks and flows enable accumulation and gives the model memory as well as enabling delays (as previously discussed in Section 3.3.2). This process starts by identifying which of the CLD variables are stocks and flows (using e.g. the 'snapshot test') and then adding any additional variables and constants that are required to complete all conversions and information and resource flows (Sterman, 2000). These additional variables include stocks, e.g. 'Matured Spin-offs' MSO and 'Marketed Licenses' $MLIC$ that are both required to implement delays but are not required to explain and understand the feedback structure; the accompanying flows, e.g. 'Maturing' M; and other variables and constants, e.g. the 'Avg Length of Collaboration' $coll$ or 'Avg Value per Contract' $conrv$. As a result, the SFD also shows 'hidden' loops, i.e. those that are not explicitly represented in CLDs (Richardson, 1986b, p. 165). An example are expiring licenses E, which are determined by the current amount of $MLIC$ and the 'Avg Lenght of Licensing' $licl$, and, in turn, affect $MLIC$.

Disclosures d are modelled as an auxiliary variable and not as a stock, which would be subject to accumulation. The interviews have demonstrated that disclosures are not shelved but are evaluated and either put forward for patenting or a spin-off or discarded if there is no perceived commercial potential.

The stock for spin-offs SO, once it reaches an integer number, will create a new company agent. This agent will then either mature or close and impact 'Maturing' M or 'Closing' C, respectively. These two flows are entirely dependent on the activities of the spin-off agents (i.e. company agents with $O_i > 0$). Similarly, the flows L, $ICON$, $ICOL$, and $ICONR$ depend on the company agents initiating one of the other four activities. Flow L is distinct, as it depends on the availability of 'Patents' (i.e. $PAT \geq 1$), otherwise there cannot be a licensing deal. This needs to be checked any time an agent approaches one of the three universities regarding a desired licensing deal.

A variable that is not mentioned in the CLD but included in the simulation model is the 'Independent Research Focus' *irf*. This variable does not influence the model behaviour and is, therefore, presented in grey in Figure 6.1. Calculated as the ratio of independent research to academic entrepreneurship, *irf* is used as an indicator for the relative importance of industry engagement. Particularly when a university changes its strategy and changes are introduced to the model at a later stage of this chapter, this variable will be used as an indicator of potential path-dependencies in the profile of universities (e.g. can growing academic entrepreneurship lead to completely re-shaping the university and, therefore, having far-reaching ramifications). A second part of the SFD that is shown in grey for the same reason is 'Project-Based Staff' *pbs*. While it does not affect the dynamics of the model, it provides an important indicator for resource implications of entrepreneurial activities and will be consulted when analysing the simulation results.

Spin-offs are seen by many universities not only as a vehicle for commercialisation and socio-economic impact, but due to the typically disruptive nature of the technologies as having the potential to yield high financial returns. However, the data for Scottish universities show these are rare occurrences and the potential returns typically do not materialise. Financial returns from spin-offs are, therefore, not included in the simulation model. This discrepancy between the literature and interviews on the one hand and secondary data on the other hand is part of a set of broader insights from the modelling process itself, which will be discussed in the next chapter.

The corresponding equations of the SD model, which mathematically define the stocks and flows and other auxiliary variables, are presented in Table 6.1. These equations (and the SFD in Figure 6.1) describe the baseline scenario, any changes for alternative scenarios will be described in the respective sections of this chapter. In the process of formalising the equations, the units of all stocks, flows, auxiliary variables and constants need to be defined. This also allows for a consistency check, which is part of the 'structural validity tests' (Barlas, 1989) and a crucial white-box validation tool for confidence building (Kleijnen, 1995b; Sterman, 2000). This test has been successfully performed for the baseline model as well as all scenarios to ensure consistency.

6.2.2 Company Agents (ABM)

To synchronise the ABM and SD modules, a uniform activation for the agents is used, i.e. every agent is activated exactly once during each time step (Axtell, 1999). This corresponds to every company having the opportunity to either initiate an interaction with a university, network with another company, or being influenced by a university according to the rules specified in Section 5.4.2. In addition, the order in which the agents are activated in every time step is randomised, which prevents path-dependencies that are coded into the model by creating a set 'picking order'.

The three SD modules within the HS are deterministic. In contrast, the ABM module is stochastic due to the probabilistic rules and initial characteristics. This enables the calculation of means as well as standard deviations and confidence intervals for key variables, if required. A stochastic simulation typically converges to certain values for each variable except in cases of chaos or oscillation, which is not expected here (Wilensky & Rand, 2015). Therefore, each simulation scenario, including the baseline model, is run 100 times with a new agent population for each run. This number is based on two factors. First, using the approach by Secchi & Seri (2017) the number of simulation runs n can be calculated as a function of the range of parameter configurations J and the effect size ES using the following formula:

$$n(J, ES) \simeq 14.091 * J^{-0.640} * ES^{-1.986}. \tag{6.1}$$

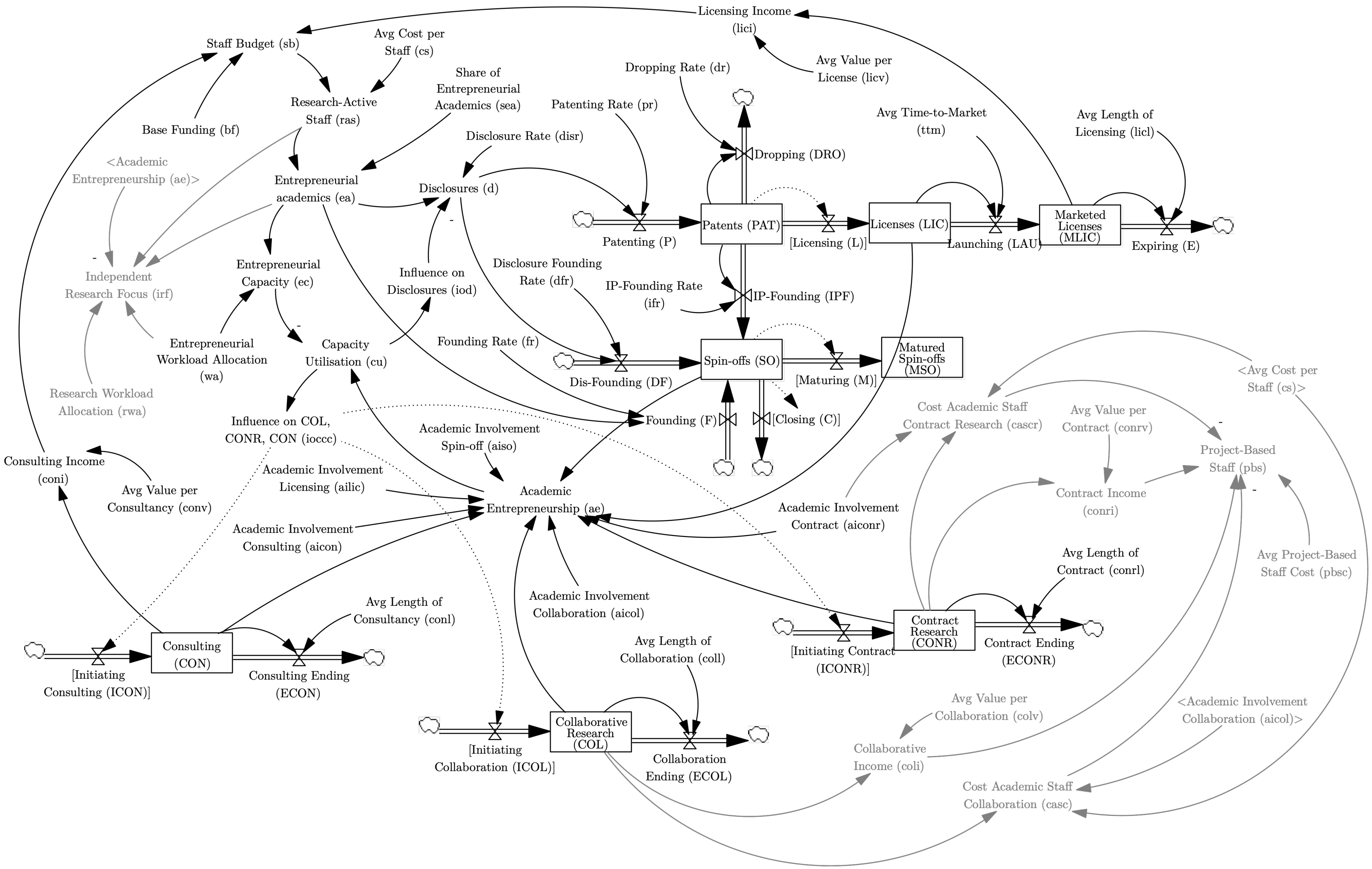


Figure 6.1: Baseline model SFD of university agents (crossing of the module boundaries within the HS is highlighted by the dashed lines and the squared brackets around the variables)

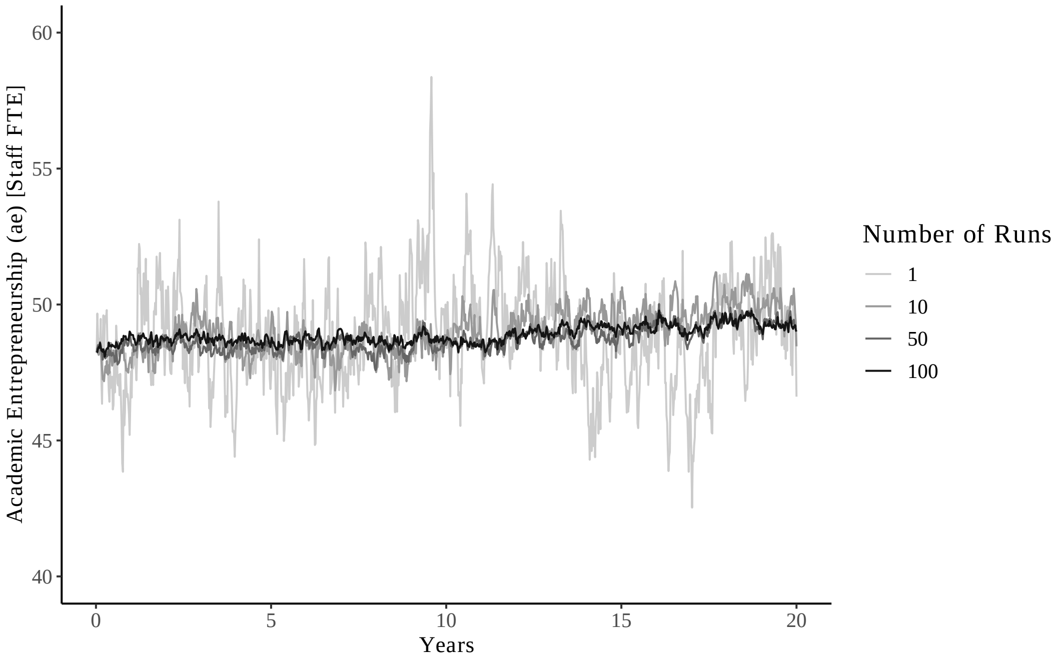


Figure 6.2: Simulation output showing 'ae' for Alpha based on the average of a varying number of runs for the baseline scenario.

Based on $J = 65$, which includes all sensitivity analyses and scenarios and an effect size $ES = 0.1$ the simulation should be run for $n = 94.34$ times.[57] Second, the simulation was run then run and the results for a varying number of runs analysed. To illustrate this, the results for ae for Alpha are plotted in Figure 6.2 and a convergence can be observed for $n = 100$.

6.2.3 SD-ABM Interface

This model includes an ABM module with all company agents and their probabilistic decision making as well as three SD modules, which are embedded in the ABM as a special type of agent with a rich internal structure (Swinerd & McNaught, 2012). The previous sections have detailed the individual modules and this section explains how they are integrated to form an HS, including the interface between the modules to ensure both logical and data consistency and illustrate how complex events are implemented.

6.2.3.1 Compatibility between SD and ABM

Developing integrated HS comes with a number of methodological challenges (see Section 3.6.6 for a general discussion). The six main issues are discussed in

[57]For a discussion about individual parameters please refer to the original paper, this is beyond the scope of this thesis.

Table 6.1: Equations of the SD modules

Stocks
COL [projects] = INTEGRAL(ICOL - ECOL)
CON [projects] = INTEGRAL(ICON - ECON)
CONR [projects] = INTEGRAL(ICONR - ECONR)
LIC [licenses] = INTEGRAL(L - LAU)
MLIC [licenses] = INTEGRAL(LAU - E)
MSO [spin-offs] = INTEGRAL(M)
PAT [patents] = INTEGRAL(P - IPF - L - DRO)
SO [spin-offs] = INTEGRAL(F + IPF + DF - M - C)
Flows
C [spin-offs/week] = [ABM module]
DF [spin-offs/week] = d [disclosures/week] * dfr [spin-offs/disclosure]
DRO [patents/week] = PAT [patents] * dr [1/week]
E [licenses/week] = MLIC [licenses] / licl [weeks]
ECOL [projects/week] = COL [projects] / coll [weeks]
ECON [projects/week] = CON [projects] / conl [weeks]
ECONR [projects/week] = CONR [projects] / conrl [weeks]
F [spin-offs/week]= ea [staff FTE] * fr [spin-offs/staff FTE]
ICOL [projects/week] = [ABM module]
ICON [projects/week] = [ABM module]
ICONR [projects/week] = [ABM module]
IPF [spin-offs/week] = PAT [patents] * ifr [spin-offs/patent/week]
L [licenses/week] = [ABM module]
LAU [licenses/week] = LIC [licenses] / ttm [weeks]
M [spin-offs/week] = [ABM module]
P [patents/week] = d [disclosures/week] * pr [patents/disclosures]
Auxiliary variables
ae [staff FTE] = (COL [projects] * aicol [staff FTE/project]) + (CON [projects] * aicon [staff FTE/project]) + (CONR [projects] * aiconr [staff FTE/project]) + (LIC [licenses] * ailic [staff FTE/license]) + (SO [spin-offs] * aiso [staff FTE/spin-off])
casc [£000/week] = COL [projects] * aicol [staff FTE/project] * cs [£000/staff FTE/week]
cascr [£000/week] = CONR [projects] * aiconr [staff FTE/project] * cs [£000/staff FTE/week]
coli [£000/week] = COL [projects] * colv [£000/project/week]
coni [£000/week] = CON [projects] * conv [£000/project/week]
conri [£000/week] = CONR [projects] * conrv [£000/project/week]
cu [dimensionless] = ae [staff FTE] / ec [staff FTE]
d [disclosures/week] = ea [staff FTE] * disr [disclosures/staff FTE/week] / iod [dimensionless]
ea [staff FTE] = ras [staff FTE] * sea [dimensionless]
ec [staff FTE] = ea [staff FTE] * wa [dimensionless]
ioccc [dimensionless] = f(cu) [dimensionless] = $1\chi_{[0,1[} + 0.75\chi_{[1,1.1[} + 0.5\chi_{[1.1,1.2[} + 0.25\chi_{[1.2,1.3[} + 0\chi_{[1.3,\infty]}$
iod [dimensionless] = MAX(1,cu) [dimensionless]
irf [dimensionless] = (ras [staff FTE] * wa [dimensionless] - ae [staff FTE]) / ae [staff FTE]
lici [£000/week] = LIC [licenses] * licv [£000/license/week]
pbs [staff FTE] = (coli [£000/week] + conri [£000/week] - casc [£000/week] - cascr [£000/week]) / pbsc [£000/staff FTE/week]
ras [staff FTE] = sb [£000/week] / cs [£000/staff FTE/week]
sb [£000/week] = bf [£000/week] + lici [£000/week] + coni [£000/week]

the following and how they are handled in this simulation. First, both SD and ABM are dynamic modelling approaches, with the SD modules being time-driven and the ABM modules event-driven. Time and events are synchronised in this simulation through the randomisation of the agents at every time step and the limitation to no more than one state change per time step. This assumes, that all agents' activities happen simultaneously within that given time step, i.e. the SD modules are dictating the pace of the simulation. Related to this is the second issue of multiple bases for values. This HS is designed as a continuous simulation (based on the SD modules), in which the ABM modules are pseudo-continuous through the randomisation of the order in which all agents are activated.

The third issue concerns the typically deterministic behaviour of SD and stochastic nature of ABMs. In practise, this means that the simulation will be run many times to account for the variability within the ABM module and that results will be presented as mean values for each variable or stock. Fourth, despite the high number of runs for each simulation scenario, the HS will be executed in a serial way. This avoids synchronisation issues as well as causality constraints. The last two issues, expression and resolution, are related. SD is expressed in differential equations and ABM through logic sentences. Individually, the respective expressions are outlined in this chapter and the next one (for the SD equations). This leads to the resolution of the HS, which includes aggregate states (SD modules) and individual rules (ABM module). The touching points of the SD and ABM modules have been mentioned throughout this chapter and the following sections will provide further details and show, how information is aggregated into parameters or stocks and how emergence behaviour is recognised.

6.2.3.2 Interaction Points at the Module Boundary

The novel insights from the model are enabled by the feedback between the SD and ABM modules within the hybrid framework. Feedback between different modules represents a unique set of challenges (for a full discussion see Section 3.6.7). In a first step, the interaction points between the SD and ABM modules are described and what information is exchanged and how.

Information from the ABM module is aggregated using a modified 'stocked agents' design (Swinerd & McNaught, 2012). Modelling stocked agents can be realised by either using the aggregated number of agents in a particular state as the current value of the respective stock or to influence the inflow of the corresponding stock in the SD module. In this case, the latter will be used for the inflows for licensing L, contract research $ICONR$, collaborative research

ICOL, consulting *ICON*, matured spin-offs *MSO* as well as the outflow closing *C* for spin-offs that have not survived. These flows are formalised in equations 6.2 to 6.7. This design is in line with one of the main underlying assumptions of the model, namely that all agents are limited to one interaction with one university at any point in time. For the agents, the time spent in one of these activities is not important, only for the universities and their resource internal allocations. Therefore, the SD module will use the input from the ABM module to calculate the stock of active interactions with companies and also create the outflow based on the average duration of each activity (as described in the previous section).

$$L_{j,t} = \sum_{i=1}^{i=A} e_{i,j,k=1,t} = \sum state1j \tag{6.2}$$

$$ICOL_{j,t} = \sum_{i=1}^{i=A} e_{i,j,k=2,t} = \sum state2j \tag{6.3}$$

$$ICONR_{j,t} = \sum_{i=1}^{i=A} e_{i,j,k=3,t} = \sum state3j \tag{6.4}$$

$$ICON_{j,t} = \sum_{i=1}^{i=A} e_{i,j,k=4,t} = \sum state4j \tag{6.5}$$

$$M_{j,t} = \sum stateM_j \tag{6.6}$$

$$C_{j,t} = \sum stateC_j \tag{6.7}$$

The inflow L has a distinctive feature as it depends on the availability of a patent at the time t when agent a_i approaches university j, i.e. $PAT_j(t) \geq 1$. This is checked in the ABM module before the agent can engage in the licensing activity. If the patent stock PAT is too low, the company agent is turned away and will remain in state 'W', which is the default 'working' state for all agents. Companies that approach a particular university might also not be able to actually engage with the university via consulting, contract or collaborative research because the university is already exceeding its entrepreneurial capital ec. Every time a company approaches a university, there is a probabilistic check for whether the university will be able to engage. If the university is operating below its entrepreneurial capacity, i.e. $ae \leq ec$, the probability of engaging with the company is one. If $ae > ec$, the probability gets increasingly lower and, the company agent might be rejected and remains in state 'W'.

Another distinctive stock is spin-offs SO, which is slightly different from the formerly described four stocked agents. The stock accumulates in the respective SD module for Alpha, Beta, and Gamma and, whenever the stock reaches the next highest integer number, a new agent is initialised in the ABM module as a spin-off company of the respective university. The stock has two outflows, maturing M and closing C, which have been described above.

The final interaction point between universities and firms is through external marketing of the universities, although the actual interaction between the modules is limited here. The number of companies that will be contacted by a university is pre-determined when the simulation is set up, this is also included as an input to the SD module and used to calculate the resource implications of these activities. This concludes all interaction points between the SD and ABM modules and a conceptual definition of how information from the ABM module is aggregated into stocks in the SD module as well as how information from the SD modules informs the ABM module.

6.2.3.3 Complex Events and Emergent Behaviour

To address the research questions, three types of complex events have to be identified: partnerships (repeated interactions between the same companies and universities), external marketing (interactions following marketing activities of universities), and reputational effects (interactions with universities following word-of-mouth among companies). These have been conceptualised in Figure 3.23 in Section 3.7.4. Partnerships represent a distinct form of complex events as they capture emergent behaviour at the interface of the ABM and one of the SD modules, yet they can neither be recognised through simple state aggregation of the agents, nor can they be observed from the respective SD module. The identification of all three types of complex events will be performed post-simulation (Szabo & Teo, 2013; Szabo et al., 2014).

The enabling conditions for this analysis are (1) all relevant activities and actions are represented with a unique company agent state, (2) an agent can only be in one of these states at any point in time, and (3) all states are recorded for all agents for the full duration of the simulation. The states have been presented in Section 5.4.2 and agents must, per definition, be in one of these at any point during the simulation. Figure 6.3 illustrates the states of four artificial agents a_1 to a_4 for ten time steps, hereby showing how the third condition is met. The technical details of how the simulation data are stored in practise and analysed will be explained in Section 6.4.3.

	$\mathbf{t_1}$		$\mathbf{t_2}$		$\mathbf{t_3}$		$\mathbf{t_4}$		$\mathbf{t_5}$		$\mathbf{t_6}$		$\mathbf{t_7}$		$\mathbf{t_8}$		...
$\mathbf{a_1}$	W	$\longrightarrow$	W	$\longrightarrow$	W	$\longrightarrow$	W	$\longrightarrow$	W	$\longrightarrow$	W	$\longrightarrow$	W	$\longrightarrow$	W	$\longrightarrow$	...
$\mathbf{a_2}$	W	$\longrightarrow$	W	$\longrightarrow$	W	$\longrightarrow$	11	$\longrightarrow$	W	$\longrightarrow$	W	$\longrightarrow$	W	$\longrightarrow$	W	$\longrightarrow$	...
$\mathbf{a_3}$	W	$\longrightarrow$	W	$\longrightarrow$	$M2$	$\longrightarrow$	W	$\longrightarrow$	W	$\longrightarrow$	32	$\longrightarrow$	W	$\longrightarrow$	$NS2$	$\longrightarrow$	...
$\mathbf{a_4}$	W	$\longrightarrow$	W	$\longrightarrow$	21	$\longrightarrow$	W	$\longrightarrow$	W	$\longrightarrow$	W	$\longrightarrow$	W	$\longrightarrow$	$NR2$	$\longrightarrow$	...

Figure 6.3: Pseudo states for agents a_1:a_4 during eight time steps

6.3 Parametrisation

This section presents the parameters and their sources for the SD and ABM modules for the baseline scenario, any changes for subsequent scenarios will be described in the respective sections of this chapter. The baseline scenario is parametrised with the aim of reaching an equilibrium state for all three universities with regard to each of the five entrepreneurial activities. The reference value is based on the median values of the respective universities that constitute each 'generic' university (further details are provided below, including which data are used for each module). While this does not directly correspond to the real world, it allows to create a benchmark for evaluating different interventions. Reproducing the behaviour of each generic university would have required an increased number of assumptions as the empirical data required is not available (see also Section 4.4.4.2). Consequently, both the effort required to develop the model as well as its complexity would have increased without an increase in the level of insights that the model delivers. On the other hand, addressing this issue by designing and conducting a large-scale data collection was beyond the scope of this project.

6.3.1 University Agents (SD)

Parametrisation is the penultimate step before running the simulation (assuming confidence building as an ongoing process rather than a distinct step). Parameters are not only required for running the simulation, but also provide another opportunity to contribute to building confidence by checking whether the identified or calculated parameters correspond to values observed in the real world and are consistent with everything else that is known about the system, including qualitative and descriptive information (Sterman, 2000). Table 6.2 summarises the parameters (initial values of stocks and constants) for the SD modules for Alpha, Beta, and Gamma as well as the respective sources for all parameters in alphabetical order.

In general, the parametrisation of the SD modules is based on two underlying principles. First, the averages for each university for the years of 2008/09 to 2014/15 were calculated and subsequently the median value for the universities that form the basis of Alpha, Beta, and Gamma, respectively. The median is used versus the mean to limit the influence of outliers, because the Scottish university sector is, despite a relatively small size of 14 institutions, still diverse with regard to performance, resources, and strategic objectives. Second, all absolute values such as the initial values for stocks, are calculated per 'entrepreneurial academic' for each university and then the median of those values for Alpha, Beta, and Gamma, respectively is multiplied with the number of entrepreneurial academics of the generic university. Any further assumptions and deviations from these two principles are discussed below.

HESA Table 7 provides the annual staff costs for all Scottish universities and in combination with the HESA Staff data, the number of 'Staff Budget' sb and the 'Avg Cost per Staff' cs could be estimated. However, an assumption had to be made with regard to cs and the 'Avg Project-Based Staff Cost' $pbsc$ because the data does not provide any insights at this level of granularity. While research- or teaching-only positions can be held at a variety of pay scales, similar to positions that involve research and teaching (i.e. lectureships, readerships, professorships), these are often held by post-docs as a transition step into academia. Therefore, the assumption is that $cs = 1.25 * pbsc$.

Data for HE-BCI Part A, Q15 ("Estimate the percentage of your academic staff (excluding the dedicated third stream staff returned under Q9 Infrastructure) who between 1 August 2012 & 31 July 2013 have directly provided services to: Commercial partners/clients") was missing. For Edinburgh Napier University in 2008/09, Heriot-Watt University 2009/10, Queen Margaret University Edinburgh 2008/09, and The University of the West of Scotland 2008/09. The missing values for 2008/09 were manually replaced with the values from 2009/10 and the missing value in 2009/10 with the values from 2008/09 and 2010/11 (which were the same in this case). Furthermore, this question was discontinued after the 2012/13 survey. Data entries for the years 2013/14 and 2014/15 were added manually and the value from 2012/13 was used for each university. Overall, the returned values from the universities do not have much variation, making this the option that carries the least added assumptions (which is in many cases also the average of the previous years) and is in line with the method used for adding missing values as described above. Adding all these values was necessary because a value for each university for each year is required for normalising the number of entrepreneurial activities by the number of entrepreneurial research academics.

The initial values of the stocks *CON*, *CONR*, *LIC* and *MLIC MSO*, and *SO* are based on the average for the years 2008/09-2014/15 for each university and the median value of the respective universities that constitute Alpha, Beta and Gamma. The annual number was then divided by 52 weeks (because the simulation is run with one week being one time step) and then multiplied by the average length of each activity. The stock *PAT* was calculated based on the size of the patent portfolio of the respective universities. The two stocks *LIC* and *MLIC* are based on the assumption that a patent is valid for ten years. The 'Avg Time-to-Market' *ttm* for *LIC* was set to four years (208 weeks) as an educated estimate based on an average of three to seven years from agreement to market (Friedman & Silberman, 2003) and seven years from discovery to market (Mansfield, 1991). Consequently, the 'Avg Length of Licensing' *licl* for *MLIC* was set to six years (520 weeks - 208 weeks = 312 weeks).

For collaborative research *COL*, there is only the total monetary value reported by universities, not the number of collaborative projects. From the Innovate UK database, which "includes data about all collaborative research and development (R&D), feasibility, smart and innovation voucher grants, and Knowledge Transfer Partnerships", the average value of collaborative projects was calculated.[58] Based on a total of 17498 projects that started between 01/08/2008 and 31/07/2015 (the same time period covered by HESA for this study), the average total cost of a collaborative project was £325,670.81.[59] The 'Avg Length of Collaboration' was *coll* is set to two years (104 weeks), which was supported by anecdotal evidence and also by the Innovate UK-funded projects, which had an average duration of 91 weeks.

'Research Workload Allocation' *rwa* is based on a combination of information about the author's institution, anecdotal evidence from other institutions,

[58] The database can be downloaded from https://www.gov.uk/government/publications/innovate-uk-funded-projects

[59] A higher value was calculated from 396 projects from the Technology Strategy Board, which have received £492,424.24 in grant funding on average (PACEC, 2011). However, this number includes projects with no academic institution involved (31% of all funded projects did not have any academic involvement) and also focuses on larger, typically technology-based projects whereas the Innovate UK database covers a greater variety of projects. Therefore, the latter was used in this case.

and information from Hughes et al. (2016), who have found that academics at 'top-decile research institutions' (Alpha) spend approximately 50.3% on research, for 'older Universities Est pre-1992' (Beta) this drops to 39.4%, and even further for 'younger universities est post-1992' (Gamma) to 25.1%. For Alpha ($rwa = 0.5$) and Beta ($rwa = 0.4$) these values were consistent with other sources. For Gamma ($rwa = 0.2$), a lower share was selected which seemed more on line with the practices at Scottish universities. The data by Hughes et al. (2016) also shows that academics spend an additional 8.1% on average in Scotland on knowledge exchange activities. However, academics' contracts typically do not have time dedicated to these activities. This time has to come out of either the academics' research or administrative time. While administrative tasks can usually be compromised, most academics use parts of their research time to engage with businesses. Therefore, the workload allocation for entrepreneurial activities wa for the baseline model is a subset of rwa (consistent with the workload restrictions mentioned in Section 5.3.3.7).

6.3.2 Company Agents (ABM)

Studies on innovation and collaboration usually over-represent larger and more innovative companies in particular sectors and often do not adjust for this in their analysis (Tether, 2002). This is also true for the CBR Business survey as shown in Table 6.3. This is corrected in the simulation and the values for a company agent's size S_i and innovativeness I_i are allocated based on the process outlined in Figure 6.4 to represent the size and innovativeness distribution of the UK business population. The probabilities for the three levels of innovativeness for each size band are derived from the UK Innovation Survey 2015.[60] These data only distinguish between SMEs (10-249 employees) and large companies (250+ employees), which means that the innovativeness distribution for company agents of size 1-3 are identical due to lack of data.

An overview of the variables for the ABM module and their sources is provided in Table 6.4. In the following, the methods behind the parametrisation of each agent is discussed. The basis is the categorisation into the twelve firm categories. Each agent in the same firm category has the same parameters initially.

The CBR Business Survey forms the basis for the company agent parametrisation. The survey has a total of 2,530 respondents, but not all of them are complete

[60] Department for Business Innovation & Skills (March 2016), Headline Findings from the UK Innovation Survey 2015, available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/506953/bis-16-134-uk-innovation-survey-2015.pdf

Table 6.2: Parameters of the SD modules

Name	Alpha	Beta	Gamma	Source
Initial values for stocks				
COL [projects]	87.76553	261.43404	23.99930	HE-BCI B Table 1
CON [projects]	17.32667	22.23535	7.30472	HE-BCI B Table 2
CONR [projects]	174.54790	157.89502	18.24698	HE-BCI B Table 1
LIC [licenses]	122.64130	151.47180	2.81166	HE-BCI B Table 4
MLIC [licenses]	183.96195	227.20770	4.21748	HE-BCI B Table 4
MSO [spin-offs]	41.70483	49.87049	2.39580	HE-BCI B Table 4
PAT [patents]	252.65147	175.70872	17.51233	HE-BCI B Table 4
SO [spin-offs]	5.38501	8.58433	0.41093	HE-BCI B Table 4
Values of constants				
aicol [staff FTE/project]		0.10		Estimate
aicon [staff FTE/project]		0.50		Estimate
aiconr [staff FTE/project]		0.10		Estimate
ailic [staff FTE/license]		0.10		Estimate
aiso [staff FTE/spin-off]		0.20		Hewitt-Dundas (2015)
bf [£000/week]	1,573.39671	797.12312	505.14401	HESA Finance Table 7
coll [weeks]		104		Estimate
colv [£000/project/week]	5.38877	4.08810	2.47668	HE-BCI B Table 1
conl [weeks]		4		Estimate
conrl [weeks]		26		Estimate
conrv [£000/project/week]	1.22591	1.68184	0.49181	HE-BCI B Table 1
conv [£000/project/week]	5.48771	2.20208	1.02897	HE-BCI B Table 2
cs [£000/staff FTE]	1.28000	1.24130	1.13562	HESA Finance Table 7
disr [disclosures/staff FTE]	0.00887	0.00345	0.00092	HE-BCI B Table 4
dr [1/week]		0.006		Estimate
dfr [spin-offs/disclosures]	0.00018	0.00009	0.00000	HE-BCI B Table 4
fr [spin-offs/staff FTE]	0.00000	0.00022	0.00000	HE-BCI B Table 4
ifr [spin-offs/patent]	0.00023	0.00031	0.00008	HE-BCI B Table 4
licl [weeks]		312		Estimate
licv [£000/license]	0.06017	0.10009	0.13750	HE-BCI B Table 4
pbsc [£000/staff FTE]	1.02400	0.99304	0.90850	HESA Finance Table 7
pr [patents/disclosures]	0.01618	0.01136	0.00800	HE-BCI B Table 4
rwa [dimensionless]	0.50	0.40	0.20	Estimate
sea [dimensionless]	0.10000	0.29286	0.12571	HE-BCI A 02 Infrastructure Q15
ttm [weeks]		208		Friedman & Silberman (2003); Mansfield (1991)
wa [dimensionless]	0.45	0.35	0.15	Estimate

Table 6.3: Share of companies by size

Category	Survey[1]	UK Reality[2]
1 (1-9)	39.50%	81.60%
2 (10-49)	42.50%	15.38%
3 (50-249)	8.00%	2.49%
4 (250+)	10.00%	0.53%

Notes:
[1] CBR Business Survey; for the analysis, the data was weighted based on the "distribution of firms in terms of employment size, sector and region" (Hughes & Kitson, 2013, p. 120).
[2] Rhodes (2015)

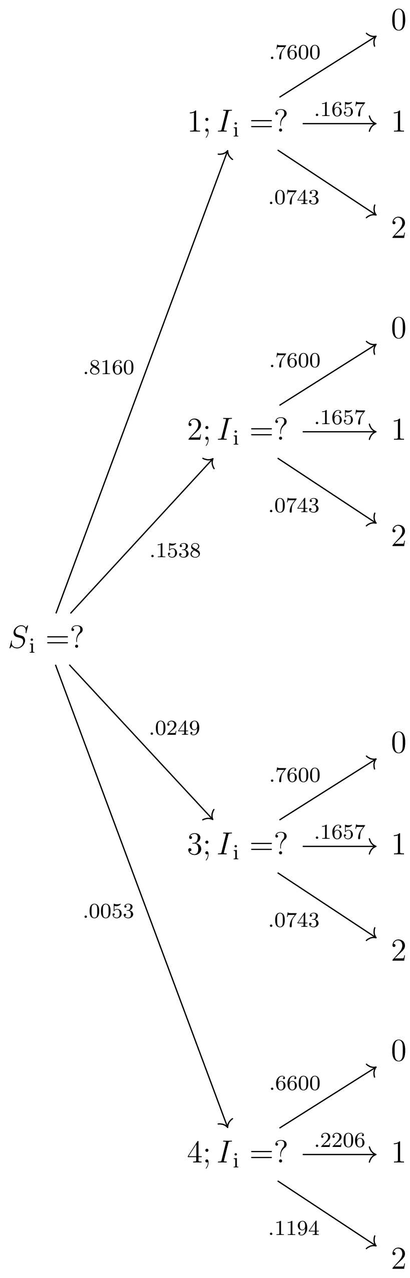


Figure 6.4: Allocation of agent characteristics size S_i and innovativeness I_i

Table 6.4: Overview of ABM variables and sources

Name	Variable	Values	Source
Population	A	26,887	Optimised to fit demand
Size	S_i	1;2;3;4	CBR Business Survey, Rhodes (2015)
Innovativeness	I_i	0;1;2	CBR Business Survey, BIS (2016)
Propensity	N_i	[0,1[	CBR Business Survey, HE-BCI
Preference	$P_{i,k}$	[0.01,0.98]	Optimised based on Laursen et al. (2011)
Experience	E_i	[0,1040]	n/a
Success rate	ts_i	[0,1]	CBR Business Survey
Update probability (successful)	$tu_{i,U=1}$	[0,1]	CBR Business Survey
Update probability (unsuccessful)	$tu_{i,U=0}$	[0,1]	CBR Business Survey
Increase need by	ni_i	[0,1]	Hewitt-Dundas et al. (2019, p. 1318)
Maturing threshold	$m_{i,f}$	0.61	Ulrichsen (2019)
Maturing age	t_m	156	HESA guidelines

responses. For example, the question regarding whether or not a company engaged in licensing ('res1') was only answered by 671 respondents and whether or not a company engaged in consulting ('probact6'), contract ('probact4') or collaborative research ('probact3') was answered by 2,480 respondents (including all 671 respondents to 'res1'). The missing values were treated as 'no' responses to not reduce the sample size as it is most likely that those who did not answer did not participate in said activities.

When activated, each agent checks its need for external input. This probability of engaging in either activity is based on those four variables. As part of question 'res1', survey respondents could indicate whether they never (0), infrequently (1-2), frequently (3-6), or very frequently (7+) acquired a patent from an HEI. No company ticked the very frequent option, for the infrequent and frequent options the mean value of the boundaries, i.e. 1.5 and 4.5 are used to determine how many licenses have been taken by each firm category $n_{i,k=1}$. For all other activities, companies could only indicate whether or not they performed that particular activity within the past three years, but not the frequency. Therefore, licensing was considered the most accurate variable and used as a reference to calibrate the other variables.

There are no variables that link the CBR Business Survey for the agents to the HESA/HE-BCI datasets for the universities. Therefore, this data had to be matched manually and optimised to create an equilibrium. The annual number of each activity for all universities from the SD data were added together and then divided by the cumulative licensing stock. Similarly, for a given number of agents, the resulting demand for each activity was calculated and divided by the demand for licensing. The ratios of each activity to licensing from the agents and the universities were then divided and the need for each firm category is multiplied by this. As a result, the initial ratios of consulting, contract and collaborative research divided by licensing from the demand created by the agents is adjusted to replicate the ratios in the SD data.

Having established the propensity to engage in each of the four activities for each firm category as well as the share of each firm category among the whole agent population, the overall demand can be calculated for any given number of agents A. This number was then optimised manually to provide the best fit with the initial values of the stocks from the SD modules (the sum for each activity for all three universities). With an agent population of $A = 26,887$, the demand from industry would keep these stocks in equilibrium.

One of the key assumptions of the model is that companies initiate the interactions with universities. Accordingly, the preference P_i of each company to approach either of the three universities is a key component of the model. P_i must now be determined for each firm category so that the overall demand is spread across the three universities so that equilibrium is reached for each university and not just for the demand as a whole. The CBR Business Survey does not include information about specific universities, only whether the academic partner(s) were in the local area, region, rest of the UK, rest of Europe, or in the rest of the world (except for licensing). This is, however, not helpful in this case. First, the location information of the agents is unknown in this version of the dataset, which means that there is no point of reference. Second, cities such as Edinburgh, Glasgow, or Aberdeen host universities that form the basis for more than one of the generic universities, which means that in the case of the former two cities, 'local' could be either a world class research university (Alpha) or a teaching-led university (Gamma).

An initial set of preferences for each activity per firm category was estimated based on the literature (mainly based on Laursen et al., 2011). The essence of this initial estimate was that the larger the firm, the more it prefers Alpha over Beta and Gamma, and the larger the company, the more it prefers working with Alpha. Using the MS Excel solver, the university preferences for all firm categories have then been optimised so that the created demand from all companies matches the initial stocks for each activity for each of the three universities.

The CBR Business Survey provides a number of success measures for companies. Because these cannot be tied to individual activities or even types of activities, each company in the CBR dataset was assigned a binary value of whether or not its interactions with universities were successful. This binary value was constructed through a multi-stage process. First, all variables 'prsucs1'-'prsucs6' and ‘susucs1’-‘susucs4’ were assigned a binary value of ‘1’ if successful, ‘-1’ if not, and ‘0’ for no response. For every company, these values were added to have a success score. This score was then again transformed into a binary value and assigned the value ‘1’ if the sum was ≥ 1 or ‘0’ if the sum was < 1. Through cross-tabulation, the number of successful and unsuccessful companies within each firm category were determined and the share of successful interactions became the success rate ts_i for each firm category.

For each firm category, the binary success measure was subsequently cross-tabulated with the ‘knowlex1’ variable with measures “Impact: It has led to new projects with HEIs”. The share of positive responses to ‘knowlex1’ for successful and unsuccessful interactions are defined as the ‘update probability (successful)’ $tu_{i,U=1}$ and ‘update probability (unsuccessful)’ $tu_{i,U=0}$, respectively. While only a small fraction of the companies answered these questions in the CBR Business Survey (‘knowlex1’ has <20 responses per firm category), which limits statistical analyses, this is still the best data available to quantify the evaluation and updating processes. The final set of parameters for all non-spin-off company agents by firm category is presented in Table 6.5.

University spin-off companies have a higher propensity for engaging with universities and their preference is skewed towards the parent university (see Section 5.4.1.2). Therefore, these agents have different parameters than non-spin-off agents. There are no data that specifically describe the characteristics and engagement behaviour of spin-offs with both their parent university as well as other academic institutions. Using the distribution of size and innovativeness for the regular business population, the assumption is that every spin-off is always one category higher. For example, if a new spin-off a_i is assigned size $S_i = 1$ and innovativeness $I_i = 1$, these will be changed to $S_i = 2$ and $I_i = 2$. The reason for this is that this model is not concerned with how well spin-offs perform or whether they grow, similar to all businesses, but their interaction with universities. And the likelihood of this happening is higher for spin-offs compared to other companies. This can be justified by their scientific roots and the additional scrutiny that university spin-offs undergo before they even get officially formed, which other start-up ideas do not have, among others.

Spin-offs, in their early stage (i.e. when part of the stock SO), go through an additional action in the first t_m time steps before, if successful, mature and enter the stock MSO. HESA provides survival rate based on a three-year time frame, so t_m will be three years (156 weeks). This is longer than average maturing time of two years (Hewitt-Dundas, 2015, which was also mentioned by interviewees),

Table 6.5: Parameters for non-spin-off agents ($O_i = 0$)

	Firm category[1]											
Variable	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
S_i	1	2	3	4	1	2	3	4	1	2	3	4
I_i	0	0	0	0	1	1	1	1	2	2	2	2
$n_{i,k=1}$	0.00000	0.00002	0.00038	0.00012	0.00011	0.00000	0.00013	0.00016	0.00035	0.00013	0.00053	0.00170
$n_{i,k=2}$	0.00004	0.00007	0.00025	0.00131	0.00026	0.00030	0.00038	0.00089	0.00050	0.00080	0.00170	0.00260
$n_{i,k=3}$	0.00017	0.00018	0.00145	0.00424	0.00122	0.00135	0.00149	0.00526	0.00131	0.00248	0.00504	0.01059
$n_{i,k=4}$	0.00016	0.00022	0.00071	0.00417	0.00090	0.00155	0.00183	0.00259	0.00129	0.00208	0.00198	0.00568
$p_{i,k=1,\alpha}$	0.30000	0.60529	0.60662	0.72544	0.36727	0.60000	0.82968	0.81056	0.34434	0.71141	0.82123	0.91954
$p_{i,k=1,\beta}$	0.50000	0.38471	0.38338	0.25830	0.62273	0.35000	0.16032	0.15344	0.64566	0.27859	0.16877	0.07046
$p_{i,k=1,\gamma}$	0.20000	0.01000	0.01000	0.01626	0.01000	0.05000	0.01000	0.03600	0.01000	0.01000	0.01000	0.01000
$p_{i,k=2,\alpha}$	0.01709	0.45521	0.62021	0.62378	0.02417	0.47148	0.77708	0.78362	0.19616	0.54811	0.74147	0.86996
$p_{i,k=2,\beta}$	0.90895	0.49341	0.32563	0.32549	0.89639	0.47730	0.17267	0.16621	0.74795	0.40011	0.20449	0.07716
$p_{i,k=2,\gamma}$	0.07395	0.05138	0.05416	0.05073	0.07944	0.05122	0.05025	0.05016	0.05590	0.05178	0.05405	0.05288
$p_{i,k=3,\alpha}$	0.21888	0.58369	0.67835	0.68831	0.44497	0.57284	0.79515	0.79528	0.63723	0.67758	0.79265	0.89412
$p_{i,k=3,\beta}$	0.62270	0.37467	0.28275	0.26769	0.54217	0.39100	0.15734	0.15734	0.34480	0.28386	0.16112	0.05800
$p_{i,k=3,\gamma}$	0.15842	0.04164	0.03890	0.04401	0.01286	0.03616	0.04751	0.04738	0.01797	0.03856	0.04624	0.04789
$p_{i,k=4,\alpha}$	0.01097	0.53966	0.66841	0.67229	0.30908	0.50558	0.78200	0.79745	0.51340	0.64314	0.79140	0.89202
$p_{i,k=4,\beta}$	0.70018	0.38747	0.26982	0.27026	0.52998	0.40828	0.16115	0.15363	0.36540	0.28507	0.15539	0.05139
$p_{i,k=4,\gamma}$	0.28886	0.07287	0.06178	0.05745	0.16095	0.08615	0.05685	0.04892	0.12120	0.07179	0.05322	0.05659
ts_i	0.57143	0.58333	1.00000	0.72222	0.66667	0.58824	0.66667	0.72727	0.80000	0.57576	0.75000	0.79545
$tu_{i,U=1}$	0.33333	0.14286	0.66667	0.15385	0.37500	0.30000	0.25000	0.37500	0.31250	0.47368	0.66667	0.60000
$tu_{i,U=0}$	0.00000	0.00000	0.00000[2]	0.50000	0.00000	0.00000	0.00000	0.33333	0.33333	0.36364	0.33333	0.33333
ni_i	0.00131	0.00131	0.00125	0.00162	0.00131	0.00131	0.00125	0.00162	0.00131	0.00131	0.00125	0.00162

Notes:
[1] Firm category are the twelve unique combinations of size S_i and innovativeness I_i.
[2] No data but also not relevant as all interactions are successful ($ts_i = 1$).

but it also takes an average of over seven years (standard deviation of 4.36 years) to generate revenues (Hewitt-Dundas, 2015). Therefore, considering three years for the maturing phase is a reasonable assumption. There are different survival rates of spin-offs in the UK, ranging from 70% (Wright & Fu, 2015) to 88% in the Beauhurst database, 60% of those covered by Spinouts UK, and 75% identified by Gateway to Research (Ulrichsen, 2019). The latter three have been combined into a comprehensive database with a survival rate of 61% (Ulrichsen, 2019), which will be used in this simulation ($m_s = 0.61$). All spin-offs that are created when the simulation is set up are assigned an initial age, which is uniformly distributed between 0 and 156 weeks, i.e. the maturing age. Spin-offs that are created throughout the simulation are initialised with age zero. Spin-off formation, maturing, and closing are recognised as states, otherwise the spin-off is working like every other company and might engage with a university.

6.4 Simulation Platform and Coding

Hybrid simulations promise to offer novel insights by combining desirable features from different simulation methods, but also pose additional challenges at the philosophical, cultural, cognitive, practical, and methodological level (see Section 3.6.6). At the operational level, the main challenges is finding the right platform to implement and execute the simulation and analyse the results. This section will present the approach used in this thesis and the implications.[61]

6.4.1 Simulation Model

There are numerous software platforms available for simulating SD, ABM, and even dedicated options for HS (Borshchev & Filippov, 2004). In terms of performance, the simulation platform has a more significant impact in ABM compared to SD. The main reason for this is sheer amount of computations for individual agents' interactions that need to be computed in ABM and their non-deterministic nature compared to the relatively simple (from a mathematical point of view) solving of differential equations in SD. ABM platforms vary greatly with regard to their features and requirements for the modeller (Abar et al., 2017). Despite these offerings, the simulations in this study were coded from scratch in Java.[62]

[61]Source code for both the simulation as well as the analysis of the results are not included the appendix for environmental reasons but can be supplied electronically by the author upon request.

[62]The basic structure of the ABM module as well as the data input/output functions were adapted from the work of Dr Andy Evans (University of Leeds). For further information see:

Table 6.6: Parameters for Alpha spin-off agents ($O_i = 1$)

Variable	Firm category[1]											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
S_i	1	2	3	4	1	2	3	4	1	2	3	4
I_i	0	0	0	0	1	1	1	1	2	2	2	2
$n_{i,k=1}$	-	-	-	-	-	0.00000	0.00013	0.00016	-	0.00013	0.00053	0.00170
$n_{i,k=2}$	-	-	-	-	-	0.00083	0.00103	0.00242	-	0.00217	0.00464	0.00709
$n_{i,k=3}$	-	-	-	-	-	0.00062	0.00069	0.00242	-	0.00114	0.00232	0.00487
$n_{i,k=4}$	-	-	-	-	-	0.00111	0.000132	0.00186	-	0.00149	0.00142	0.00408
$p_{i,k=1,\alpha}$[2]	-	-	-	-	-		0.90		-		0.90	
$p_{i,k=1,\beta}$	-	-	-	-	-		0.05		-		0.05	
$p_{i,k=1,\gamma}$	-	-	-	-	-		0.05		-		0.05	
$p_{i,k=2,\alpha}$	-	-	-	-	-		0.90		-		0.90	
$p_{i,k=2,\beta}$	-	-	-	-	-		0.05		-		0.05	
$p_{i,k=2,\gamma}$	-	-	-	-	-		0.05		-		0.05	
$p_{i,k=3,\alpha}$	-	-	-	-	-		0.90		-		0.90	
$p_{i,k=3,\beta}$	-	-	-	-	-		0.05		-		0.05	
$p_{i,k=3,\gamma}$	-	-	-	-	-		0.05		-		0.05	
$p_{i,k=4,\alpha}$	-	-	-	-	-		0.90		-		0.90	
$p_{i,k=4,\beta}$	-	-	-	-	-		0.05		-		0.05	
$p_{i,k=4,\gamma}$	-	-	-	-	-		0.05		-		0.05	
ts_i	-	-	-	-	-	0.58824	0.66667	0.72727	-	0.57576	0.75000	0.79545
$tu_{i,U=1}$	-	-	-	-	-	0.30000	0.25000	0.37500	-	0.47368	0.66667	0.60000
$tu_{i,U=0}$	-	-	-	-	-	0.00000	0.00000	0.33333	-	0.36364	0.33333	0.33333
ni_i	-	-	-	-	-	0.00131	0.00125	0.00162	-	0.00131	0.00125	0.00162
t_m	-	-	-	-	-		156		-		156	
m_s	-	-	-	-	-		0.61		-		0.61	

Notes:
[1] Firm category are the twelve unique combinations of size S_i and innovativeness I_i.
[2] Same principle for Beta ($p_{i,\alpha} = 0.05$, $p_{i,\beta} = 0.90$, $p_{i,\gamma} = 0.05$) and Gamma spin-offs ($p_{i,\alpha} = 0.05$, $p_{i,\beta} = 0.05$, $p_{i,\gamma} = 0.90$).

The characteristics of object-oriented programming languages, such as Java, correspond well to the principles of agent-based modelling and simplify coding large projects (Axelrod, 1997). Java is still not the most popular choice among authors in the Journal of Artificial Societies and Social Simulation (JASSS; a leading journal for the use of simulations and ABMs in particular for the study of social systems), but the popular software platforms Repast (the high-performance computing [HPC] version is based on C++) and Mason are Java-based applications too, which does give it a significant 'market share' (Thiele et al., 2012).

Brailsford et al. (2013) reported that switching from modelling multiple SD modules in AnyLogic, a commercial software designed to implement HS, to using a *pure* Java code for the differential equations increased the performance by a factor of 100. There are no dedicated Java libraries for SD modelling known to the author (see also Caulfield et al., 2011) and the algorithms for solving the differential equations were developed from scratch using Euler's method.

6.4.2 Result Visualisation

A layered approach is used that separates running the simulation from the data analysis of the results to streamline the simulation and speed up the run time. A similar approach was suggested by e.g. Brailsford et al. (2013) and Thiele et al. (2012). Results from the Java simulation were exported to .csv files and analysed subsequently using R. R is a free and open source software platform for statistical analyses and data science.[63] All graphics were produced with 'ggplot2'[64] and 'cowplot'[65] for grid plots.

6.4.3 Complex Event Analysis

From a methodological point of view, a unique and defining aspect of this thesis is the identification of emergent behaviour through the use of complex events. This is realised using TraMineR package, which is an add-on package for R and, therefore, allows building on the general results analyses and visualisations framework (e.g. the input procedures and data storage). While not specifically designed to analyse ABM result, TraMineR works very well with complex events:

> "TraMineR is a R-package for mining and visualizing sequences of categorical data. Its primary aim is the knowledge discovery from event

http://www.geog.leeds.ac.uk/courses/other/programming/summer-school/

[63]For further information see https://www.r-project.org

[64]https://ggplot2.tidyverse.org

[65]https://cran.r-project.org/web/packages/cowplot/vignettes/introduction.html

or state sequences describing life courses, although most of its features apply also to non-temporal data such as text or DNA sequences for instance." (Gabadinho, Ritschard, Studer, & Müller, 2011, p. 9)

The features and procedures of this package allow the analysis and visualisation of sequence data, including (Gabadinho, Ritschard, Studer, & Müller, 2011, p. 10):

- handling a large number of state and time stamped event sequence representations, simple functions for transforming to and from different formats;
- individual sequence summaries and summaries of sequence sets;
- selecting and displaying the most frequent sequences or subsequences;
- various metrics for evaluating distances between sequences; and
- aggregated and index plots of sets of sequences.

TraMineR works more efficiently and faster than other packages that deal with sequential data (Gabadinho, Ritschard, Studer, & Müller, 2011). For the analysis of complex events, sequences of states are used as opposed to event sequences. A sequence can be defined as "an ordered list of elements, where an element can be a certain status (e.g., employment or marital status), a physical object (e.g., base pair of DNA, protein, or enzyme), or an event (e.g., a dance step or bird call)" (Brzinsky-Fay et al., 2006, p. 435). These elements are in a fixed order, typically longitudinal. In this case, the elements are the agents' states depending on their behaviour, which are ordered by the elapsed simulation time (see Section 6.2.3.3).

6.5 Baseline Model Results

The results of the baseline model are based on the SFD presented in Figure 6.1 and the company agents' behaviour as outlined in Section 5.4.2 without the two 'marketing' rules R_{MKT1} and R_{MKT2}. The presentation of the simulation output is divided into three parts, namely the university agents' behaviour, the company agents' behaviour, and the identification of complex events.

6.5.1 University Behaviour

The model was parametrised with the aim of being in equilibrium for the baseline model. The results are presented in Figure 6.5 with all five activities per university and the same data organised per activity for better comparison between universities in Figure 6.6. The five activities, with the exception of licensing for Beta, are in equilibrium. The small increase in each activity over time is caused by the evaluation and updating rules of the agents after each interaction.

The results show distinct patterns in the relative importance of some activities for each university as well as some similarities across universities. The simulation reproduces the behaviours previously discussed when developing the three generic universities (Section 5.3.1) and their characteristics (Section 5.3.2). Overall, Alpha (Figure 6.5A) and Beta (Figure 6.5B) have substantially higher levels across all activities compared to Gamma (Figure 6.5C). With regard to the relative importance of individual activities, consulting (Figure 6.6B) and spin-offs (Figure 6.6E) are significantly lower for all universities. For consulting, this is partially explained by the short duration of the activity ($conl = 4$ weeks) compared to e.g. collaborative research ($coll = 104$ weeks). The levels of contract research (Figure 6.6C) and licensing (Figure 6.6D) are similar for Alpha and Beta, whereas Beta shows significantly higher levels of collaborative research compared to Alpha and, by extension, Gamma (Figure 6.6A).

All commercialisation-related stocks are plotted in Figure 6.7. This figure highlights that the demand for licenses from Beta from industry is higher than Beta's patenting rate, which results in a decline in the patent portfolio PAT. Ultimately, this means that the university has to turn away companies that want to license IP. Future patents will be licensed very shortly after they have been granted. This corresponds to a change in patenting behaviour that interviewees from Beta universities mentioned, essentially only filing a patent if there is a licensing opportunity on the horizon. Patenting budgets have declined over the years and universities are rarely taking a chance at a technology if there is no apparent opportunity to recover the costs at least.

The decline in licensing for Beta has two implications for the university. These are the income generated through this activity and for the capacity utilisation. Figure 6.8 shows the income for all three universities. Despite the attention that commercialisation activities receive both in the academic literature and from policy makers, the income that universities generate from licensing is negligible compared to consulting, contract and collaborative research. Therefore, the decline in licensing income for Beta does not affect the overall income situation for the university.

In terms of the capacity impact, Figure 6.9 shows ‘Academic Entrepreneurship’ *ae*, i.e. the FTE equivalent of all academic staff involved in entrepreneurial activities and the ‘Entrepreneurial Capacity’ *ec*, i.e. the maximum FTE equivalent staff can combined spend on entrepreneurial activities without harming the universities goals and other commitments such as teaching. Figure 6.10 shows the ‘Capacity Utilisation’ *cu*, which is the quotient of *ae* and *ec*. The decline in licensing is reflected in a decline in *ae* and *cu* for Beta, which means that the university had the potential to engage in additional activities while staying within its capacity. Both measures, *ae* and *cu* will be used again when comparing scenarios against each other as well as against the baseline when experimenting with the model.

Lastly, Figure 6.11 shows the ‘Independent Research Focus’ *irf* per university as the quotient of independent research and entrepreneurial activities. Not surprisingly, Alpha has the highest value as it is generated from ancient, research-intensive universities. Surprisingly, Gamma scores high and is much ahead of Beta. This is, however, not an indicator of research quality and two issues must be considered here. First, a key aspect of Beta is the focus on high-quality applied research that has a real-world impact. Therefore, scoring lower on this measure is not a surprise. Second, only five formal activities are considered in this study and it is likely, that academics at Gamma are more involved in other activities involving companies (Hughes et al., 2016). Therefore, Gamma’s ‘true’ score is probably lower if those were considered as well. In any case, these activities are important for all universities, particularly Beta, to supplement their academic base who are on permanent contracts with project-funded research staff (Figure 6.12).

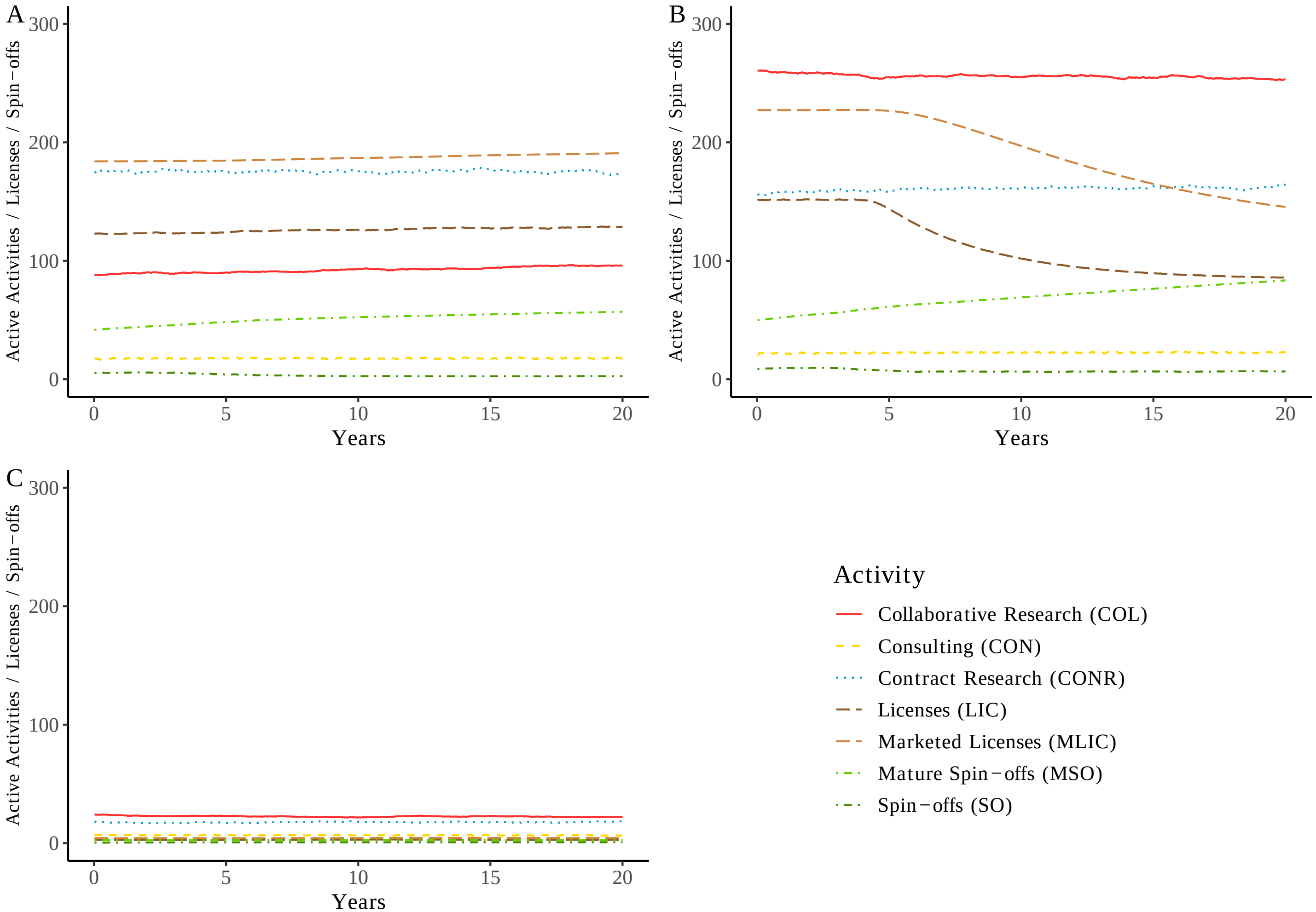


Figure 6.5: Simulation output for the baseline scenario for each university, namely Alpha (A), Beta (B), and Gamma (C).

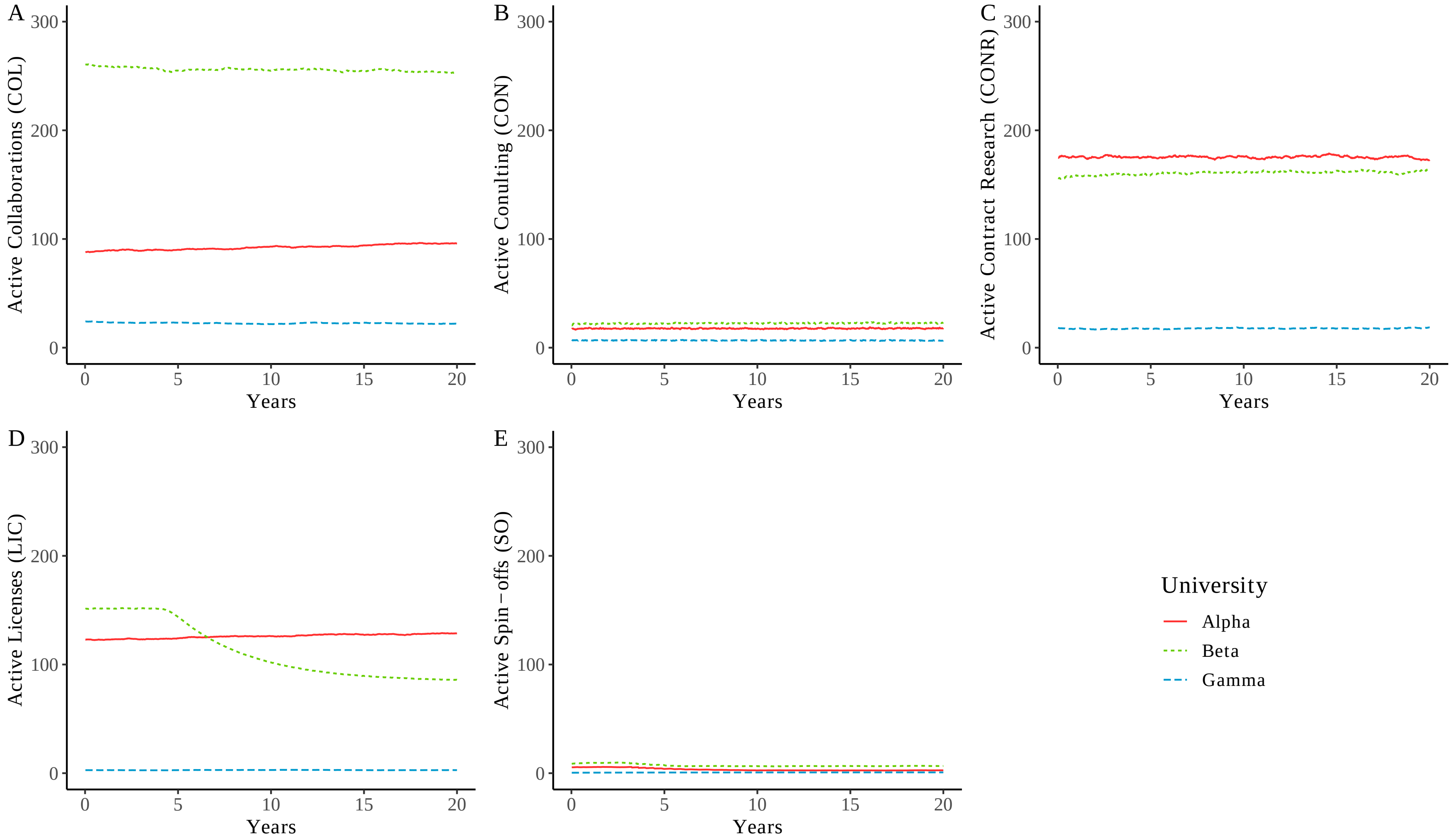


Figure 6.6: Simulation output for the baseline scenario showing the five entrepreneurial activities, namely COL (A), CON (B), CONR (C), LIC (D) and SO (E).

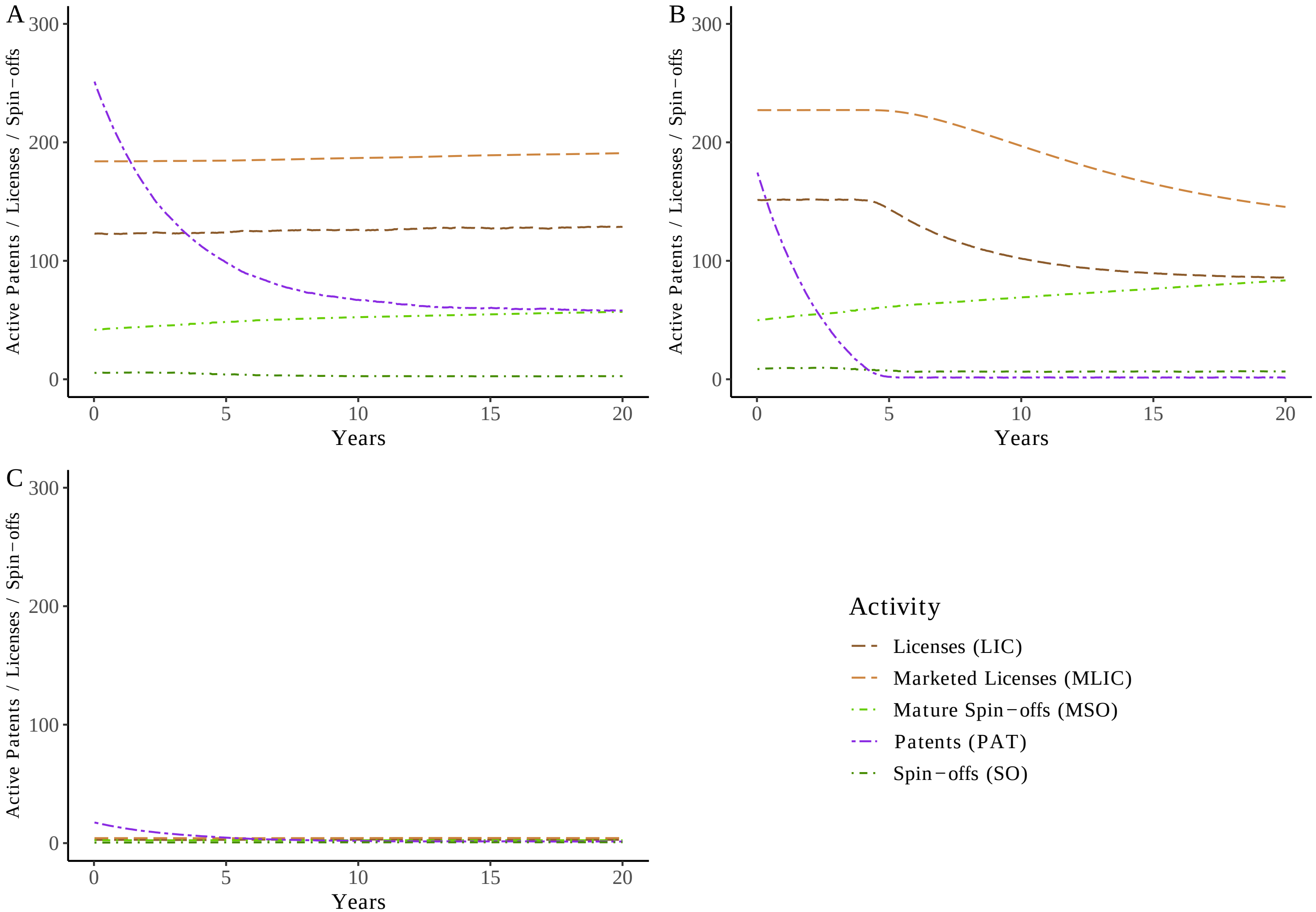


Figure 6.7: Simulation output showing commercialisation activities for baseline scenario for Alpha (A), Beta (B), and Gamma (C).

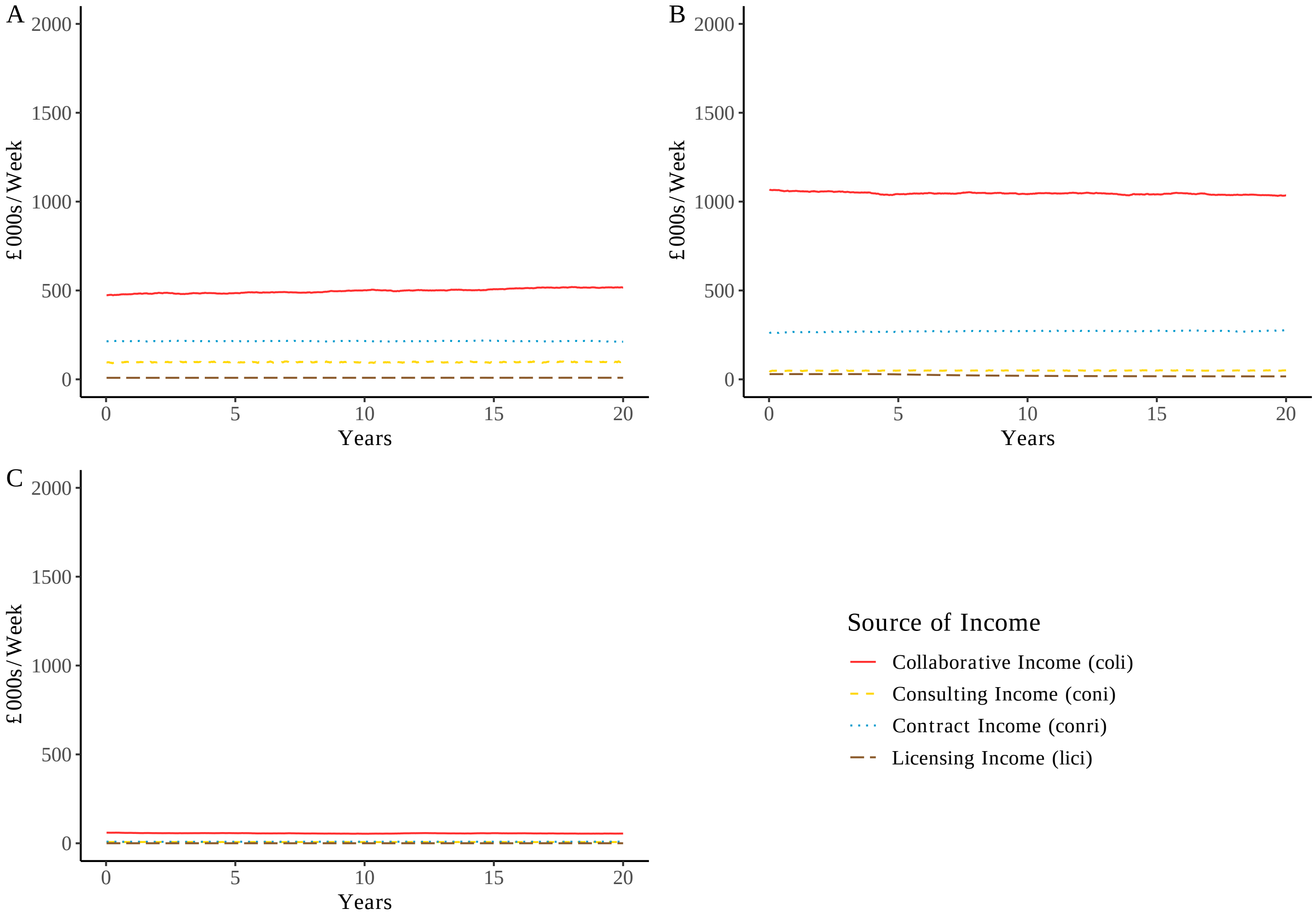


Figure 6.8: Simulation output showing the income from entrepreneurial activities for the baseline scenario for Alpha (A), Beta (B), and Gamma (C).

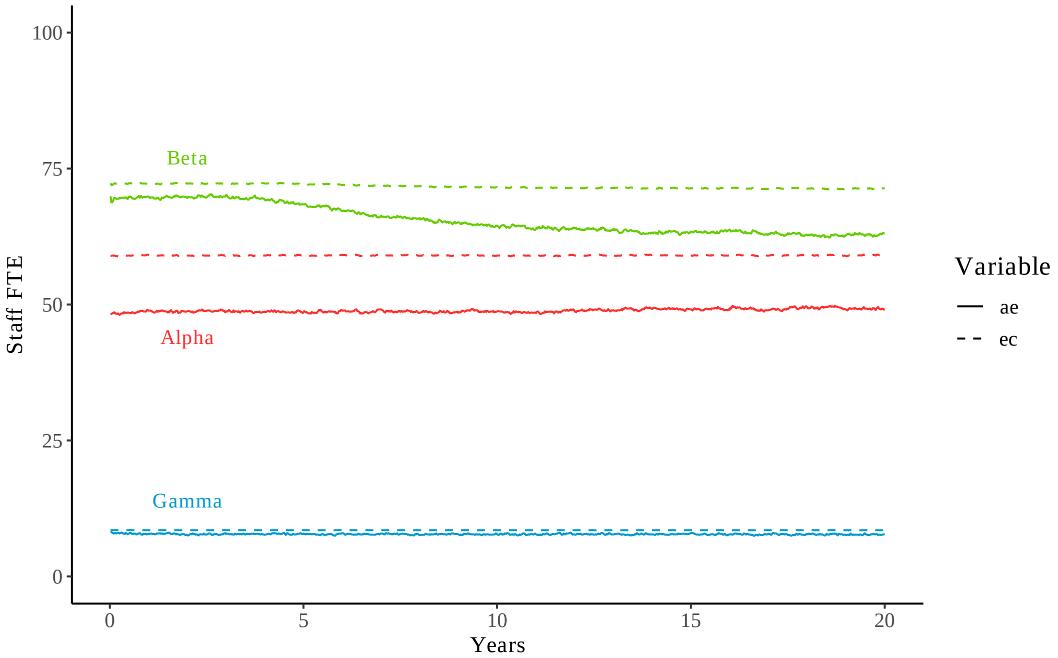


Figure 6.9: Simulation output showing 'ae' and 'ec' for the baseline scenario for all universities.

6.5.2 Company Behaviour

The behaviour of company agents shows a near-exponential relationship between the number of agents and their experience (Figure 6.13). A large number of agents have very little or no experience at all, whereas a small number of agents has a high level of experience of working with Scottish universities. More than 6,000 agents had one interaction with a university during the 20 years of the simulation, which is approximately one in four firms of the agent population.

This can be further broken down by company characteristics. Overall, large firms ($S_i = 4$, i.e. firm categories 4, 8 and 12) as well as more innovative firms ($I_i = 2$, particularly firm categories 10, 11, and 12) have more experience (Figure 6.14). Firms in category 12, i.e. large and highly innovative companies, combine the resources required with the absorptive capacity to benefit from interactions with universities. Figure 6.14 also shows that large companies with low ($I_i = 0$, firm category 4) and medium degrees of innovativeness ($I_i = 1$, firm category 8) have a similar median number of interactions with universities, with the former category (4) having a higher third quartile and maximum value compared to more other large, but more innovative companies (8).

A second aspect of the behaviour of company ages is their transition between states. Transition rates provide "information about the most frequent state changes observed in the data together with, on the diagonal, an assessment of

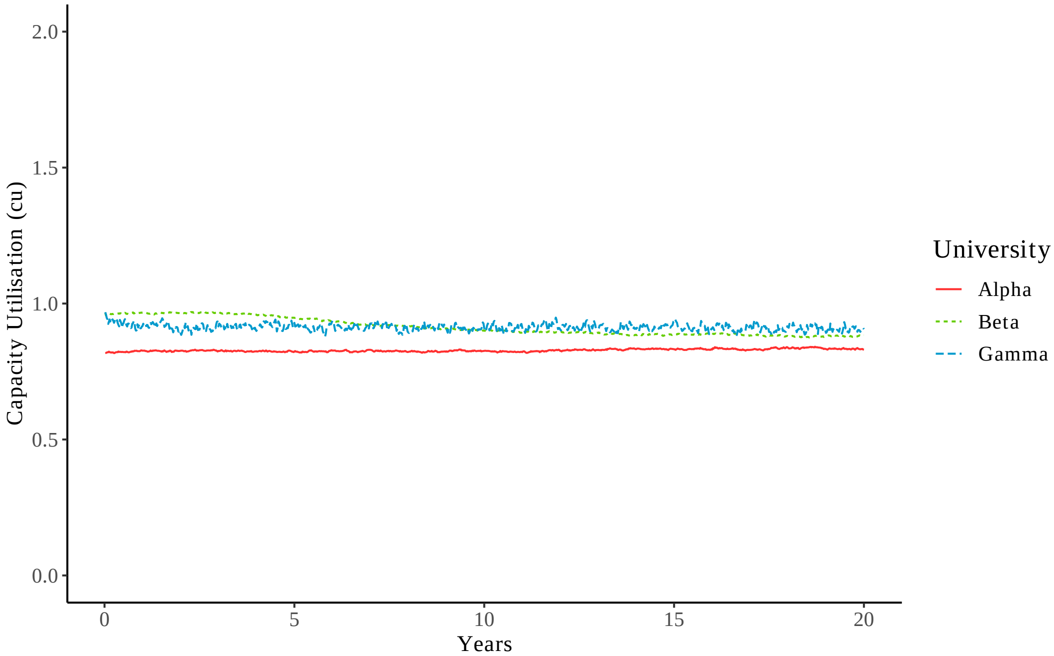


Figure 6.10: Simulation output showing ‘cu’ for the baseline scenario for all universities.

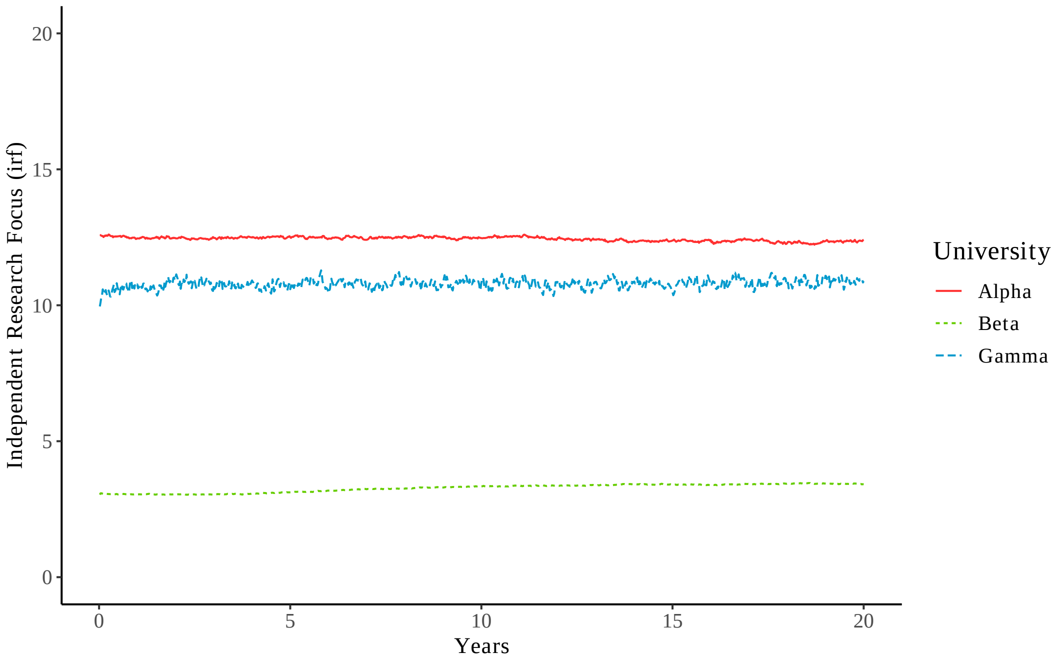


Figure 6.11: Simulation output showing ‘irf’ for the baseline scenario for all universities.

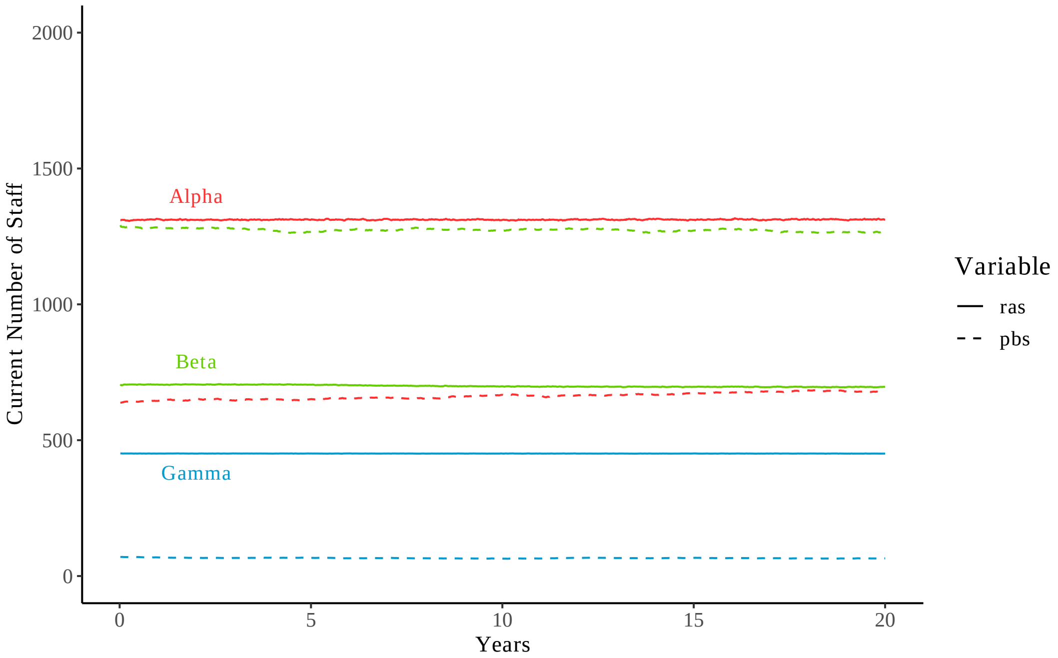


Figure 6.12: Simulation output showing 'ras' and 'pbs' for the baseline scenario for all universities.

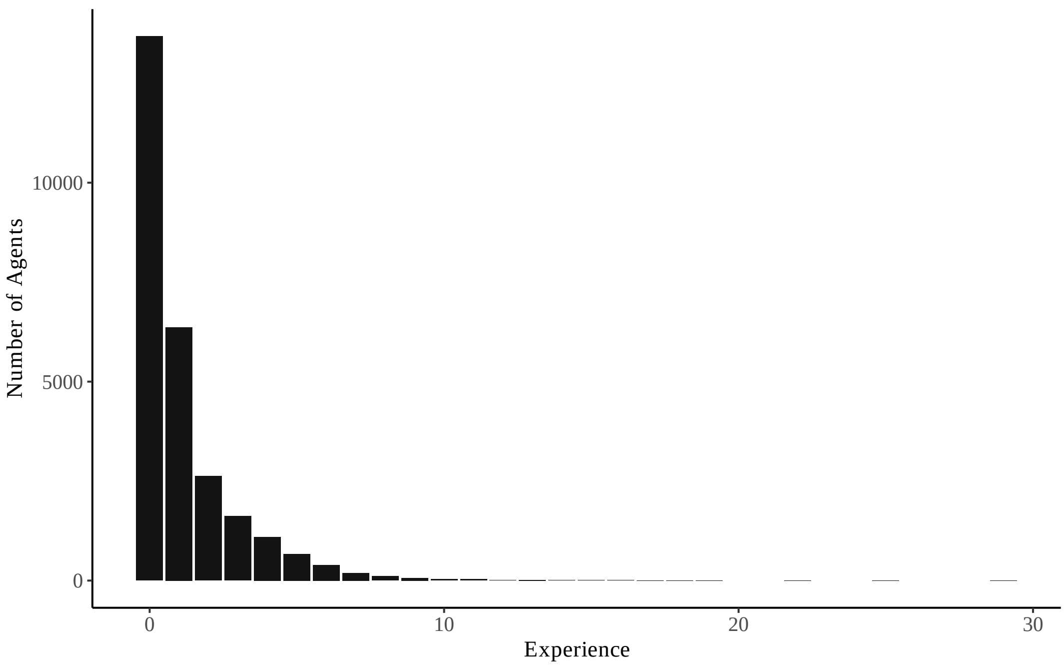


Figure 6.13: Frequency plot of experience for company agents from the baseline simulation.

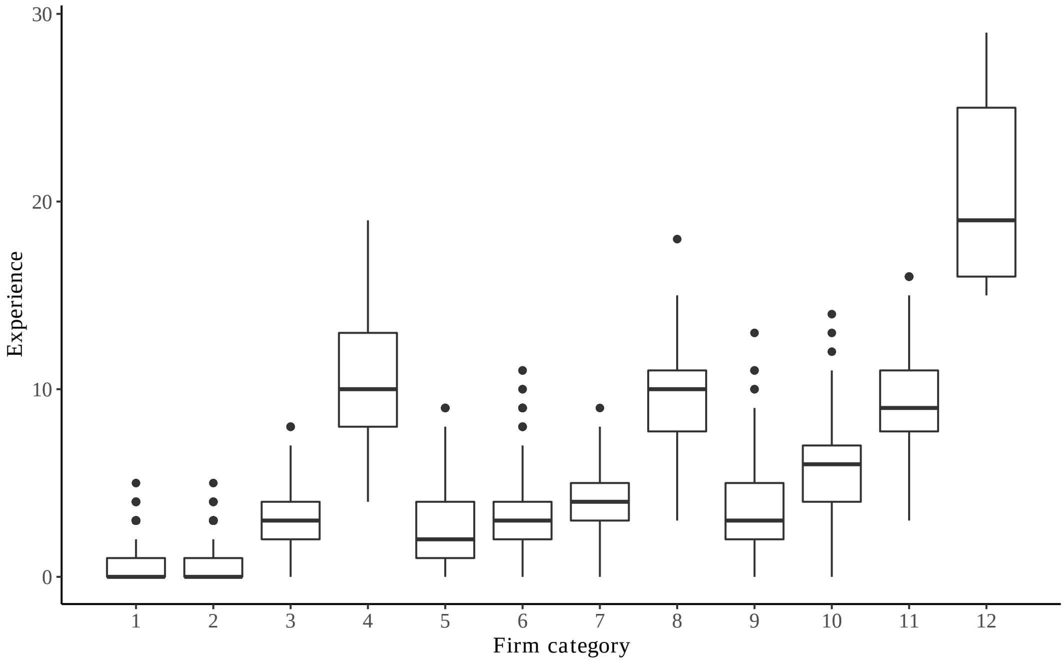


Figure 6.14: Boxplot of experience for all firm categories from the baseline simulation.

the stability of each state" (Gabadinho, Ritschard, Müller, & Studer, 2011, p. 17). In this case, the transition rate between universities will be calculated. For example, if a company a_i engaged with Beta (called state s_i for this example), what is the probability of the agent to engage with Beta again the next time or approach Alpha or Gamma instead (called state s_j for this example). The *seqtrate()* function in the TraMineR package, which returns the transition matrix, works as follows (Gabadinho, Ritschard, Müller, & Studer, 2011, p. 17):

> "Let $n_t(s_i)$ be the number of sequences that do not end in t with state s_i at position t and let $n_{t,t+1}(s_i, s_j)$ be the number of sequences with state s_i at position t and state s_j at position $t+1$. The transition rate $p(s_j|s_i)$ between states s_i and s_j is obtained as [using Equation 6.8] with L the maximal observed sequence length."

$$p(s_j|s_i) = \frac{\sum_{t=1}^{L-1} n_{t,t+1}(s_i, s_j)}{\sum_{t=1}^{L-1} n_t(s_i)} \tag{6.8}$$

The transition state matrix for the baseline model is shown in Table 6.7. This transition matrix and all subsequent transition matrices are based on a single simulation run and not the average of all simulation for a particular scenario. This would have required a substantial amount of additional work, which would increase accuracy (the variability between run is in most cases +/- 0.01) to a

Table 6.7: Transition matrix from the baseline model aggregated by universities with all interactions with Alpha (1), Beta (2), and Gamma (3).

	→ 1	**→ 2**	**→ 3**
1 →	0.64	0.31	0.05
2 →	0.35	0.59	0.06
3 →	0.36	0.41	0.23

level that is not justified given issues surrounding the input data and which is not required to both conceptually and practically address the research questions of this thesis.

Table 6.7 shows a significantly higher retention rate, i.e. a company engaging with the same university again, for Alpha (0.64) and Beta (0.59) compared to Gamma (0.23). Furthermore, the transition rates from Alpha to Gamma (0.05) and Beta to Gamma (0.06) are significantly lower than the transition rates between Alpha and Beta (0.31 from Alpha to Beta and 0.35 from Beta to Alpha).

6.5.3 Complex Events

A unique feature of this study and the simulation model is the explicit recognition of complex events as a means of capturing emergent behaviour as defined in Section 3.7.3. Emergent behaviour, as opposed to emergent states, do not represent emergence from an ontological point of view but recurring patterns in behaviour over time. This goes beyond the transition matrix and includes information about what happened in the interim between two interaction with either the same or different universities. Three types of emergent behaviour have been defined that are relevant to address the research questions of this study: partnerships, external marketing success, and reputational (word-of-mouth) effects (Section 3.7.4).

The TraMineR package has been used to identify the most frequent events and complex events (i.e. the combination of at least two simple events as defined in Section 3.7.3). Similar to the transition matrix in the previous section, all activities with a particular university have been aggregated into '1' for Alpha, '2' for Beta, and '3' for Gamma. The ten most common events (including complex events and three simple events) as well as the most frequent partnership and reputational effect complex events are shown in Table 6.8).

The results on the left-hand side of Table 6.8 show that interactions with Beta (9344 instances) and Alpha (6324 instances) are the most prevalent (simple) events, followed by combinations of interactions with Beta and Alpha (2426 instances) and contrariwise (2413 instances). In line with highest retention rate (as described in Section 6.5.2 and Table 6.7), Alpha has the highest number of

Table 6.8: Complex events from baseline model

Most Popular		Partnerships		Reputational Effects	
Count	Sequence	Count	Sequence	Count	Sequence
9344	(2)	219	(1)-(1)-(1)	28	(NR24)-(2)
6324	(1)	150	(2)-(2)-(2)	26	(NR23)-(2)
2426	(2)-(1)	66	(1)-(1)-(1)-(2)	24	(NR22)-(2)
2413	(1)-(2)	61	(2)-(1)-(1)-(1)	22	(NR21)-(2)
2248	(3)	58	(2)-(2)-(2)-(1)	18	(NR11)-(1)
1278	(1)-(1)	56	(1)-(2)-(2)-(2)	17	(NR13)-(1)
1185	(2)-(2)	43	(1)-(1)-(1)-(1)	17	(NR14)-(1)
967	(1)-(2)-(1)	36	(1)-(1)-(1)-(2)-(1)	12	(NR12)-(1)
932	(2)-(1)-(2)	30	(1)-(2)-(2)-(2)-(1)	6	(2)-(NR21)-(2)
573	(2)-(3)	23	(3)-(3)-(3)	6	(NR11)-(1)-(2)

partnerships (219), followed by Beta (150), and Gamma (23) as shown in the middle part of Table 6.8. It is noteworthy that even four subsequent interactions with Alpha (43 instances) are more common than partnerships with Gamma. Reputational effects are most prevalent for all four entrepreneurial activities with Beta, followed by all four activities for Alpha as shown on the right-hand side of Table 6.8. In the baseline scenario, Gamma does not get a significant benefit from networking among the company agents.

6.6 Confidence Building

Building confidence that the model is robust and 'useful' with regard to the research questions is a crucial aspect of the modelling process. Before using the model for experimentation, this section will provide an overview of the tools and practices that have been applied to develop confidence in the appropriateness of the model. As a response to the lack of systemic approaches for building confidence in HS as outlined in Section 4.2.3.5 and the recommendations by Brailsford et al. (2019), methods and tools are adapted from SD and ABM practices that are appropriate to gain confidence in both the module as well as the overall HS.

6.6.1 Code Verification

All functions and processes within the Java code were tested individually before being implemented in the main simulation code. For example, networking or external marketing were tested on a single mock agent to determine whether the changes in the agent's university preference are as specified according to the rules in Section 5.4.2. Similarly, small-scale SD simulations were coded in Java and compared to the same simulation run in Vensim to verify the results of the code. Once the code passed this test, the SD modules were implemented in the main simulation. Lastly, the final university preferences P_i, k were exported with all the states of each agent throughout the course of the simulation. This allowed to check whether the individual preference for each activity/university $\{p_{i,k,\alpha}, p_{i,k,\beta}, p_{i,k,\gamma}\},\ p_{i,k,\alpha}, p_{i,k,\beta}, p_{i,k,\gamma} \in [0,1],\ p_{i,k,\alpha} + p_{i,k,\beta} + p_{i,k,\gamma} = 1\ \forall\ i, k$, and, therefore, the updating procedures during the simulation are correct.

6.6.2 Black-Box Validation

The key measure for black-box validation is the ability of the simulation to either produce an output that corresponds to empirical data or reproduce the reference mode (for SD) or general patterns of behaviour (for ABM). The application of black-box validation is limited in this case due to how the simulation model is designed and parametrised. First, Scottish universities have been combined into three 'generic' universities, which are based on median values of a subset of all Scottish universities. Consequently, combine the strengths and weaknesses of multiple universities. Second, the three university agents and the company agents are parametrised so that the number of the five entrepreneurial activities are in equilibrium for the baseline model. This means, the model is not designed to reproduce empirical data as such. It does, however, successfully create the equilibrium as expected.

Particular aspects of the model can also be used for black-box validation. A particular aspect from the ABM module is the experience at the end of the simulation run. The frequency distribution of agents' experience (Figure 6.13) and the boxplot diagram for the same data disaggregated by firm size (Figure 6.14) are consistent with the model input. Tables 6.5 and 6.6 show that larger and more innovative firms have a higher propensity to engage with universities, which is also what the simulation output shows.

6.6.3 White-Box Validation

Throughout the modelling process, the structure was continuously assessed. Examples include an assessment of SD and ABM as suitable mono-method approaches to address the research questions in Section 3.5, with the conclusion that a hybrid approach is required to have the right level of aggregation for each part of the system. The individual SD and ABM modules were then developed by triangulating insights from the literature, interviews, and secondary data to ensure that the model appropriately represents the real world and includes the relevant mechanisms ('structure assessment'). In line with general modelling practice in MS/OR, the focus was on modelling the problem (as represented by the research questions) as opposed to the system as a whole in order to clearly define appropriate boundaries ('boundary adequacy'). Each equation has been checked for 'dimensional consistency' without having to use arbitrary variable that have no real-world equivalent (see Section 6.2.1). Lastly, sensitivity analyses were performed and the results will be presented separately in Section 6.6.5.

For HS, it is not sufficient to validate individual modules but also the interfaces of these modules and, by extension, the overall design of the HS. This can be seen as part of white-box validation, but particularly when feedback loops are spanning module boundaries, it is worth highlighting the efforts undertaken to ensure consistency separately. In the absence of established guidelines, this is designed to motivate other modellers to adopt a framework that distinguishes between validating individual modules and their interfaces for a more robust understanding of the HS. The following section will reflect on the practices within this modelling process.

6.6.4 Interface Validation

There are two distinct, yet related rationales for validating the SD-ABM interface. First, the interfaces must be designed in a way that relevant information does not get lost. Second, the interfaces must allow the synchronisation of the modules to avoid causality errors (Mustafee, Sahnoun, et al., 2015, see also Section 3.6.6). Section 6.2.3 has provided a detailed account of the interaction points and what data is exchanged between the ABM and SD modules, hereby showing that all relevant data are captured and exchanged without the loss of relevant information.

6.6.5 Sensitivity Analysis

The dynamic behaviour of a system is based on its structure and the parameters. Exploring the sensitivity of the model to crucial variables can improve intuition about the system behaviour, help establish the robustness of the results and the uncertainty involved, guide data collection, and identify levers for new policies and interventions (Sterman, 2000). Sensitivity is, however, not limited to parameter sensitivity but also includes structural changes and alternative formulations of the model structure and model boundaries (Sterman, 2000). Parameter sensitivity analysis is used for similar purposes in ABM, yet only a small fraction of published papers reports any form of systematic or structured analysis (Thiele et al., 2014). For ABMs, established methods such as 'one-at-a-time' (OAT) or 'one-factor-at-a-time' (OFAT; considers a larger range of possible values compared to OAT) parameter sensitivity approaches provide "insight into qualitative aspects of model behaviour and the patterns that emerge from the model [... including the ...] functional form of the relationships between parameters and output variables [and the] existence of tipping points and other strong nonlinearities" (Tten Broeke et al., 2016, p. 13).

Sensitivity testing should be done in controlled experiments, which in this case is done via univariate analyses to fully understand the effects that each change has on the behaviour of the model. It is recommended as a "starting point for any sensitivity analysis of an ABM [and for SD models as explained above], in particular when one wants to gain insight into the mechanisms and patterns that [the models] produce, which is a typical goal of many social simulation studies" (Tten Broeke et al., 2016, p. 14). Furthermore, the use of optimisation methods for the size of the agent population A and the university preferences $P_{i,k}$ can be classified as tools for sensitivity analysis for identifying the best values for parameters of the simulation (Sterman, 2000, p. 861).

The sensitivity analysis for this model is structured around the critical mechanisms and variables with regard to the four research questions. In particular, the following univariate analyses were performed (detailed descriptions and results are presented in Appendix E):

- *Demand*: The demand from industry (number of agents times their propensity to engage with universities N_i) is one of the two features that link company and university agents and, by extension, the different datasets that were mainly used for each type of agent. For the purpose of understanding the sensitivity of the model to this crucial aspect of the model, six additional configurations have been created. In particular, these include a minimum demand with 1,000 agents, 50% of the original demand with 13,444 agents, 75% of the original demand with 20,165 agents, 125% of the original demand with 33,609 agents, 150% of the original demand with 40,331 agents, and 200% of the original demand with 53,774 agents.

- *Agents' university preference*: The second feature is the university preference $P_{i,k}$, which distributes the overall demand for interactions with universities among the three universities. To test the sensitivity of the model to these parameters, three additional configurations have been developed. The basis for each configuration is the values for non-spin-off agents. Then, the preferences $p_{i,k,\alpha}$, $p_{i,k,\beta}$, and $p_{i,k,\gamma}$ are increased by 10% for each scenario, respectively, and difference deducted proportionally from the preference for the other two universities.

- *Licensing Equilibrium*: How does the model react to different parameters for Beta's 'Disclosure Rate' *disr* and 'Patenting Rate '*pr*? What are the implications for Beta if licensing is in equilibrium like all other activities? What are the systemic implications and how might this affect the experimentation with different scenarios? Two alternative configurations have been developed to test the sensitivity of the model with regard to the *PAT* stock. First, the 'Patenting Rate' *pr* for Beta is set to the *pr* of Alpha. Second, the 'Disclosure Rate' *disr* of Beta is also increased to the value of Alpha.

- *KE Allowance 'wa'*: Most universities want to grow their entrepreneurial activities, but interviews and the HE-BCI data have shown that there is a small number of academics who are heavily involved in entrepreneurial activities whereas the vast majority of academics do not engage at all. The amount of time that a single academic can dedicate to working with industry is, therefore, crucial in determining the overall capacity of the university. Two additional configurations are tested, namely a lower ($wa_\alpha = 0.40$, $wa_\beta = 0.30$, $wa_\gamma = 0.10$) and a higher workload allowance for all universities ($wa_\alpha = 0.50$, $wa_\beta = 0.40$, $wa_\gamma = 0.20$).

- *Academic Involvement Collaborative Research 'aicol'*: Collaborative research projects come with major capacity commitments from academics over many years (on average two in this study) and have, therefore, also implications for the entrepreneurial capacity of the university. There is a general trend towards larger, multi-partner projects, which means that the current value of $aicol = 0.1$ might increase in the future. The model is tested with $aicol = 0.2$ and $aicol = 0.3$ as well as the option for staff to buy out time through a change in structure of the SD modules for all universities.

- *Learning from past interactions*: Organisational capacity has been identified as a key mechanism to develop partnerships and interactions between universities and industry in general (Section 2.4), which can be achieved through learning and adaptation from previous interactions. In this model, learning lies on the side of the company agents and the sensitivity of the model to these learning practices needs to be assessed (especially because there is a high level of uncertainty due to the small sample sizes). The sensitivity of the model is tested by simulating three cases, namely (1) no learning from previous interactions at all; (2) using a success rate of 1.0; and (3) updating the university preference and need for additional input after every interaction, regardless its success.

- *Networking*: There is no conclusive evidence in the literature regarding the word-of-mouth effects among companies but most interviewees have pointed to the fact that a good entrepreneurial reputation spreads among companies and will attract new companies. While this can be a promising lever for universities, its impact could also be marginal. This is important to know before experimenting with other university initiatives. In the baseline configuration, a maximum of five universities network per time step, which equals 260 companies per year (i.e. 1% of the agent population). Two alternative configurations are tested, namely 10 agents per time step (520 companies or approximately 2% of the agent population per year) and 52 agents per time step (2,704 companies or approximately 10% of the agent population per year).

With regard to behavioural sensitivity, i.e. "when a change in assumptions changes the patterns of behavior generated by the model" (Sterman, 2000, p. 883), the results do not show any unexpected behavioural changes to the parameter ranges that were tested. The most drastic changes include licensing equilibrium for Beta can be achieved if both the 'Disclosure Rate' *disr* and the 'Patenting Rate' *pr* of Beta would rise to the values of Alpha. Furthermore, particularly Beta is very close to its 'Entrepreneurial Capacity' *ec*, which means that any numerical sensitivity, i.e. "when a change in assumptions changes the numerical values of the results" (Sterman, 2000, p. 883), leading to a higher 'Capacity Utilisation' *cu* will lead to Beta being unable to engage will all companies that approach the university. Both Alpha and Gamma have more flexibility here, but significant increases in demand from industry or reductions in e.g. the 'KE Allowance' *wa* lead to similar effects. The variability in the results from the sensitivity analyses will be taken in account when discussing and interpreting the results from the experimentation.

6.7 Experimentation

Experimentation and designing new policies are more than simply changing parameters, including "the creation of entirely new strategies, structures, and decision rules" (Sterman, 2000, p. 104). Often, these policies alter the loop dominance of the model. While this notion is rooted in SD modelling, the principle applies for ABM and hybrid modelling as well as effective policies would stimulate interactions among agents that amplify a certain systemic behaviour.

The interviews have highlighted two major strategies for growing academic entrepreneurship, namely supply stimulation through internal marketing and demand stimulation through external marketing. The latter can be performed either with or without the involvement of academics. These mechanisms have been described conceptually in Chapter 5 and will be simulated and assessed in the following. First, the three scenarios will be assessed individually and, in a second step, internal marketing (scenario 1) and external marketing with academics' involvement (scenario 3) will be combined in scenario 4. It is important to consider the interaction of new policies as they might reinforce or interfere with each other. The sensitivity of all scenarios to its key parameters will be assessed to determine the robustness of the proposed interventions by universities (Sterman, 2000).

6.7.1 Scenario 1: Internal Marketing

Internal marketing represents stimulating the 'supply' side, i.e. growing the number of entrepreneurial academics who are interested in working with industry (which can be motivated by a personal interest, department or institutional norms, peer effects, leadership, or by promotion purposes, among others). The changes to the model structure for the three university agents is shown in Figure 6.15. The auxiliary variable 'entrepreneurial academics' *ea*, which is a product of 'Research-Active Staff' *ras* and the 'Share of Entrepreneurial Academics' *sea* in the baseline model, is only used as the 'Initial Entrepreneurial Academics' *iea* for the stock 'Entrepreneurial Academics' *EA*. This new part of the model (all additions are highlighted in bold in Figure 6.15) produces s-shaped growth, starting from *iea* until the stock *EA* reaches the 'Target Share of Entrepreneurial Academics' *tsea*. All equations and parameter values are listed in Table 6.9.

The growth in the number of 'Entrepreneurial Academics' *EA* is shown in Figure 6.16. For all three universities, the growth of the number of entrepreneurial academics, in this case those that are currently involved in one of the five entrepreneurial activities and those who are interested and willing to engage with businesses or commercialisation activities, follows the s-shaped growth pattern as described in the description of the model changes above. An important issue is the time frame in which these changes happen. The simulation results in Figure 6.16 show that depending on the parameters 'Friction Fraction' *ff* and 'Marketing

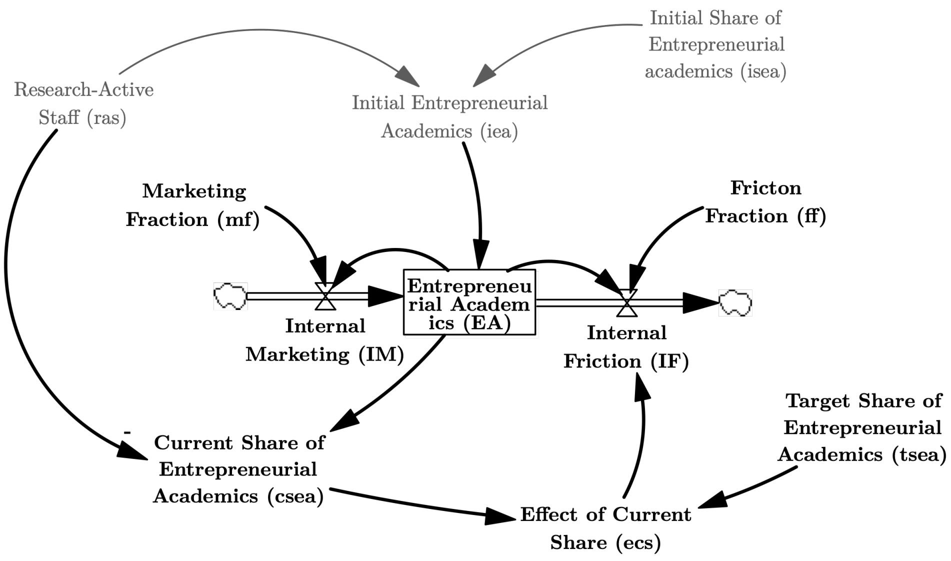


Figure 6.15: SFD of internal marketing

Table 6.9: SD equations and parameters for scenario 1

Stocks
EA = INTEGRAL(IM - IF)
Flows
IF = EA * ff * ecs
IM = EA * mf
Auxiliary variables
csea = EA / ras
ecs = csea / tsea
iea = ras * isea
Values of constants
isea = sea[1]
ff[2] = 0.1 | 0.05 | 0.01
mf[2] = 0.1 | 0.05 | 0.01
tsea[2] = 1.5*isea | 2*isea | 0.5

Notes:
[1] See Table 6.2 for the values for each university.
[2] These values are tested in different scenarios.

Friction' *mf*, reaching the respective target share can take between a few months and about eight years. Ultimately, this is mainly affected by the amount of resources that the university and the TTO commit to internal marketing activities. the strategic direction of the university, and the individual members of staff.

This also has implications for the 'Capacity Utilisation' cu (Figure 6.17). Even increasing the number of EA by 50% compared to the status quo does increase the capacity significantly and opens up new opportunities for potential collaborations with industry (Figure 6.17A). The decline in cu is also due to only company agents initiating interactions with universities (Section 5.2.4), which means that increasing the number of entrepreneurial academics does not automatically increase consulting, contract and collaborative research, or licensing.

However, an increase in EA does influence commercialisation activities within the university through an increase in disclosures and, by extension, patents. Both the number of patents PAT and entrepreneurial academics EA contribute to the formation of spin-offs SO (Figure 6.18). For Beta, more patents will also enable more licensing as Beta's stock of patents goes to zero and the university has to turn company agents away in the baseline scenario. In this scenario, the stock of patents PAT does not go to zero under certain configurations, which means that Beta has enough patents for all requests from company agents (Figure 6.18B).

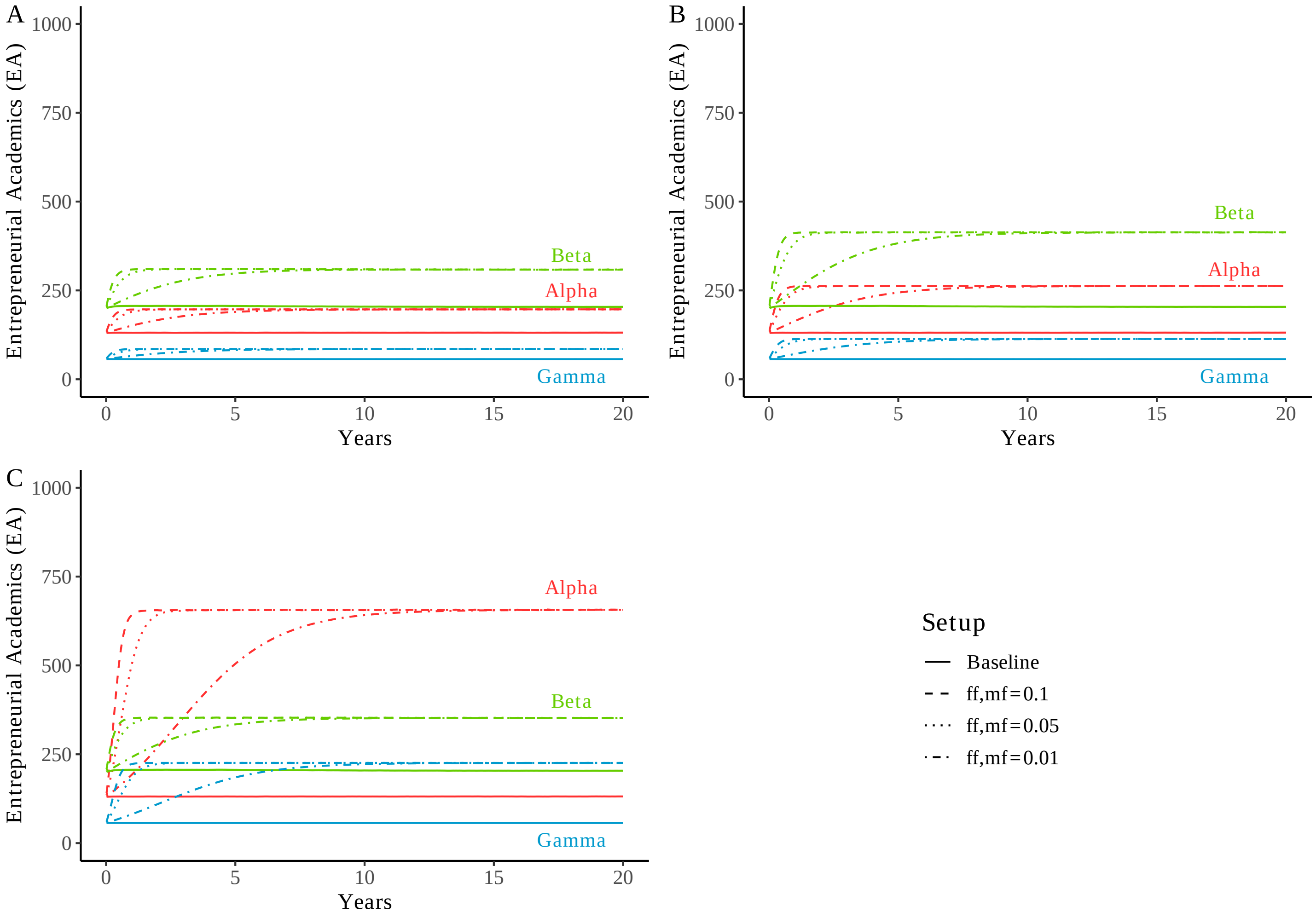


Figure 6.16: Simulation output showing 'EA' for scenario 1 for $tsea = 1.5 * sea$ (A), $tsea = 2 * sea$ (B), and $tsea = 0.5$ (C) for all universities.

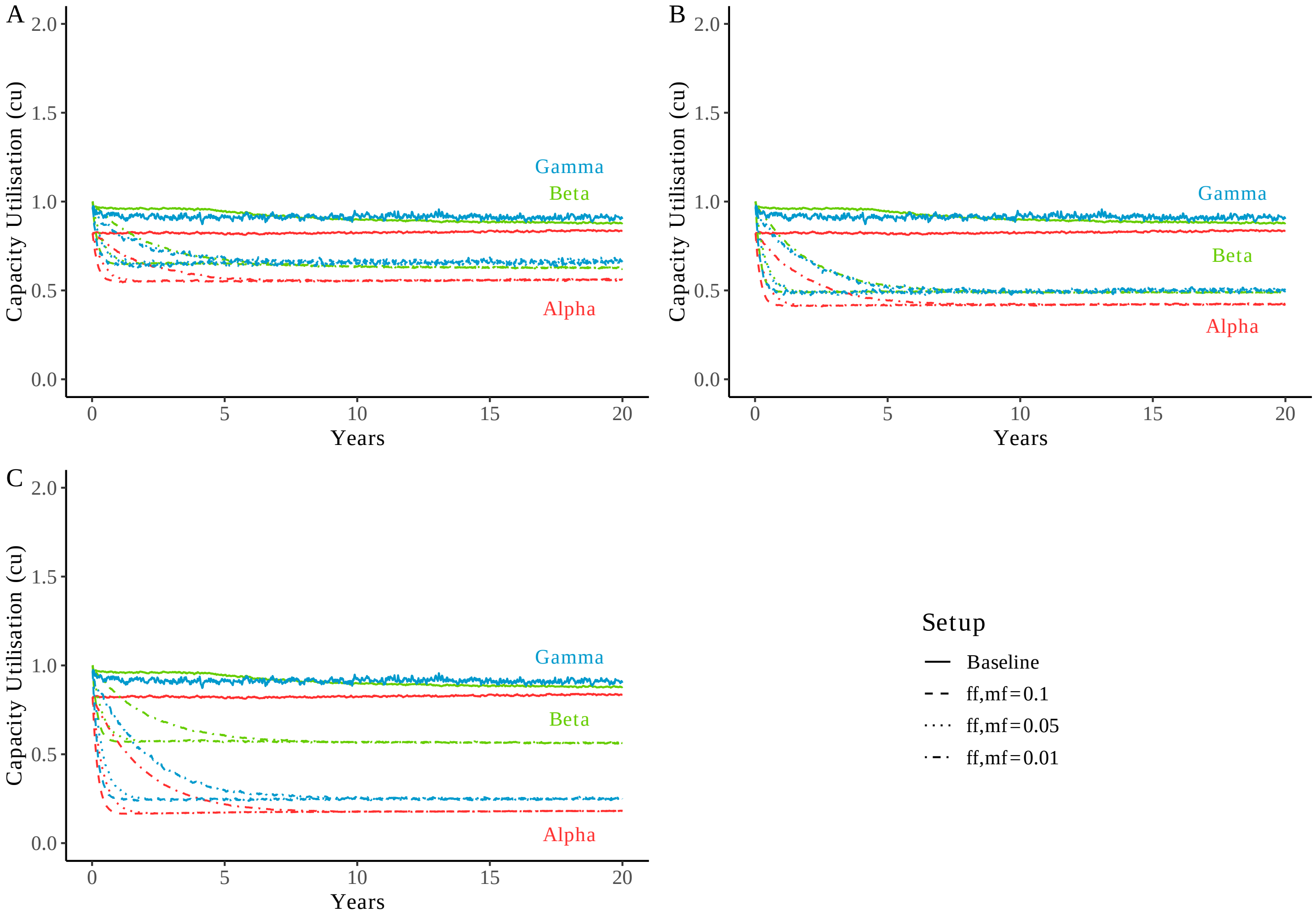


Figure 6.17: Simulation output showing 'cu' for scenario 1 for $tsea = 1.5 * sea$ (A), $tsea = 2 * sea$ (B), and $tsea = 0.5$ (C) for all universities.

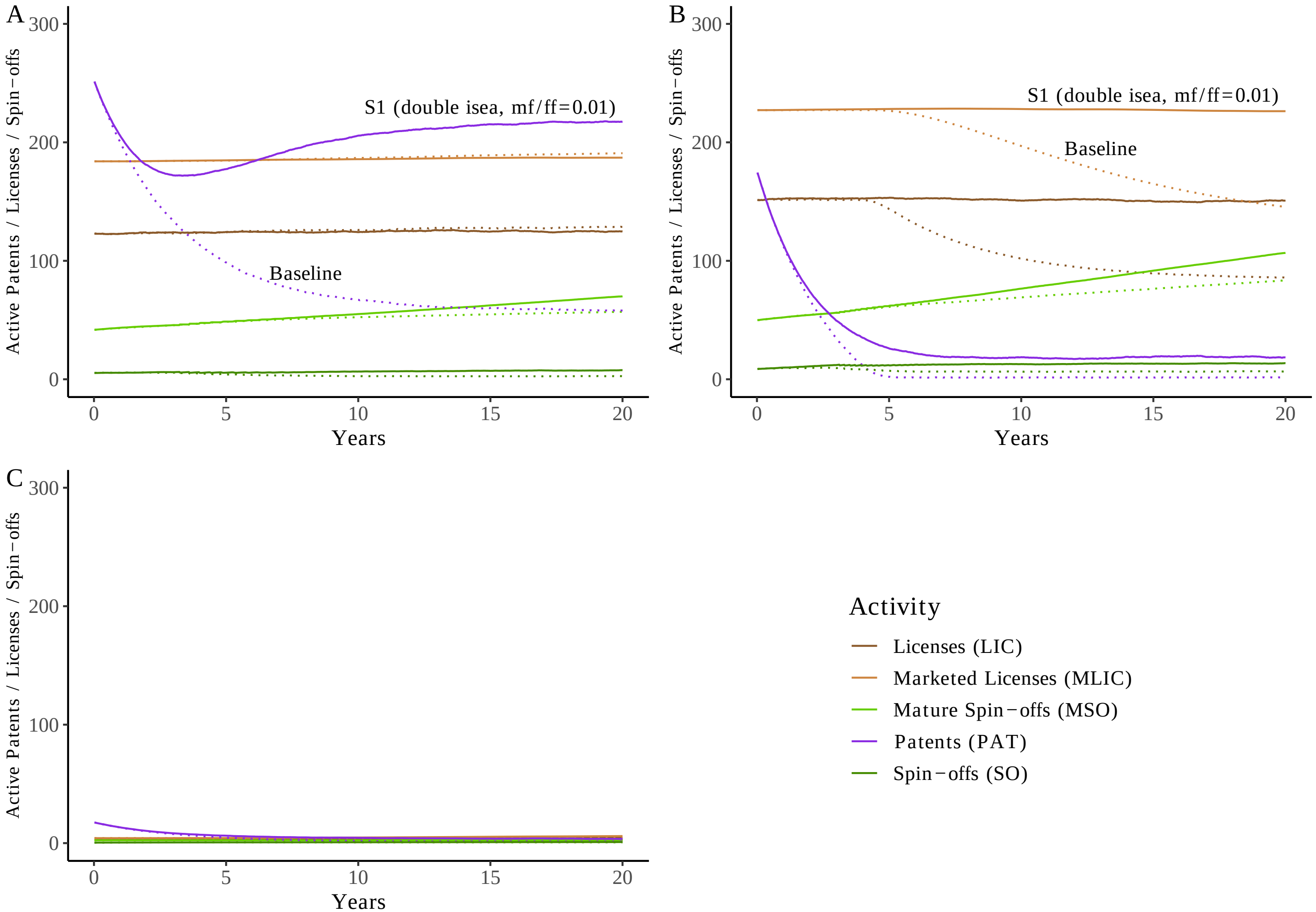


Figure 6.18: Simulation output showing commercialisation activities for scenario 1 for Alpha (A), Beta (B), and Gamma (C).

6.7.2 Scenario 2: External Marketing

External marketing includes all efforts undertaken by universities to advertise their capabilities, expertise, and IP to companies. In this scenario, these activities are solely performed by TTO or other professional staff but without the involvement of academics. This means, that there are no entrepreneurial capacity implications from undertaking the activities alone. For company agents, marketing rule R_{MKT1} is used in this scenario. This rule specifies that if a company agent gets approached by a university, its preference for one activity will be altered.

The influence of this scenario is assessed in nine configurations, which represent the possible combinations of two measures. The first one represents which type of agent is being approached by universities. The distinction is made between randomly selecting any agent without any restriction (as long as that agent is still 'working' in that time step has not engaged in any entrepreneurial activity); a random agent with $I_i \geq 1$; and a random agent with $I_i = 2$. The second measure is how many agents a company approaches per time step, namely $em = 1$; $em = 5$; and $em = 10$.

The results, illustrated by 'Academic Entrepreneurship' ae for each university under the different configurations, are shown in Figure 6.19. As expected, the overall effect of this scenario increases with an increase in em. When looking at the effect on each university, the more agents the universities approach and the higher the innovativeness of the targeted agents, the more Gamma benefits. By default, the preference for Gamma of those highly innovative companies is very low, so Gamma is able to make the most gains compared to the other universities. Alpha, for example, has very little to gain as its preference is in many cases already > 0.7 and in some cases even > 0.9.

This also has implications for the capacity utilisation. Figure 6.20 shows the dynamics of cu over time for all nine scenarios. In line with the changes in ae, Gamma records increases in cu that even exceed a value of $cu = 1$ and still increases despite the university starting to declining opportunities to work with company agents. For Gamma, this is therefore a very viable opportunity to grow their ecosystem and increase their entrepreneurial activity.

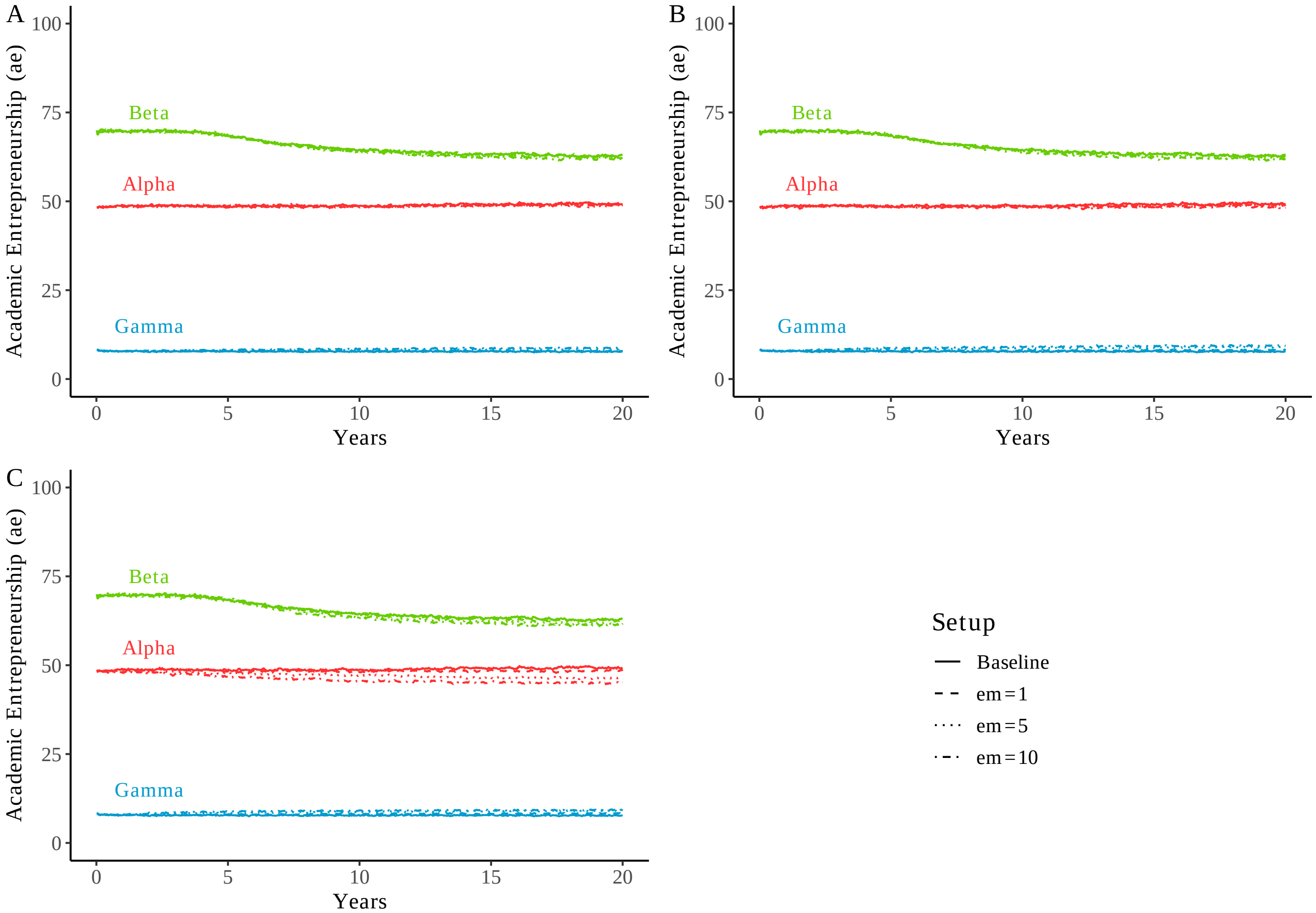


Figure 6.19: Simulation output showing 'ae' for scenario 2 for randomly selected agents (A), only approaching agents with $I \geq 1$ (B), and agents with $I = 2$ (C).

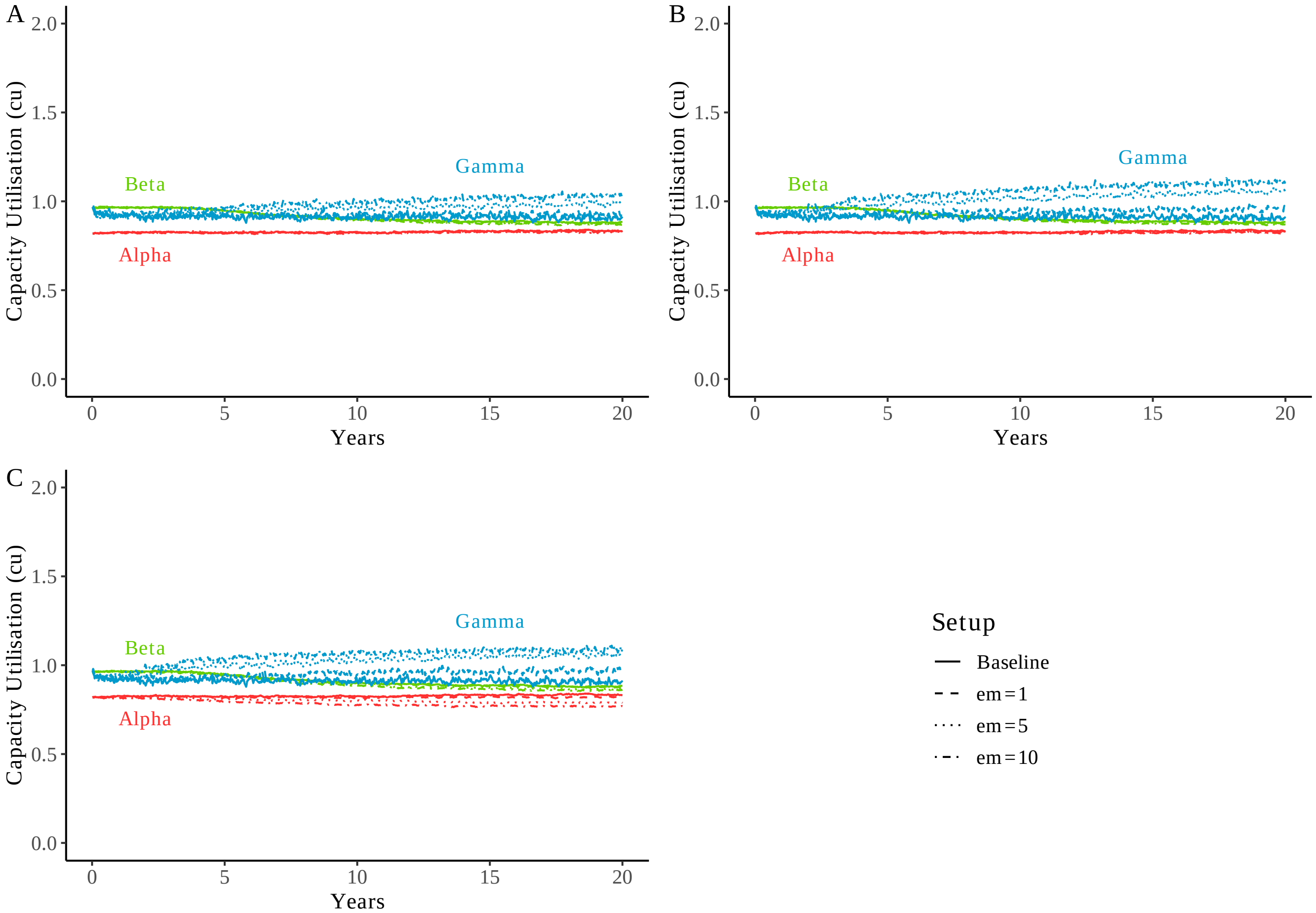


Figure 6.20: Simulation output showing ‘cu’ for scenario 2 for randomly selected agents (A), only approaching agents with $I \geq 1$ (B), and agents with $I = 2$ (C).

Table 6.10: Transition matrix for scenario 2 ($em = 10$, no restriction)

	→ **1**	→ **2**	→ **3**
1 →	0.62	0.32	0.06
2 →	0.35	0.59	0.06
3 →	0.37	0.39	0.23

Table 6.11: Transition matrix for scenario 2 ($em = 10$, $I \geq 1$)

	→ **1**	→ **2**	→ **3**
1 →	0.61	0.32	0.07
2 →	0.34	0.58	0.08
3 →	0.36	0.40	0.24

Table 6.12: Transition matrix for scenario 2 ($em = 10$, $I = 2$)

	→ **1**	→ **2**	→ **3**
1 →	0.60	0.33	0.07
2 →	0.33	0.60	0.08
3 →	0.35	0.39	0.26

These shifts are also reflected in the transition matrices. For clarity, only the three configurations with $em = 10$ are shown. In particular, universities approach random agents with no restriction for the agents' innovativeness in Table 6.10, only approach agents with $I \geq 1$ in Table 6.11, and with $I = 2$ in Table 6.12. Particularly when approaching more innovative agents, Gamma is able to increase its retention rate and (even if only marginally) increase the transition rate for agents who have previously engaged with Alpha or Beta.

6.7.3 Scenario 3: External Marketing with Academics

The interviews have highlighted that external marketing efforts benefit from the involvement of academics. While only anecdotal evidence exists for the success of such approaches, they are intuitively reasonable and worth exploring by universities. This scenario uses marketing rule R_{MKT2} for the company agents, which will update the university preferences for all activities if the company is approached by a university.

The involvement of academics in the external marketing efforts carry implications for the SD structure and internal resource dynamics of the three universities, which is shown in Figure 6.21. With external marketing being part of the academics' entrepreneurial activities, 'Academic Entrepreneurship' ae contains an additional summand as defined in Equation 6.9:

$$ae = (COL * aicol) + (CON * aicon) + (CONR * aiconr) + (LIC * ailic) + (SO * aiso) + (em * aiem) \tag{6.9}$$

The impact of these changes is assessed using the same nine configurations (varying numbers of companies that are approached by each university per time step and whether universities select companies randomly or look for varying degrees if innovativeness) as in scenario 2 in the previous section. The results with regard to 'Academic Entrepreneurship' ae for each university under the different configurations are shown in Figure 6.22. The overall findings are similar to scenario 2. Gamma is increasing its overall academic entrepreneurship whereas Alpha's and Beta's ae is decreasing over time after an initial increase. Interestingly, Beta's ae decreases the most when agents with $I \geq 1$ are targeted (Figure 6.22B) and less when only those highly innovative agents with $I = 2$ are targeted (Figure 6.22C). This is likely caused by the relatively higher preference for Beta among those agents.

The implications for 'Capacity Utilisation' cu based on the changes in ae are similar, but due to the involvement of the academics in the and that they are workloaded for this, there is an additional summand to ae. The results are shown in Figure 6.23. Gamma is, again, able to grow and sustain a demand from industry that is beyond the universities capacity whereas Alpha and Beta are essentially freeing up capacity. Particularly for Beta, however, the decrease in cu is marginal.

The transition matrices for the different configurations differ less from the baseline model than those from scenario 2. For simplicity and comparability, the matrices for the same three configurations are shown as previously for scenario 2: Table 6.13 shows the matrix for $em = 10$ and randomly selecting agents with no restrictions, Table 6.14 for with $I \geq 1$, and Table 6.15 for agents with $I = 2$. Gamma is able to slightly improve their retention rate whereas there is not a clear trend for Alpha and Beta. However, overall there is very little variability between the configurations and also compared to the baseline scenario.

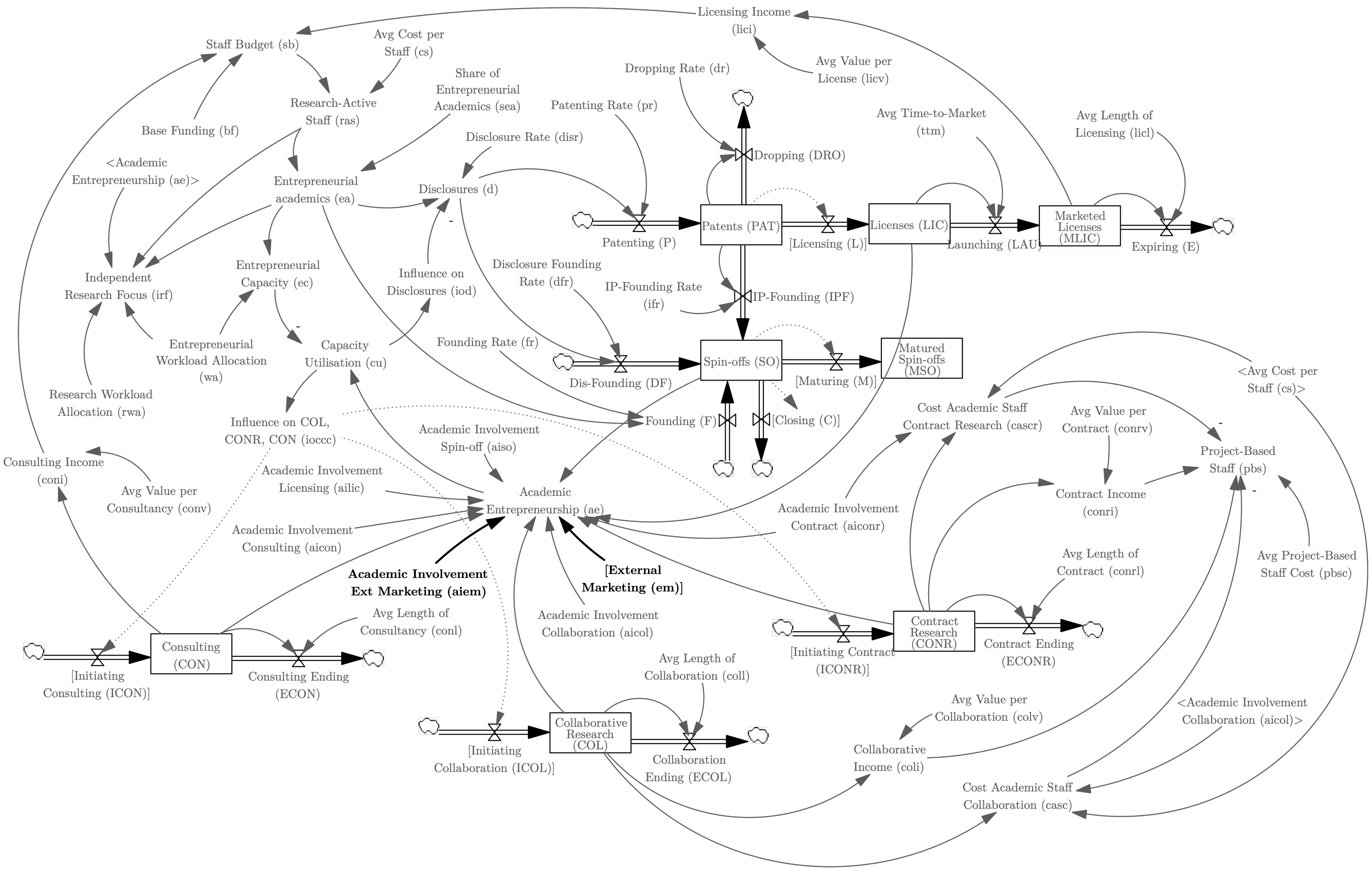


Figure 6.21: SFD of external marketing with involvement of academics

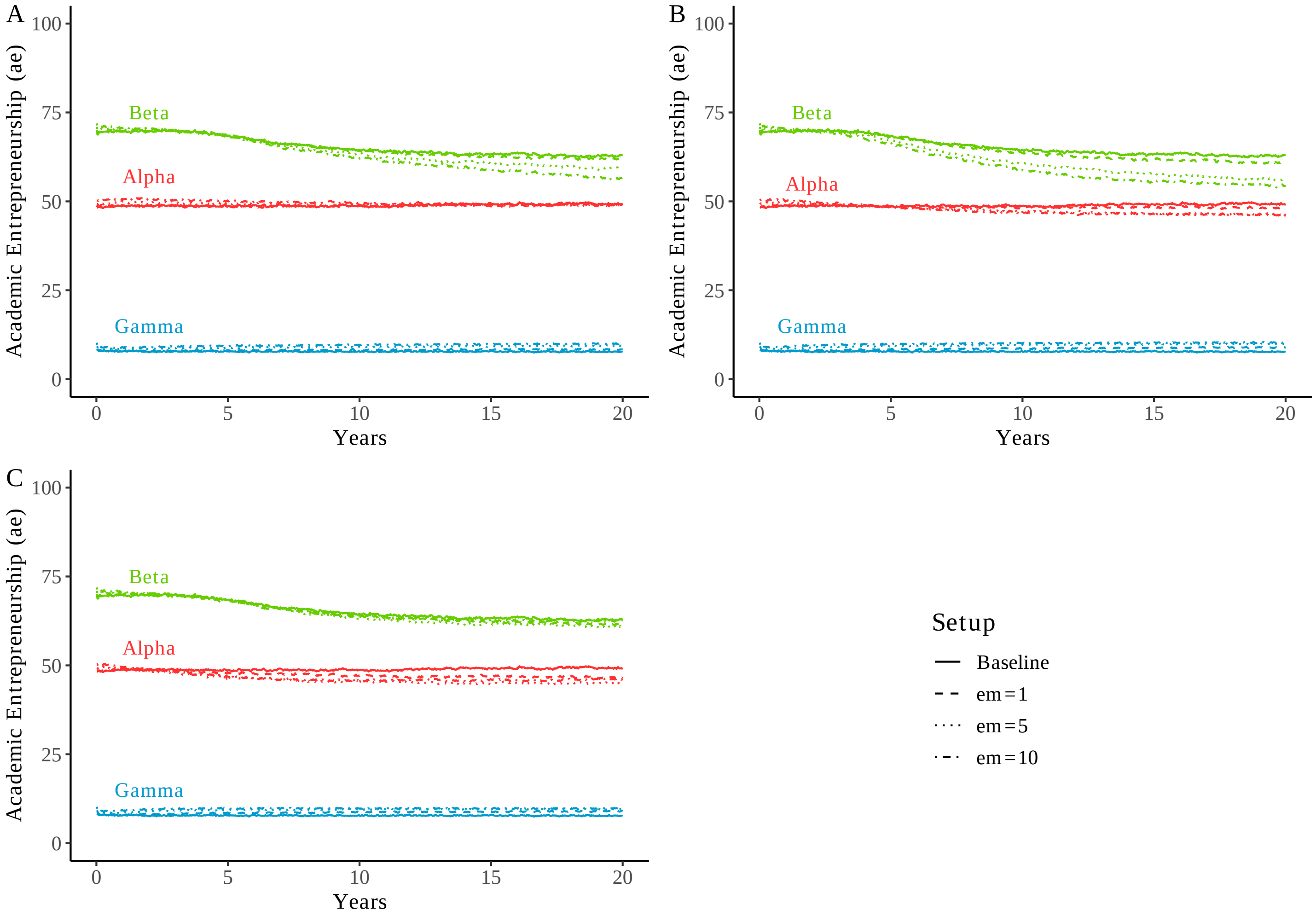


Figure 6.22: Simulation output showing 'ae' for scenario 3 for randomly selected agents (A), only approaching agents with $I \geq 1$ (B), and agents with $I = 2$ (C).

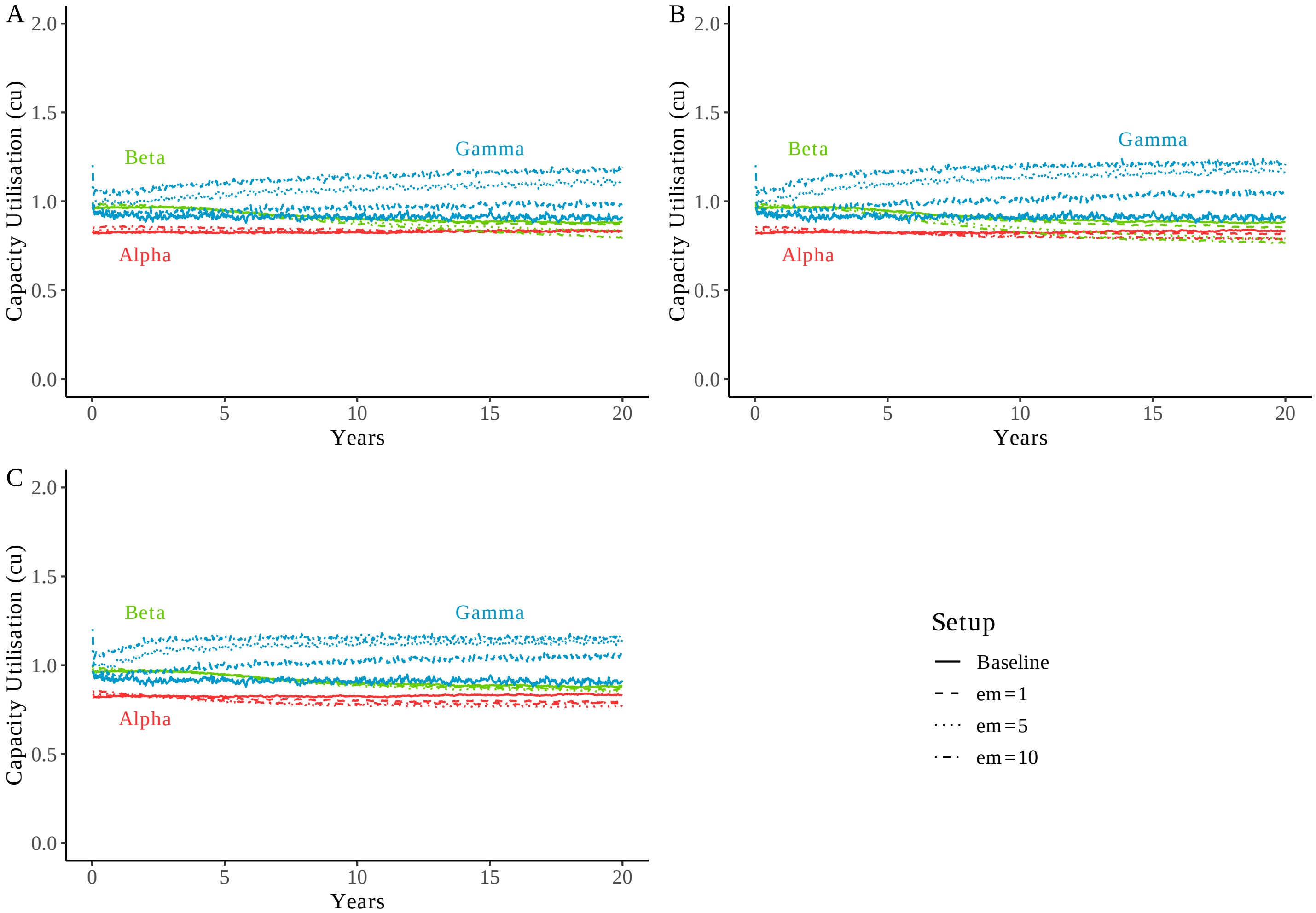


Figure 6.23: Simulation output showing 'cu' for scenario 3 for randomly selected agents (A), only approaching agents with $I \geq 1$ (B), and agents with $I = 2$ (C).

Table 6.13: Transition matrix for scenario 3 ($em = 10$, no restriction)

	→ **1**	→ **2**	→ **3**
1 →	0.64	0.31	0.05
2 →	0.34	0.60	0.06
3 →	0.36	0.37	0.27

Table 6.14: Transition matrix for scenario 3 ($em = 10$, $I \geq 1$)

	→ **1**	→ **2**	→ **3**
1 →	0.63	0.30	0.07
2 →	0.33	0.59	0.08
3 →	0.37	0.37	0.27

Table 6.15: Transition matrix for scenario 3 ($em = 10$, $I = 2$)

	→ **1**	→ **2**	→ **3**
1 →	0.58	0.35	0.06
2 →	0.33	0.61	0.07
3 →	0.34	0.38	0.27

6.7.4 Scenario 4: Combination of Scenarios 1 and 3

In the fourth scenario, the mechanisms for internal marketing (scenario 1) and external marketing with involvement of academics (scenario 3) are combined. The aim of this scenario is to model a comprehensive approach to increasing entrepreneurial activities and growing the university ecosystem. A total of eight initial configurations are designed, four with $tsea = 1.5 * sea$ and four with $tsea = 2 * sea$ for the internal marketing component. For each of these, two configurations are based on $em = 5$ and $em = 10$, respectively, and each of these is run with approaching agents with $I_i \geq 1$ and $I_i = 2$ for the external marketing component. These are more 'intensive' external marketing efforts, because it is more likely that if universities pursue a more comprehensive strategy, they will also have a more strategic approach as to which companies they contact.

The results for these eight configurations are shown in Figure 6.24 (illustrated by ae) and Figure 6.25 (illustrated by cu). Gamma is able to increase the amount of academic entrepreneurship, particularly when the university is doubling its share of entrepreneurial academics (Figure 6.24C and 6.24D). This helps the university to cope with the increased demand from industry due to their external marketing. Except for the configuration in Figure 6.24D, the university operates with $cu > 1$ (latest after around five years) in each scenario. Both Alpha and Beta, on the other hand, decrease their capacity utilisation to approximately 0.45-0.60, even for the configurations where only agents with $I_i = 2$ are targeted

Table 6.16: Transition matrix for scenario 4 ($em = 10$, $I = 2$, $tsea = 1.5 * sea$)

	→ 1	**→ 2**	**→ 3**
1 →	0.57	0.34	0.09
2 →	0.30	0.61	0.09
3 →	0.32	0.36	0.32

Table 6.17: Transition matrix for scenario 4 ($em = 10$, $I = 2$, $tsea = 2 * sea$)

	→ 1	**→ 2**	**→ 3**
1 →	0.57	0.33	0.11
2 →	0.30	0.59	0.11
3 →	0.30	0.34	0.36

and Beta actually grows its academic entrepreneurship activities (Figure 6.24B and 6.24C). Alpha ends up with a decrease in their entrepreneurial activities in all configurations in this scenario.

Two transition matrices are shown in Table 6.16 (for $em = 10$, $I = 2$, $tsea = 1.5 * sea$) and Table 6.17 (for $em = 10$, $I = 2$, $tsea = 2 * sea$). Both show a similar picture: Gamma is able to significantly increase its retention rate and also the transition rate from other universities, particularly for $tsea = 2 * sea$ (Table 6.17). This shows the effectiveness of external marketing for Gamma and the importance of simultaneously increasing the number of entrepreneurial academics to cope with the new demand. Beta can improve its retention rate for $tsea = 1.5 * sea$ (Table 6.16), whereas Alpha cannot maintain the status quo of the baseline model in either of these configurations.

Up to this point, all universities have pursued the same strategies. Three additional simulations are run in which only one of the three universities pursues an aggressive entrepreneurial growth strategy and the other two continue with their baseline configuration. The results are presented in Figure 6.26 (Alpha pursues growth strategy), Figure 6.27 (Beta), and Figure 6.28 (Gamma). When either Alpha or Beta is the only university pursuing this strategy, they are mostly attracting companies that would have otherwise worked with the respective other university (Figures 6.26 and 6.27). Except for collaborative research, Gamma's increase mainly results in a decrease for Alpha. The Independent Research Focus 'irf' declines substantially for Alpha when it invests in academic entrepreneurship but also increases by an even larger margin when one of the other two universities pursues this strategy (Figure 6.29). For Beta and Gamma, the changes are less significant compared to Alpha.

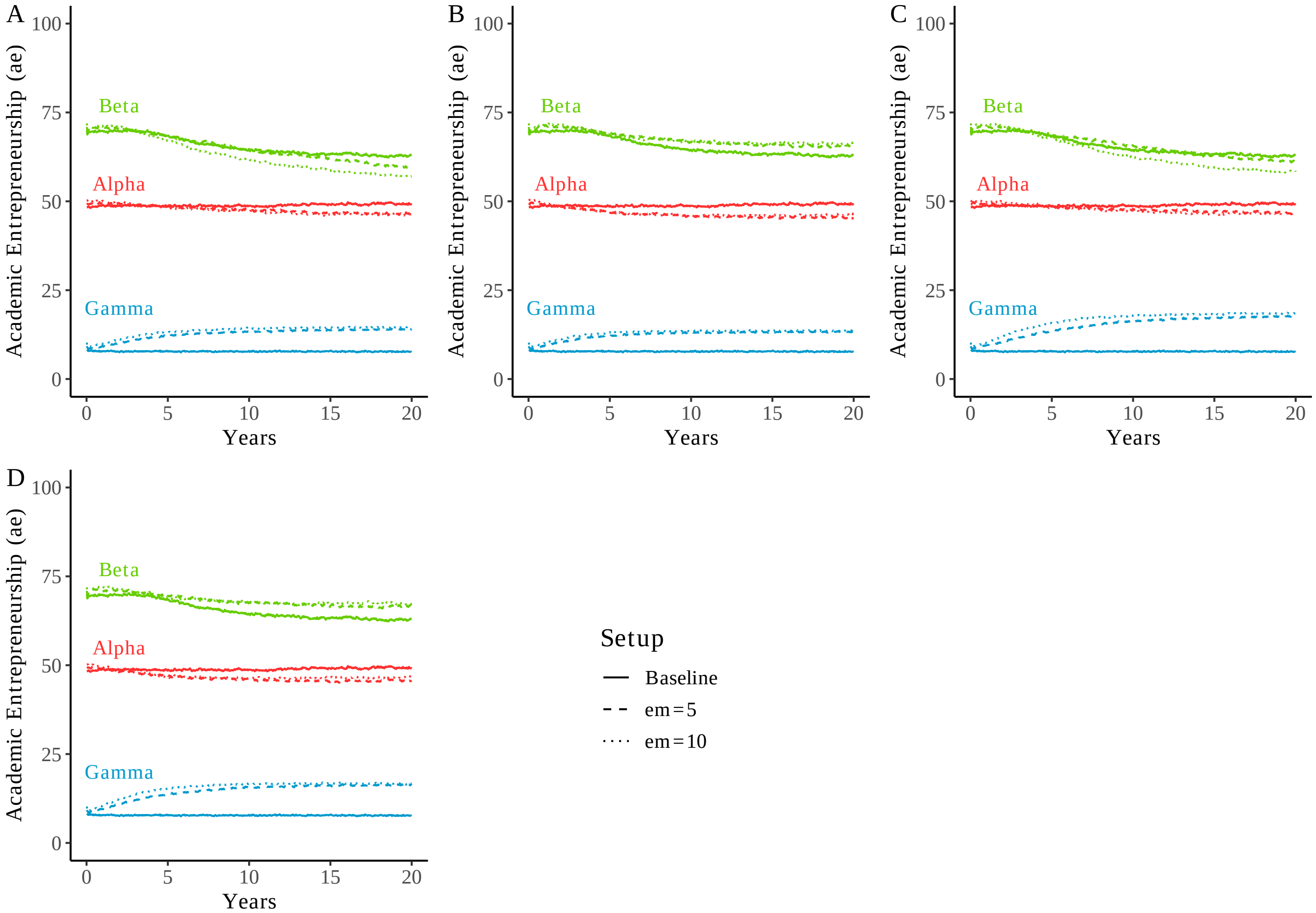


Figure 6.24: Simulation output showing 'ae' for scenario 4 for $tsea = 1.5 * sea$ and $I_i \geq 1$ (A), $tsea = 1.5 * sea$ and $I_i = 2$ (B), $tsea = 2 * sea$ and $I_i \geq 1$ (C), and $tsea = 2 * sea$ and $I_i = 2$ (D).

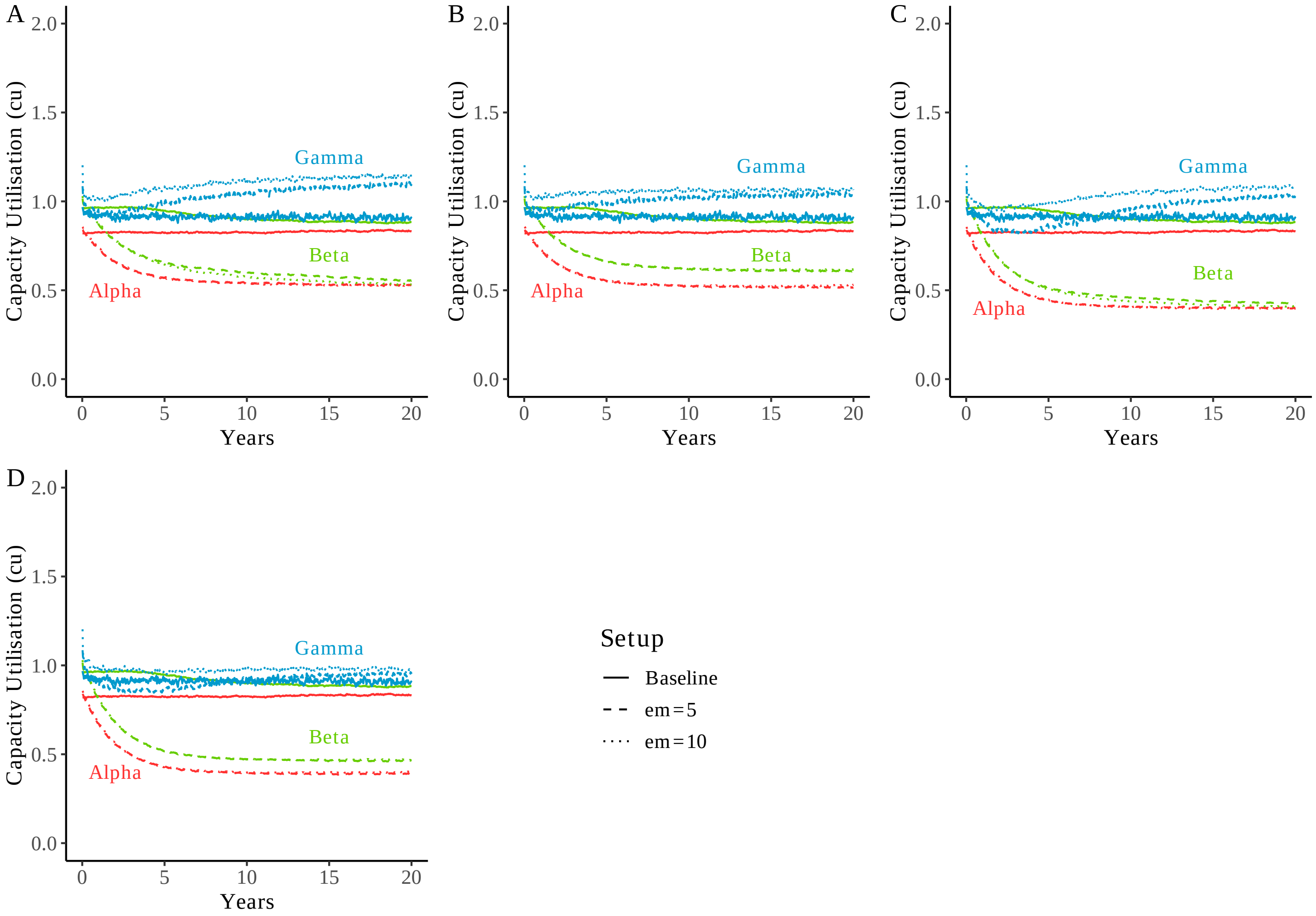


Figure 6.25: Simulation output showing 'cu' for scenario 4 for $tsea = 1.5 * sea$ and $I_i \geq 1$ (A), $tsea = 1.5 * sea$ and $I_i = 2$ (B), $tsea = 2 * sea$ and $I_i \geq 1$ (C), and $tsea = 2 * sea$ and $I_i = 2$ (D).

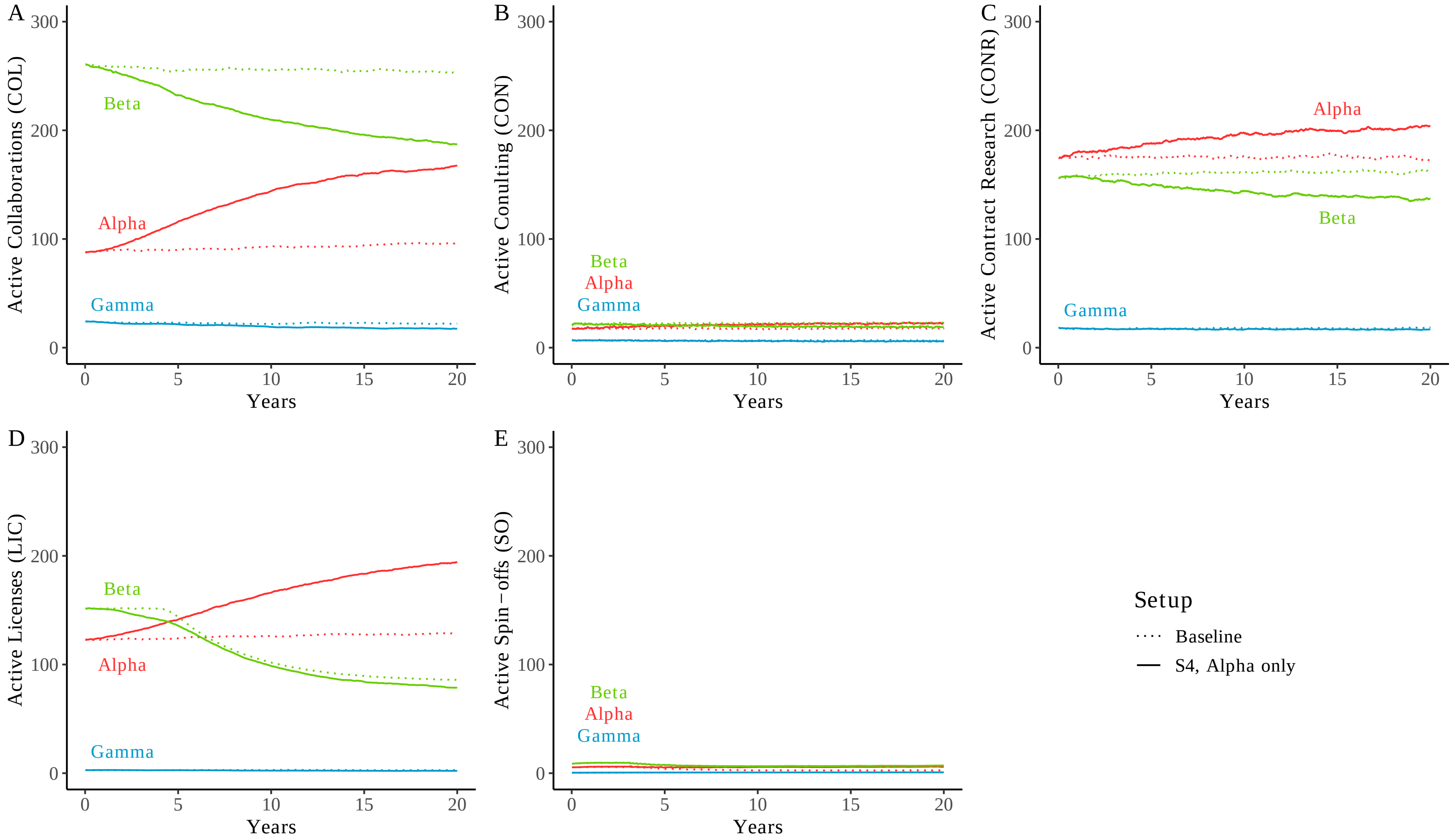


Figure 6.26: Simulation output for scenario 4 where only Alpha invests in AE. Results are shown for each activity, namely COL (A), CON (B), CONR (C), LIC (D) and SO (E).

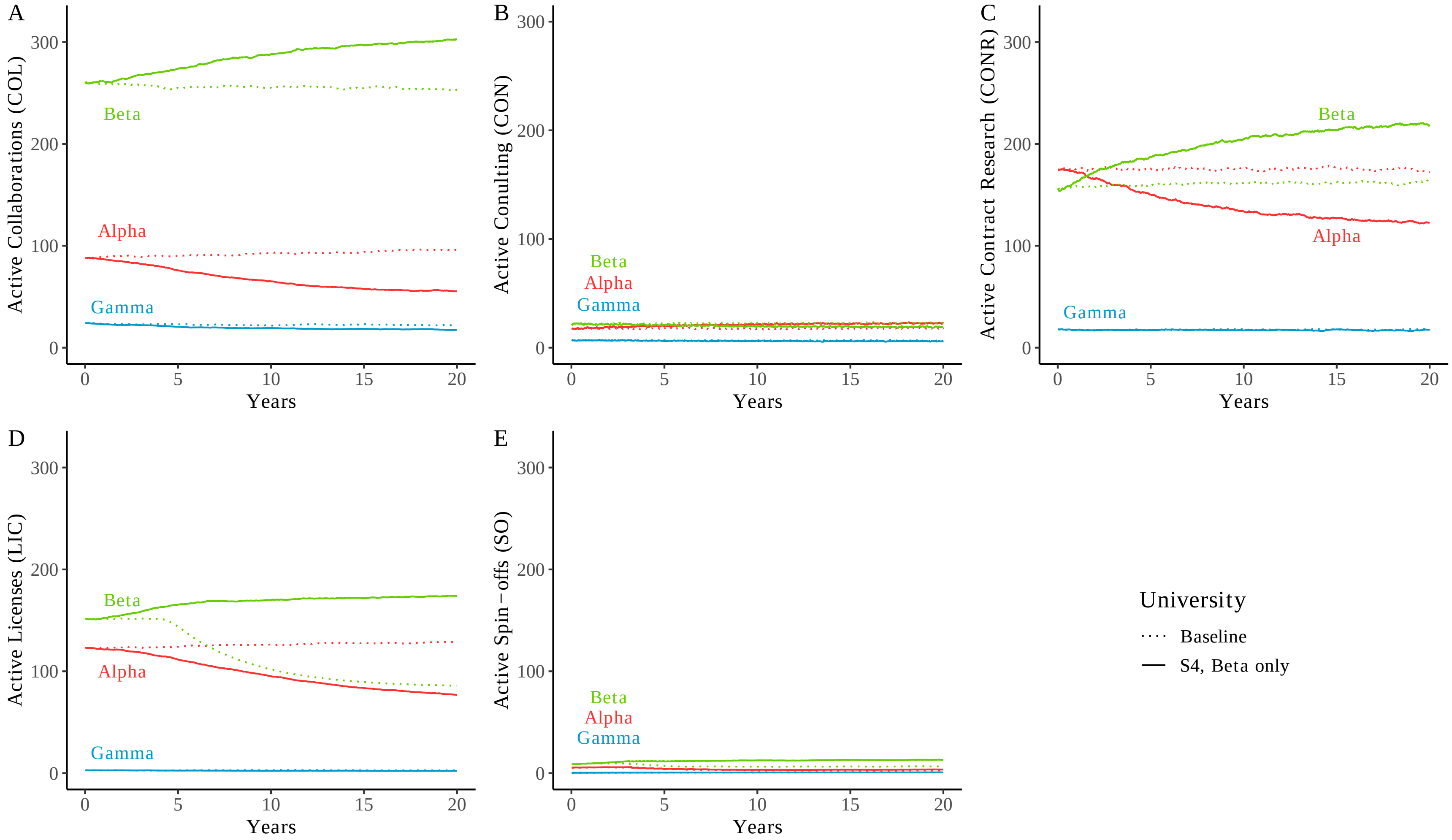


Figure 6.27: Simulation output for scenario 4 where only Beta invests in AE. Results are shown for each activity, namely COL (A), CON (B), CONR (C), LIC (D) and SO (E).

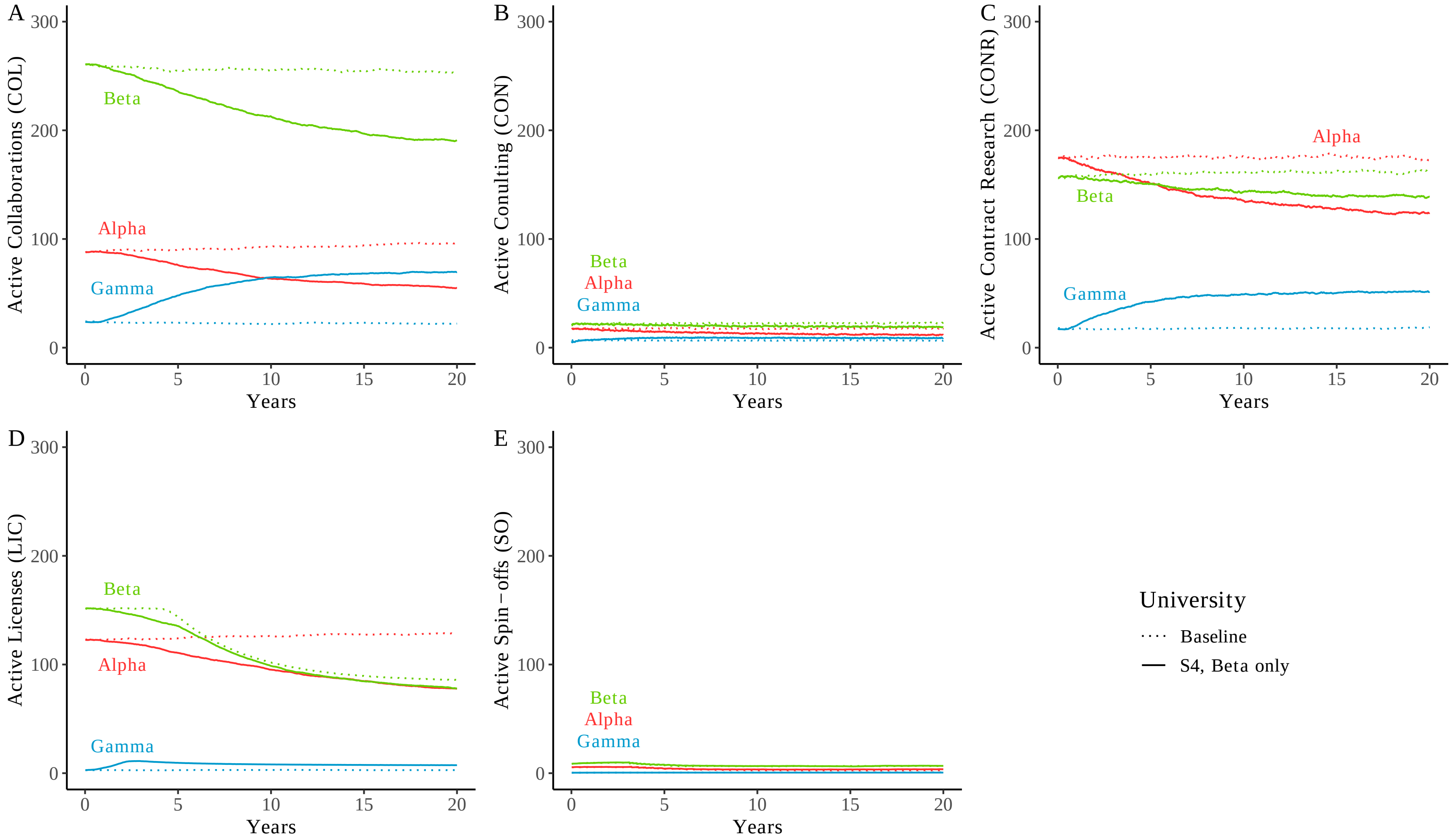


Figure 6.28: Simulation output for scenario 4 where only Gamma invests in AE. Results are shown for each activity, namely COL (A), CON (B), CONR (C), LIC (D) and SO (E).

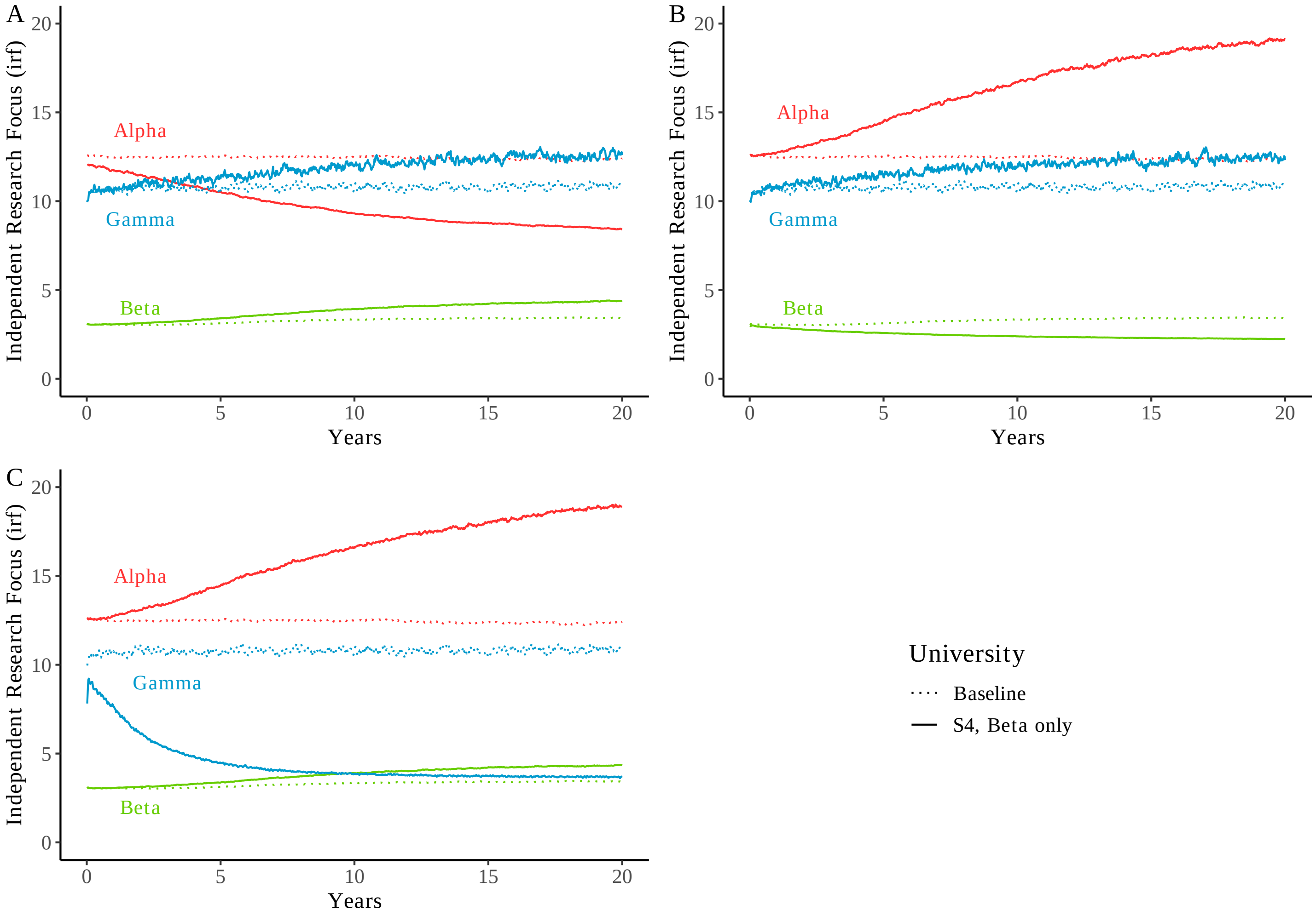


Figure 6.29: Simulation output showing 'irf' for scenario 4 where only Alpha invests in AE (A), only Beta invests in AE (B), and only Gamma invests in AE (C).

Table 6.18: Transition matrix for scenario 4 (only Alpha pursuing growth)

	→ 1	**→ 2**	**→ 3**
1 →	0.78	0.20	0.02
2 →	0.37	0.56	0.06
3 →	0.34	0.44	0.23

Table 6.19: Transition matrix for scenario 4 (only Beta pursuing growth)

	→ 1	**→ 2**	**→ 3**
1 →	0.56	0.39	0.05
2 →	0.21	0.75	0.04
3 →	0.29	0.48	0.23

Table 6.20: Transition matrix for scenario 4 (only Gamma pursuing growth)

	→ 1	**→ 2**	**→ 3**
1 →	0.56	0.32	0.12
2 →	0.31	0.59	0.10
3 →	0.15	0.18	0.67

The state transition matrices for each simulation run tell a similar story. The respective matrices are shown in Tables 6.18 (Alpha pursues growth), 6.19 (Beta), and 6.20 (Gamma). The university that is pursuing the growth strategy is seeing higher retention rates and an increased transition rate from the more popular of the remaining two universities. For example, Beta attracts more companies that used to work with Alpha than those that worked with Gamma (Table 6.19).

This can be further explained using complex events. The ten most frequent complex events for partnerships (Table 6.21), reputational effects (Table 6.22), and external marketing success (Table 6.23) are presented in the following. While the university that does pursue the growth strategy is the one that establishes most partnerships, the number of these partnerships for Alpha and Beta is three times higher than for Gamma (Table 6.21). Despite these efforts by Gamma, this is clear evidence of a path dependency that has manifested itself over the past decades. Alpha and Beta have established bases of companies that are both likely to interact with universities and them in particular.

Reputational effects, in comparison to partnerships, are almost negligible in terms of the number of occurrences for all universities (Table 6.21), which is in line with the sensitivity analysis in Appendix E.3. Particularly for Gamma, there is very little gains from this (there is only one complex event with four instances involving Gamma across all three configurations in which one of the universities pursues a growth strategy).

External marketing does support the development of partnerships and stim-

Table 6.21: Partnership complex events from scenario 4

Alpha pursues growth		**Beta pursues growth**		**Gamma pursues growth**	
Count	Sequence	Count	Sequence	Count	Sequence
848	(1)-(1)-(1)	794	(2)-(2)-(2)	259	(3)-(3)-(3)
724	(1)-(1)-(M1)-(1)	551	(M2)-(2)-(2)-(2)	247	(M3)-(3)-(3)-(3)
702	(1)-(M1)-(1)-(1)	526	(M2)-(2)-(2)-(M2)-(2)	241	(3)-(M3)-(3)-(3)
685	(1)-(M1)-(1)-(M1)-(1)	525	(M2)-(2)-(M2)-(2)-(2)	239	(3)-(3)-(M3)-(3)
569	(M1)-(1)-(1)-(1)	499	(M2)-(2)-(M2)-(2)-(M2)-(2)	236	(M3)-(3)-(M3)-(3)-(3)
552	(M1)-(1)-(1)-(M1)-(1)	448	(2)-(2)-(2)-(M2)	235	(M3)-(3)-(3)-(M3)-(3)
543	(M1)-(1)-(M1)-(1)-(1)	426	(2)-(M2)-(2)-(2)-(M2)	231	(3)-(M3)-(3)-(M3)-(3)
527	(M1)-(1)-(M1)-(1)-(M1)-(1)	420	(2)-(2)-(M2)-(2)-(M2)	227	(M3)-(3)-(M3)-(3)-(M3)-(3)
515	(1)-(1)-(1)-(M1)	400	(2)-(M2)-(2)-(M2)-(2)-(M2)	159	(3)-(3)-(3)-(M3)
502	(1)-(1)-(M1)-(1)-(M1)	339	(M2)-(2)-(2)-(2)-(M2)	154	(1)-(1)-(1)

Table 6.22: Reputational effects complex events from scenario 4

Alpha pursues growth		**Beta pursues growth**		**Gamma pursues growth**	
Count	Sequence	Count	Sequence	Count	Sequence
28	(NR13)-(1)	40	(NR21)-(2)	27	(NR24)-(2)
24	(NR14)-(1)	37	(NR24)-(2)	23	(NR23)-(2)
23	(NR21)-(2)	32	(NR22)-(2)	14	(NR13)-(1)
22	(NR22)-(2)	13	(NR13)-(1)	14	(NR21)-(2)
21	(NR11)-(1)	10	(2)-(NR21)-(2)	11	(NR22)-(2)
17	(NR24)-(2)	9	(NR24)-(2)-(1)	10	(NR14)-(1)
16	(NR23)-(2)	7	(NR22)-(M2)-(2)	7	(NR11)-(1)
13	(NR12)-(1)	6	(NR11)-(1)	6	(NR11)-(1)-(2)
8	(1)-(NR14)-(1)	6	(NR22)-(2)-(1)	5	(NR12)-(1)
6	(1)-(NR11)-(1)	6	(NR22)-(2)-(M2)	4	(NR33)-(3)

ulates interactions. In absolute numbers, these complex event types outrank the other two by a large margin (Table 6.23). When Alpha pursued a growth strategy, it has seen more than twice as many external marketing success events than partnerships. For Gamma, this ratio increases to more than five times as many external marketing events compared to partnerships. Beyond the absolute numbers, there is a risk for Alpha and Beta to waste efforts on companies that potentially might have approached them anyway. Additional information is required but the prevalence of external marketing efforts in many of the partnership complex events provides an important aspect for universities to look at and to re-evaluate their current efforts.

Table 6.23: External marketing complex events from scenario 4

Alpha pursues growth		Beta pursues growth		Gamma pursues growth	
Count	Sequence	Count	Sequence	Count	Sequence
1825	(M1)-(1)	1803	(M2)-(2)	1420	(M3)-(3)
1612	(M1)-(1)-(M1)	1612	(M2)-(2)-(M2)	1226	(M3)-(3)-(M3)
1355	(1)-(M1)-(1)	1361	(2)-(M2)-(2)	868	(M3)-(M3)-(3)
1276	(M1)-(M1)-(1)	1314	(M2)-(M2)-(2)	701	(M3)-(3)-(3)
1204	(M1)-(1)-(1)	1237	(M2)-(2)-(2)	691	(3)-(M3)-(3)
1172	(M1)-(1)-(M1)-(1)	1201	(M2)-(2)-(M2)-(2)	666	(M3)-(3)-(M3)-(3)
1117	(1)-(M1)-(M1)	1060	(2)-(2)-(M2)	661	(M3)-(M3)-(3)-(M3)
1101	(1)-(1)-(M1)	1019	(2)-(M2)-(2)-(M2)	554	(M3)-(3)-(M3)-(M3)
1057	(1)-(M1)-(1)-(M1)	960	(M2)-(M2)-(2)-(M2)	548	(1)-(M3)-(3)
963	(M1)-(M1)-(1)-(M1)	906	(M2)-(2)-(M2)-(M2)	510	(M3)-(3)-(3)-(M3)

6.8 Summary

This chapter provided a detailed description of the simulation model, most notably the transformation of the CLD to the SFD for university agents. In a second step, the parametrisation process with the aim of creating an equilibrium model under baseline conditions for the five entrepreneurial activities was outlined before describing how the simulation model will be implemented in Java, simulated, and the outputs eventually analysed. The output from the baseline scenario is presented as a model of the status quo of the interaction between Scottish universities and UK businesses. The baseline model has also been used to demonstrate the feasibility of the HS design in general and the complex events approach. Through this type of post-simulation analysis, key information can be obtained that would otherwise be lost when simply looking at aggregated values from the ABM module.

The four scenarios have provided insights into how universities can grow their entrepreneurial activities. Depending on the goals of the university and its priorities with regard to the three main pillars (e.g. prioritising independent research over knowledge exchange and external engagement or vice versa), a university must develop a combination of internal and external marketing strategies. The simulations have highlighted that there is a great deal of path dependencies involved, which means that universities must carefully account for their current position, their resources and capabilities when designing these strategies. For example, for Gamma, scenario 2 is a viable option and does not require them going above and beyond what other universities are doing. It would take extraordinary efforts (relative to the rest of the sector) for a university to completely re-position itself. These insights will be discussed and contextualised in the next chapter.

Chapter 7

Discussion

7.1 Introduction

This penultimate chapter of this thesis reflects on the insights from the modelling process itself (Section 7.2) and subsequently contextualises the simulation results and discusses their implications. This discussion is organised around the four research questions, focusing on the development of the university ecosystem (Q1) in Section 7.3; path dependencies for universities (Q2) in Section 7.4; partnerships and temporal dynamics of firms' activities (Q3) in Section 7.5; and the co-evolutionary dynamics of a university's reputation, social capital, and organisational proximity (Q4) in Section 7.6. In addition, TTOs, although not modelled explicitly, play an important role as described during the development of the conceptual model in Chapter 5 and the simulation model and the results in Chapter 6. There are implications particularly for TTOs which are discussed in Section 7.7. Finally, in Section 7.8, insights and learning about the modelling process and the implications for developing hybrid simulations in the future are discussed.

7.2 Learning from the Modelling Process and the 'Big Picture'

Learning takes place at all stages of the modelling process and is not limited to the evaluation of the simulation output. This study is no exception to this rule and a number of insights were gained prior to running the simulation. Before discussing the simulation results in more detail, this section will reflect on the more general learning that has occurred throughout this process.

Reviewing the existing literature on (university) ecosystems and the role of universities in different ecosystem configurations with the aim of deriving a general conceptualisation as part of the problem articulation stage of the modelling process has led to several insights. First, much of the literature as well as policy and practice have been inspired, if not directly led, by efforts and the success of regions such as Silicon Valley or Route 128 around Boston with universities such as Stanford and MIT at their heart. Similarly, these universities as well as other success stories have been studied extensively and many authors have aimed to develop a blueprint for how universities can become more entrepreneurial (as discussed in Chapter 2). The geographical and demographical attributes of these places as well as the accumulation of different types of human and financial capital, among others, make comparisons and policy adaptations problematic at best. This is mainly caused by the research intensity, funding and resource endowment of the respective university as well as human capital in close proximity.

The interviews have shown that many Scottish universities face challenges that are very different to those faced by 1) world-leading research universities or 2) those located in cities and metropolitan areas such as Boston, New York, or London. Common issues are TTO funding, research time for academics, as well as absorptive capacity and appetite of local companies for engaging with universities (see also Appendix D.2). Like many dynamic processes such as the diffusion of innovation, the structure of this model if applied to e.g. universities in the US would look very similar, but the output based on a parametrisation with US data would most likely look very different. This highlights the importance of context and should serve as a reminder for Scottish universities to not blindly follow 'best practices' from other universities or regions. Furthermore, this also highlights the need to contextualise the insights from this simulation model and the three generic universities.

A second issue is the focus on commercialisation activities. Spin-offs and licensing have been and continue to dominate the academic discourse and policy interventions around academic entrepreneurship and entrepreneurial universities. This has implications for a variety of areas. Data collection has over-emphasised IP-based activities and covered these activities in greater depth. For example, the number of collaborative research projects is not recorded in the HE-BCI B data. The CBR Business Survey includes details about how often companies have licensed IP from a university, but only a binary indicator of whether or not the company engaged in e.g. contract or collaborative research. Researchers have pointed out that the focus need to be widened but this needs to be addressed in future data collection efforts (Abreu & Grinevich, 2013; Perkmann et al., 2013). The current survey designs hinder progress with regard to developing a holistic understanding of university-industry interactions and skews research in favour of commercialisation activities.

This emphasis on spin-offs and licensing has also morphed into the policy sphere and even created tensions between the two modes of knowledge commercialisation. For example, the focus on spin-offs as opposed to licensing and the funding available has led to unintended and sometimes even perverse consequences. An interviewee explained that the university and a company have formed a spin-off with the sole purpose of licensing a technology to that spin-off to be eligible for further funding in an attempt to bridge the 'valley of death'. The result are inefficiencies at the systemic level – the opposite of what the policies intend to achieve originally (see Appendix D.1).

This is not to say that universities or governments should stop supporting licensing or spin-off creation. Roessner et al. (2013, p. 23) have estimated that licensing of university IP between 1996–2010 has contributed $122.2 billion (2005 dollars) to the US economy based on "a moderately conservative estimate based on 5% royalty rates". Under the assumption of no product substitution effects, these agreements have created an additional employment of at least 277,000 person-years in that time frame (Roessner et al., 2013). Similarly, licensing-based spin-offs "are both an important vehicle of technology transfer, and an important mechanism for economic activity" (Di Gregorio & Shane, 2003, p. 209).

Much of this 'direct' economic impact (and, hence, monetary returns to the respective university) comes from a small number of licenses and spin-offs, which leads to the issue of 'picking winners'. This has been a widely discussed issue in industrial economics and entrepreneurship policy. Introduced to the field of entrepreneurship policy by Birley (1987), it subsequently gained traction in the literature but both early accounts (Storey, 1994) and more recent research (Coad et al., 2014; David et al., 2000) shows that government and support policies should refrain from selecting promising businesses or sectors. Universities face similar challenges, mostly due to the embryonic nature of the technologies and the information asymmetries for licensing as discussed in Section 2.3.3.1 (see also Shane, 2004b; Macho-Stadler et al., 2007; Poyago-Theotoky et al., 2002) and the challenges that spin-offs face (Vohora et al., 2004, and Section 2.3.3.2).

The effect of problem with 'picking winners' is reflected in the absence of returns from spin-offs in the simulation model. This link does exist in the real world, but there is a lack of reliable data as only two universities in Scotland have recorded revenues from sales in shares in the time period considered in this study. Many Scottish universities are operating on a smaller budget for protecting IP, which means that they cannot take many chances on technologies that might have a high return but are also at an embryonic state and come with high uncertainties. This might prevent the commercialisation of *homerun* technologies in favour of more incremental technologies that can be translated into a marketable product or service faster and with less effort.

More important than the direct impact are 'indirect' contributions of commercialisation activities for universities. First, commercialisation activities signal a willingness to engage with industry. Particularly spin-offs have reputational benefits for the university (Zomer et al., 2010), which Scottish universities are increasingly aware of. The interviews have highlighted that universities consider the signalling effects of spin-offs and the reputational benefits compared to licenses, which, from a marketing point of view, are typically constrained by non-disclosure agreements. Second, spin-offs are important for the university ecosystem by providing jobs for graduates and linking the university to other companies in their sector, both locally and globally. Third, creating spin-offs is a means of legitimising public funding by creating value for the economy and society (Zomer et al., 2010), another aspect that Scottish universities are accounting for when formalising commercialisation strategies (see Appendix D.1). A crucial aspect is the legitimisation not just for economic reasons but also to provide social benefits.[66] From an (eco)systemic point of view, it is not just about widening the focus and looking at a wide range of activities, but even more so at their complex interactions (an issue which has also been raised in Section 2.3.2).

7.3 Academic Entrepreneurship and University Ecosystems

The first research question is *what is the dynamic relationship between universities' internal capabilities and resources (organisational arrangements), the volume and share of different entrepreneurial activities, and the evolution of the university ecosystem?*

The role of universities within society and the economy has changed significantly over time (Section 2.2.3). These dynamics have led to the development of

[66] Many universities already use the United Nation's Sustainable Development Goals (SDGs) as an organising framework for their entrepreneurial and outreach activities, which provide a number of rationales beyond direct economic benefits.

the Third Mission of universities (Section 2.3.1) and ignited the evolution from technology transfer to the entrepreneurial university (Section 2.3.2). In essence, universities have moved from a relatively passive role to a more active, multi-faceted role within their regional ecosystem and the economy as a whole. These multi-faceted interactions are "coevolutionary and strongly shaped, for good or ill, by past relations, by the growth or decline of relevant industries, and by current university leadership" (Heaton et al., 2019, p. 15). Universities, like other ecosystems actors, do not only adapt to the ecosystem but also shape the ecosystem and the environment for other actors through their adaptations and actions (Kay et al., 2018). This is a crucial point as it is both a rationale for using a simulation model (due to its ability to account for the changing landscape and adaptations of individual actors) and carries implications for the results presented in the previous chapter.

Growing the ecosystem requires continuous investment. This is not unique to university ecosystems but shared by technologies, institutions, and organisations. There is no immediate success, most breakthroughs take years if not decades, the most recent example being artificial intelligence (AI) that has a long intellectual history. Similarly, when establishing new universities (Cermeño, 2019) or when large multi-national companies re-locate, spillover effects vanish over time if there are no subsequent investments (Bhawe & Zahra, 2019). The reason is that knowledge bases and regional absorptive capacity need to be developed, which allows "spawning different types of entrepreneurial ventures that combine both replicative (imitative) and truly innovative local firms" (Bhawe & Zahra, 2019, p. 437). Link & Sarala (2019) have shown that absorptive capacity moderates the success (measured as an increase in sales) of interacting with universities for entrepreneurial firms. This requires investments in collaborations but also a steady stream of research funding; which is a mix of different entrepreneurial activities that are considered in this model (and others beyond these five modes of interaction).

Two types of variety can be distinguished when discussing university-industry interactions, which represent a set of complimentary indicators (D'Este & Patel, 2007, based on Stirling, 1998). *Variety I* involves whether an academic (or a university as a whole) are engaging in "broad or narrow range of interactions", hereby measuring the breadth, i.e. "how many distinct forms of interaction the individual researcher is engaged in" (D'Este & Patel, 2007, p. 1304). This simulation is limited to four entrepreneurial activities for the direct interaction between universities and companies in addition to the creation of spin-offs. *Variety II* covers the “number of distinct forms of interaction in which a researcher has engaged more frequently than the average” and measures the frequency, i.e. “how much the individual interacts within each category of interaction” (D’Este & Patel, 2007, p. 1305). For universities, the frequency (or intensity when divided by the number of research-active staff) has been used to identify the universities that form the basis of each generic university (Section 5.3.1).

The share of different activities does not change significantly for any university in this simulation, even when comparing the baseline scenario in Section 6.5.1 to scenario 4 with the most significant changes to the structure of university agents and their external activities in Section 6.7.4. The reason is that the learning from past interactions and external marketing without involvement of academics is applied randomly to only one of the four activities based on a uniform distribution and external marketing with involvement of academics applies to all four activities. Quantitative empirical evidence for how a particular activity leads to either a repetition of the same activity or another entrepreneurial activity does not exist, qualitative data that was collected as part of this research is inconclusive (see Appendix D.7). This issue can only be addressed through a survey that is similar to the CBR Business Survey in terms of size and reach, but includes additional details about each type of interaction and the implications (which is, again, beyond the scope of this study).

This study has, however, led to other insights regarding universities’ entrepreneurial activities and external marketing efforts and the development of the ecosystem. Depending on the state of the ecosystem, universities have to take on different roles (Heaton et al., 2019). Essentially, this requires universities to be *curators*, who do not just engage in individual activities to support the growth of absorptive capacity but also creating new formal and informal institutions and rules. Universities must consider this and develop a holistic strategy for their engagement with the ecosystem beyond entrepreneurial activities.

The need for a holistic approach by universities has been demonstrated through the complex events in scenario 4, where only one university at a time pursues a growth strategy with regard to its entrepreneurial activities. To illustrate this, the sequence consisting of two marketing activities from Alpha followed by an interaction with Alpha (“(M1)-(M1)-(1)”) was the fourth most frequent external marketing complex event with 1,276 instances when only Alpha pursued a growth strategy, therefore more than twice as frequent than e.g. the partnership complex event with three subsequent interactions with Alpha after a marketing activity (“(M1)-(1)-(1)-(1)”) with 569 instances. Furthermore, the second most frequent partnership complex event for Alpha is two interactions with Alpha, followed by a marketing activity from Alpha and the third interaction ("(1)-(1)-(M1)-(1)"), whereas for Beta and Gamma the second most frequent ones are a marketing activity followed by three subsequent interactions with Beta ("(M2)-(2)-(2)-(2)") and Gamma ("(M3)-(3)-(3)-(3)"), respectively.

For Alpha to invest in marketing efforts with a company, that either was already targeted by marketing efforts recently or that has already worked twice in a row with Alpha is in most cases wasted effort. The involvement of academics in external marketing is a costly activity for the university, both in direct monetary terms but also in terms of opportunity costs as these academics could be working on publications or teaching. Universities must, therefore, balance the additional benefits of involving academics to build organisational proximity and establishing a culture of collaboration with its other priorities. Particularly in the early stages, a lot of the work can be done by TTO staff. As the ecosystem evolves and matures (alongside new technologies and platforms that the involved companies are commercialising), external marketing efforts require academics who are able to put forward new research agendas and 'sell' these to businesses for continuous (regional) collaborations (Heaton et al., 2019).

7.4 Path Dependencies

The second research question asks *whether there is a path dependency for universities based on different research and entrepreneurial profiles, resource endowments, and historical backgrounds?*

The three generic Scottish universities Alpha, Beta, and Gamma have very distinct profiles across research, teaching, and their knowledge exchange activities (as discussed in depth in Section 5.3.2). These have manifested over decades and, in some cases, centuries and impact both the university's entrepreneurial strategy as well as its entrepreneurial performance. For Alpha, for example, entrepreneurial activities are a clear second to conducting high-quality research. The existing research prestige and the continuous focus on world-leading research have led to reputational effects in the form of an institutional halo for Alpha. Another important aspect is the size of Alpha, which allows for more flexibility as the research base is not diminished easily. This is reflected in a high *irf* value (see Figure 6.11 in Section 6.5.1), which is still higher than Beta's even in the case of Alpha being the only university that pursues an entrepreneurial growth strategy (Figure 6.29).

There are also opportunity costs for leading research universities when it comes to working with industry. Reducing the time spent on research means less publications, which can have a detrimental impact on rankings and the university's prestige. This prestige does not only lead to the aforementioned halo, but also allows universities to charge higher fees, particularly for postgraduate taught students (PGT). In many cases, PGT has a much higher revenue potential than small-scale entrepreneurial activities. This becomes a problem when the university wants to grow entrepreneurial activities, as there is a lack of institutional incentives because entrepreneurial activities are usually not workloaded, whereas teaching is. This is also why universities should consider experimenting with an institutional arrangement as described in scenario 3.

For Beta, entrepreneurial activities are as much about creating impact and making research relevant to society and the economy as it is a means to increase the research budget in an attempt to close the gap to the world-leading research-intensive universities. This is reflected in a comparably lower irf value (see Figure 6.11 in Section 6.5.1). Gamma's irf value is misleading and higher than it actually is, which is cause by the type of entrepreneurial activities that are considered in this model (as discussed in Section 6.5.1). Both Beta and Gamma are significantly smaller than Alpha and academics are also constrained by a lower share of their workload dedicated to research rwa. In the absence of the institutional halo that Alpha benefits from, entrepreneurial activities are vital to both universities and their development.

Independent research is, nevertheless, important as publications are still the single most important aspect of the REF. While high-quality publications can result from collaborative research or other forms of engagement with industry, there is typically no time to write up these papers during the collaborative project. And even if some time is reserved for writing papers, the lengthy and potentially labour-intense peer-review process with multiple rounds of 'revise-and-resubmit' (R&R) goes beyond the scope of the project. Therefore, academics' independent research time must be protected if universities want to remain a high research output and a 'Capacity Utilisation' cu approaching one becomes a critical issue for the university. A key factor in this process are post-doctoral research assistants (PDRAs), which are also associated with higher future research funding (Rosenbloom & Ginther, 2017). With a larger research base, Alpha is better able to fund and retain PDRAs as they can also be co-funded by multiple projects, which strengthens their future position.

This underlines the importance for universities to focus less on blueprints based on universities that operate within different contexts and have different capabilities and resources to start with. Rather, the results in the previous chapter as well as the previous discussions in this chapter with regard to the importance of considering the state of the ecosystem have underlined the need for universities to adopt a *dynamic states model* as proposed in Section 2.2.3. The dynamic states model requires universities to evaluate their current situation, tailor new initiatives, and embrace the *variability of newness* (Levie & Lichtenstein, 2010). As a consequence, universities will mostly follow unique paths as there are hurdles and considerable investments required to massively change a university's trajectory.

These path-dependencies are, however, not necessarily negative. The diversity of the university sector is a strength of the UK system and path-dependencies can also be interpreted as resilience on the side of universities within a changing environment at an increasing pace. The increased focus on 'impact' (Hughes & Kitson, 2013) and simple output measures (Rossi & Rosli, 2015) might turn out to be detrimental to the university sector as a whole. Universities might have to engage in many activities that individually do not have a great impact or can easily be summarised in an impact case study for REF, but collectively support the growth of the ecosystem and its absorptive capacity. Using a 'one-size-fits-all' approach for measuring and evaluating entrepreneurial universities is, therefore, not desirable (Baglieri et al., 2018). Another reason for avoiding measuring all universities based on one set of criteria is *Goodhart's Law*, which postulates that when measures become targets, they are no longer useful measures (Elton, 2004).

The nature of university-industry interaction has evolved over the past decades, encompassing a variety of activities and configurations (Grimaldi et al., 2011; Perkmann et al., 2013). All of this is based on the underlying assumption that these interactions are beneficial. However, what is beneficial for one university might not be for another given the different starting points from where universities operate. These path dependencies can be balancing and stabilising, which is evident from very stable behaviour of the three universities across different configurations in the four scenarios. The question remains if universities should attempt to shift their path dependency and, if so, what activities and resources are required (Ahuja & Katila, 2004; Grimaldi et al., 2011). Addressing this question must go beyond a simplistic account of 'history matters' (Kay, 2005, p. 553), where rich structures are reduced to the ones who are showing some sort of path-dependent behaviour, and instead working towards "understanding temporality – of which one will be path dependency" (Kay, 2005, p. 569). Universities slowly evolved within a number of environments, such as their university ecosystem and national higher education systems, among others, which lead to incremental changes, often in a different way than anticipated by policy makers (Djelic & Quack, 2007; Krücken, 2003; Mustar & Wright, 2010). The viability of the overall system does, however, depend on heterogeneity of universities, where reducing variety is similar to 'picking winners', which might work in the short-run but will lead to more fundamental issues in the long-run (Krücken, 2003).

7.5 Partnerships and Firms' Activities

The third research question is *what are the temporal dynamics of different entrepreneurial activities in the evolution from ad hoc interactions to strategic partnerships between universities and firms?*

The temporal order of different activities can be observed from the ABM module, but this chapter has already highlighted that these orders are generated by chance and are not grounded in empirical data and causal effects. This research has shown that there are limitations in data collection and empirical research in general with regard to the interdependencies between different activities. While this is part of the learning from the modelling process, the actual simulation results also offer further insights into firm behaviour and the evolution from ad hoc interactions to strategic partnerships between universities and firms.

Long-term partnerships are desirable for both universities and companies in order to enable more effective knowledge exchange (see Section 2.6.3). However, there is also a risk of technological lock-ins as a result of repeated interactions with the same university, i.e. partnerships, when both partners become too close along the cognitive/technological dimension (e.g. Meyer-Krahmer & Schmoch, 1998; Nelson & Winter, 1982, see also Section 2.4). The quality of the interaction is static and proxied by the stochastic evaluation rule R_{EVAL} (see Section 5.4.2.5). This rule has little impact on partnering (see also the sensitivity analysis for learning from past interactions in Appendix E.7). Similarly, networking among agents does not affect agents' behaviour significantly (Appendix E.3).

Partnerships are mainly affected by external marketing efforts from university, ideally combined with internal marketing activities to cope with an increased demand. In this simulation, partnerships are identified through complex events, but also the transition matrices can reveal insights into firms' behaviour. Gamma is able to increase its retention rate (which essentially is the repeated interaction between a company and Gamma, i.e. the first step towards a 'partnership') when its TTO staff approaches more innovative companies ($I = 2$ in particular) in scenario 2. In scenario 3, the resulting transition matrices differ less from the baseline scenario. It takes considerable effort to change transition matrices, such as in scenario 4 (particularly for the $em = 10$, $I = 2$, and $tsea = 2 * sea$ configuration).

There are more significant changes in the prevalence of partnerships between companies and universities when comparing the baseline scenario (Table 6.8) to scenario 4, where only one university pursues an entrepreneurial growth strategy (Table 6.21). In the baseline scenario, there are 219 partnerships with Alpha (agent state sequence "(1)-(1)-(1)"), which rises to 848 or by 387% when only Alpha invests in internal and external marketing. Even more drastically, the prevalence of partnerships with Beta (agent state sequence "(2)-(2)-(2)") rises from 150 in the baseline scenario to 794 (or by 529%) when Beta pursues growth and for Gamma (agent state sequence "(3)-(3)-(3)") from 23 to 259, which is an increase of 1,126%. This shows that while Gamma benefits the most, if the level of effort is similar among universities, but the real change is the result of one university investing considerably more than the rest. These effects would most likely be stronger if a wider range of activities is considered as other studies have, for example, shown that "the routines of establishing partnerships with local and regional bodies [...] are positively related to CPD" (Zhou & Tang, 2020, p. 1).

Partnerships, i.e. repeated or continuous collaboration between firms and universities, are desirable as the efficiency of the interaction increases with growing organisational proximity (Gulati, 1995), tacit knowledge is exchanged more easily (Gilsing & Nooteboom, 2006), and it signals to other ecosystem actors that the involved partners are reliable and valuable collaborators (Nooteboom, 2004). For firms, this comes down to being able to adapt their processes and practices for increasing connectivity and knowledge flows (De Silva & Rossi, 2018; Hughes & Kitson, 2013). Relationships between firms and universities in general and partnerships in particular are heterogeneous in nature, as shown by the simulation model, which means that both parties need to continue working on innovative solutions (Fontana et al., 2006).

New approaches for facilitating close partnerships is the creation of joint appointments of faculty. This does not only allow them to gain insights from industry but also to supplement their salaries. Universities in certain geographical areas or certain faculties or departments of universities that are located in favourable locations suffer from a brain drain because salaries outwith academia are higher. In addition, these types of joint appointments would also allow researchers to stay active within academic communities and continue to supervise students. The latter might require new contracts, information sharing agreements, and data access protocols to get the best of both worlds: academic freedom combined with data and equipment from industry.[67]

7.6 Co-Evolutionary Dynamics

The fourth and final research question asks *how do the co-evolutionary dynamics between a university's research prestige, entrepreneurial reputation, organisational proximity, and social capital affect its entrepreneurial performance?*

The role of universities and the expectations that are put on them in terms of their contribution to society and the economy have changed over the past century. As a response to these demands and changes in funding structures and the legal environment, *entrepreneurial universities* have emerged (Section 2.3). Many universities are celebrated for their impact on the economy and regional development through their Third Mission activities and used as examples to encourage other universities to follow. However, there is a risk that attention of universities is diverted from things that they are good at such as independent research and teaching to things that they are not good at such as licensing and spin-off creation. These activities require skills and expertise that are naturally not present within an academic institution. These skills must be acquired, which can be achieved either through hiring or training staff, but also requires investing in the infrastructure to support these efforts. From an (eco)systemic perspective, this also raises the question whether this is the most effective approach.

For the intra-organisational co-evolutionary dynamics, this points to a crucial issue: academic entrepreneurship is fundamentally a people-based endeavour, even commercialisation activities such as licensing heavily depend on the involvement of the academics and TTO staff. This has been highlighted by multiple interviewees and is also reflected in the model. Particularly Beta is very close to its entrepreneurial capacity at the start (see Section 6.5.1). The key resource is, hence, entrepreneurial academics, i.e. those academics who are interested in working with external partners and are able to successfully integrate this into their research and teaching efforts. Section 5.3.3.9 has already introduced the *paradox of entrepreneurial academics*, who chose to be academics in the first place as opposed to working in the private sector or in other settings in the public sector. When looking at the institutional level, another paradox arises.

[67]An exemplary case is the case of Raquel Urtasun, who is a professor at the University of Toronto and the Chief scientist at Uber Advanced Technologies Group, where the latter has invested $200 million over five years in Toronto to enable and expand this collaboration.

Academics are expected to act in an entrepreneurial way by exploring new collaborations, initiating consulting activities, or commercialising their IP, among other things. Many of these activities involve 1) a lot of work upfront and 2) limited chances of success (particularly when additional funding needs to be sought). In most cases, academics take these risks whereas most of the benefits are reaped at the institution level. This is *corporate* rather than entrepreneurial behaviour on the part of universities, which questions whether entrepreneurial universities are truly *entrepreneurial.*

The benefits of a holistic approach to academic entrepreneurship has been demonstrated in scenarios 3 and 4. By including the development of new entrepreneurial activities in the workload model, universities share and institutionalise the risks associated with exploratory activities (this is currently only done to a limited extent as discussed in Section 2.3.4). Beside the direct effects (particularly the increased effectiveness of attracting companies), there are further benefits to the universities. First, this is likely to support internal marketing efforts as potential entrepreneurial academics can get a taste of what working with external partners is like without having to sacrifice their research or compromise their teaching. Second, universities see an increase in organisational proximity. In this study, organisational proximity is defined by its function, i.e. the ability of a university to interact with external organisations and individuals (Knoben & Oerlemans, 2006). Having more academics work with TTO staff and external organisations increases the level of understanding of how companies work and what they currently work on (Nooteboom, 1999; Wuyts et al., 2005).

This supports the direct learning from past interactions, which also leads to a mutual understanding among project partners (see also Appendix E.7). In combination with external marketing efforts, both with (scenario 3) and without (scenario 2) the involvement of academics, this can lead to *Matthew effects*. Engagement with companies leads to a higher likelihood of future engagement with the same company, which most likely increases the amount of engagement and so on. Scenario 4 extends this through improving organisational proximity at multiple levels within the university (Al-Tabbaa & Ankrah, 2019; Knoben & Oerlemans, 2006; Nahapiet & Ghoshal, 1998).

The result is not only an increase in organisational proximity, but also in social capital. Social capital can be evaluated in two ways in this model (Adler & Kwon, 2002; Koka & Prescott, 2002; Lorenzen, 2007). First, the retention rate in the transition matrices can be used as a proxy for the structural aspect of social capital. This shows the access that universities have and their network position, i.e. are companies likely to come back to the same university or can they easily approach others. Second, the relational aspect of social capital, which includes personal relationships and the strength of ties with companies can be evaluated through partnerships. The simulation has shown how both the retention rate and the prevalence of partnerships are influenced by the entrepreneurial reputation of each university as well as its resource base to actually accommodate this demand. This is most clear in scenario 4 when only one university invests in academic entrepreneurship and, therefore, increases its entrepreneurial reputation relative to other universities.

This aligns with prior research, which highlights the "inestimable benefit of combining a world-class academic reputation for teaching and research with the nurturing of an 'entrepreneurial attitude of mind' among faculty and students" (Bramwell & Wolfe, 2008, p. 1186). However, this research extends these findings by showing how the *perceived* reputation drives inter-organisational collaboration between universities and industry (see also Appendix E.6). Entrepreneurial reputation, in this study, is defined as the perception among companies that a university is a credible partner for value creation through formal and informal interactions. It is, therefore, not a means to an end but serves a purpose for universities: attracting and retaining industrial partners for both new and continuous interactions. Consequently, "costs of technology transfer should therefore be seen not as a source of income, but rather as investments in research dissemination" (Norn, 2016, p. 8). This closes the loop and leads back to the funding of high-quality research. Contract and collaborative research can be seen as direct research income (the way they are treated in this model). Income from commercialisation activities is not reliable (the best example is the need to exclude spin-off income from the simulation model) and, therefore, not suitable for hiring PDRAs for example. However, commercialisation income is appealing to universities and individual academics as it is unrestricted money and gives the university flexibility.

7.7 Further Insights: A Note on TTOs

The multi-actor model in this study consists of the three generic universities and companies of different sizes and varying degrees of innovativeness. A crucial factor at the interface of the actors are the university technology transfer offices. TTOs have evolved beyond marketing of university IP and negotiating licensing agreements. In many universities, TTOs are the nexus of all entrepreneurial and knowledge exchange activities (see also Section 2.3.4).

TTOs are involved in all activities that are considered in this model and are crucial to all scenarios that are explored on Section 6.7 for growing academic entrepreneurship. This has crucial resource implications for universities, as many interviewees have highlighted that TTO staff across universities are already constrained by the limited TTO budget and the work that is expected from them (see Appendix D.2). In many cases, TTO staff are working to capacity with the current amount of entrepreneurial activities, which does not leave them with any time to engage in internal or external marketing.

Scenario 2 (external marketing by TTOs) and scenario 3 (external marketing by TTOs and academics), for example, have shown the potential increases in entrepreneurial activities if TTOs use a pro-active approach to identifying and working with companies. Particularly when working with inexperienced companies, a key activity is to increase organisational proximity (Villani et al., 2017). Previous sections in this chapter have discussed a necessary shift in the mindset, from looking at entrepreneurial activities as a pure income generator and a means to an end to entrepreneurial activities as *complex mechanisms* for a variety of purposes with direct and indirect effects. While investments in the TTO are required, it is, however, not just the size of the TTO but the alignment between the university strategy and the support that the university puts in place (usually through the TTO) that determines the effectiveness of entrepreneurial activities (Horner et al., 2019). Both the development of an institution-wide strategy and making the necessary investments in the TTO are challenges that are particularly hard for smaller universities and those in rural areas.

An idea put forward in the Lambert Review of Business-University Collaboration, which had a wide-spread impact in the UK more than 15 years ago, was cross-university TTOs for those universities with a weaker research base or those that are embedded in a weaker regional ecosystem (Lambert, 2003). For commercialisation activities, private companies like the IP Group[68] have emerged in the UK as specialist commercialisation partners with the aim of creating synergies and pooling expertise and resources. Another pan-university organisation is Interface (as introduced as an emergent entity in Section 3.7.1), which provides a shared point of contact for businesses who want to engage with Scottish universities beyond commercialisation activities. There is still room for new forms of (hybrid) organisations that actively foster organisational proximity and connect companies and universities, particular as a response to the vast opportunities for

[68]https://www.ipgroupplc.com

Gamma universities. These universities typically also have the least amount of resources devoted to entrepreneurial activities and, hence, are limited in their abilities when trying to grow these activities on their own.

TTOs, whether or not they work for their parent university or collaboratively with other TTOs, should also look at new "digital tools to facilitate the identification of potential research partners, complemented by clear signposting and access to support from appropriately informed people" (Dowling, 2015, p. 2-3). A service like this does not exist yet and lies outside the scope of most individual TTOs. However, simulations that include external marketing targeted at highly innovative companies ($I_i = 2$) have shown the potential gains for universities. A more systematic approach to identifying these companies and managing relationships is therefore necessary and potentially worth the investment.

7.8 Learning about the Modelling Process

Hybrid simulations in general and combinations of SD and ABM in particular are becoming increasingly popular (Brailsford et al., 2019; Swinerd & McNaught, 2012; Zolfagharian et al., 2018). This has led to advances in the areas of HS modelling processes (Section 4.2.1) and decision support for whether or not an HS is required and what type of HS (Section 3.6.3 and particularly the work by Chahal et al., 2013; Swinerd, 2014). By developing an HS simulation and using both SD and ABM modules to answer research questions, this research has supported the argument that SD and ABM are, in fact, complementary and "regions in a space of modelling assumptions" as opposed to contradicting methods (Rahmandad & Sterman, 2008, p. 1001). The implications of combining SD and ABM are, however, not yet fully understood and in many publications not documented properly (Brailsford et al., 2019). This research has highlighted important implications of combining SD and ABM in the following aspects:

1. conceptual modelling and connecting feedback loops across module boundaries;
2. recognising and embedding emergent behaviour;
3. special stocks that correspond to the agent population as opposed to attributes of particular agents;
4. confidence building; and
5. understanding and contextualising the results.

Three of these aspects have already been covered in depth, namely the importance of triangulating data for the conceptual modelling process (see Chapter 5 and a reflection in Section 6.6.3); recognising emergent behaviour and defining three types of complex events for this study in Section 3.7; and the importance of understanding and contextualising the results in this chapter. Two aspects are worth reflecting on in more detail at this point, special forms of 'stocked agents' and confidence building.

A review of existing hybrid SD-ABM designs by Swinerd & McNaught (2012) has identified a number of published papers that use a 'stocked agents' integrated HS design. However, the stocks in these papers accumulate a particular characteristic of the respective agent population. The stocks 'Spin-offs' SO and 'Mature Spin-offs' MSO differ from these designs as they correspond to the number of agents, in this case spin-offs or matured spin-offs among the agent population (see Section 6.2.3.2). All four possible configurations are presented in Figure 7.1, with SO corresponding to Figure 7.1D and MSO corresponding to Figure 7.1A or B (as there is no outflow from MSO). Whenever SO reaches the next highest integer number, a new spin-off agent from the respective university is created. If a spin-off agent either closes or matures, the ABM module affects the outflow C or M from SO, respectively. M also serves as the inflow for MSO.

Linking a stock in an SD module to the number of agents, either the entire population or a sub-group with a particular characteristic (similar to this case with university spin-offs), provides a new mechanism for building an integrated HS simulation. This has not been discussed in the existing literature, but has implications for complex systems in many areas where agent populations, whatever they represent, are not constant.

A major appeal of hybrid SD-ABM simulations is their promise of providing a better representation of complex systems (Swinerd & McNaught, 2012), but this does also provide additional challenges. A particularly ill-developed part of the modelling process for hybrid simulations is confidence building (Brailsford et al., 2019). This research has adopted tools from both SD and ABM as appropriate. Structuring the process of confidence building into four main areas, namely code verification, black-box and white-box validation, and validating the interfaces has been a very helpful approach (see Section 6.6). Differentiating between white-box validation and validating the interfaces is highly recommended as it forces the modeller to pay close attention to how data is exchanged between modules. It is easy to miss potential issues when only superficially checking the corresponding variables without describing how they are connected mathematically.

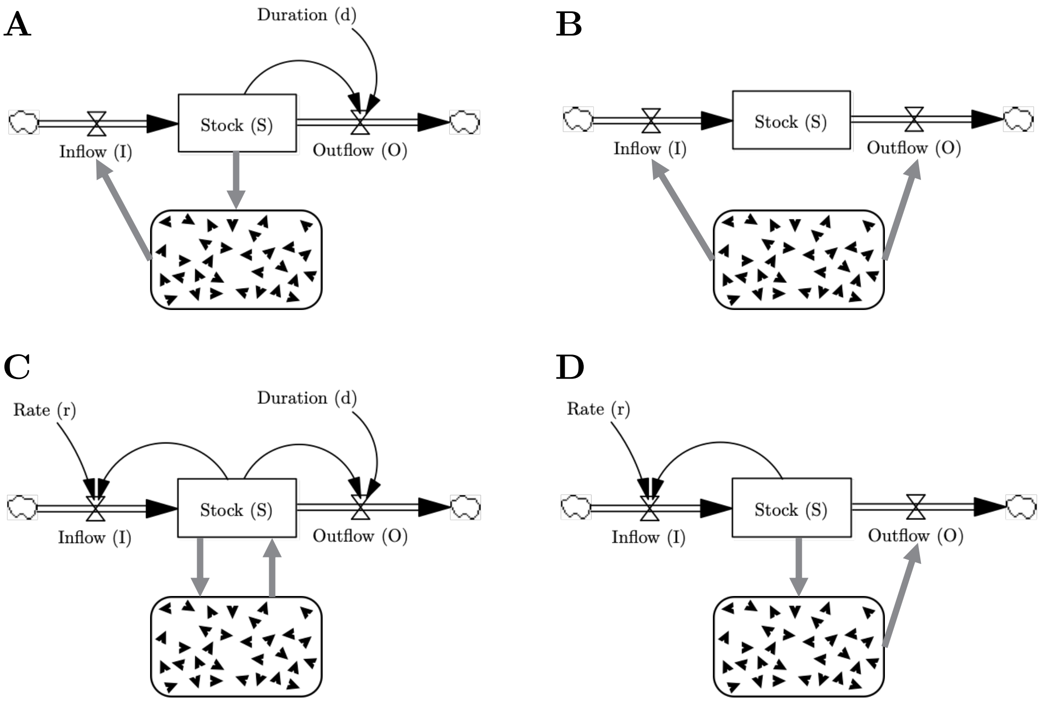


Figure 7.1: Overview of a HS mechanisms for an SD stock representing the agent population where new agents are created in the ABM module and agents get deleted based on the current value of the stock (A); agents are both created and deleted in the ABM module (B); agents are created and deleted based on the value of the stock (C); and the value of the stock creates new agents and their rules within the ABM determine when they get deleted (D).

7.9 Summary

The development of intra- and inter-organisational university ecosystems are the result of complex processes. Simulating academic entrepreneurship and inter-organisational collaboration in university ecosystems through a hybrid system dynamics agent-based model has led to a number of insights, both from the modelling process and the simulation results. This chapter has reflected on these insights and contextualised them. This research, not just the simulation results, has shed a light on how a university's research prestige, entrepreneurial reputation, organisational proximity, and social capital co-evolve and affect the university's entrepreneurial performance. All of the five entrepreneurial activities have their place and purpose, but they must be embedded in a holistic strategy and used as a mechanism to increase organisational proximity and social capital. This is an important step towards understanding how universities engage and shape their ecosystem and *vice versa*. Many of these relationships have either been studied in isolation or not considered some of these feedback effects. In addition, this model considers multiple universities and how the actions of one can have significant effects on other universities, which highlights the interconnectedness within and among overlapping university ecosystems.

Referring back to Section 3.5, which has established the need for an HS, this chapter has shown that an HS was the right approach because a pure SD approach would not have revealed insights into partnerships and the role of organisational proximity and social capital in general, whereas a pure ABM approach would not have been able to reveal the organisation-level dynamics within universities given the existing data and knowledge about the system.

Chapter 8

Conclusion

8.1 Introduction

This is the concluding chapter of this thesis. The chapter first summarises the research (Section 8.2) and, subsequently, details the theoretical, methodological, and empirical contributions to the fields of management science and entrepreneurship (Section 8.3). Furthermore, practical and policy-relevant implications are described in Section 8.4 before a combined discussion on the limitations of this research and opportunities for future research conclude this chapter and this thesis (Section 8.5).

8.2 Research Summary

This thesis is the outcome of an exploratory research endeavour that is positioned at the intersection of management science and entrepreneurship. The research aims to develop a model of universities' interaction with businesses that combines the internal dynamics (the 'supply' side) and the external dynamics within the university's ecosystem (the 'demand' side) and explore how they co-evolve.

Chapter 2 provides a comprehensive review of academic entrepreneurship in university ecosystems. First, a theoretically sound conceptualisation of a university ecosystem is developed from an inter-organisational perspective. Within this framework, the entrepreneurial university is discussed with a focus on five formal entrepreneurial activities (licensing, spin-offs, consulting, contract and collaborative research). The importance of organisational proximity and social capital are discussed as crucial concepts that help characterise the relationships between universities and companies within the ecosystem. After reviewing the drivers of academic entrepreneurship and also considering the companies' perspective, the chapter concludes with a description of the gap in the literature and the following research questions for this study.

1. What is the dynamic relationship between universities' internal capabilities and resources (organisational arrangements), the volume and share of different entrepreneurial activities, and the evolution of the university ecosystem?

2. Is there a path dependency for universities based on different research and entrepreneurial profiles, resource endowments, and historical backgrounds?

3. What are the temporal dynamics of different entrepreneurial activities in the evolution from ad hoc interactions to strategic partnerships between universities and firms?

4. How do the co-evolutionary dynamics between a university's research prestige, entrepreneurial reputation, organisational proximity, and social capital affect its entrepreneurial performance?

Chapter 3 introduces the concept of complex systems and presents system dynamics and agent-based modelling as potential methods to simulate academic entrepreneurship. In this particular case, neither method is sufficiently suited to answer the research questions, thus a hybrid simulation framework is developed. Answering the research questions requires the explicit recognition of emergent behaviour in the hybrid simulation, an issue that has not yet been addressed properly in the literature. Complex events are proposed as a mechanism to overcome current limitations.

Chapter 4 reviews existing model development processes and presents a tailored approach for this thesis. In the following, the philosophical and methodological foundations for this research are described. This study takes a critical realist perspective and shows, how a complexity approach in combination with a critical realist perspective can be used to combine a functionalist and radical structuralist approach to social science research. A particular focus of this chapter is the way information is gathered and how insights from interviews, secondary data, and the literature are triangulated throughout the model development process.

Chapter 5 describes the conceptual model, including the main assumptions of the model and the feedback structure of the system dynamics modules in the form of a causal loop diagram and the characteristics and rules of the company agents as part of the agent-based module. These structures are based on and supported by the previously described data triangulation. These conceptualisations provide contributions themselves as they provide a visualisation of crucial dynamics, whose descriptions have previously been spread over a large number of individual publications.

Chapter 6 describes the simulation model as well as the parametrisation and coding of the simulation and output analyses. After running the baseline scenario and performing sensitivity analyses on the relevant parameters, the model is used for experimentation with four different scenarios that were derived from the interviews. These include internal marketing, external marketing with and without the involvement of academics, and a combination of the latter and internal marketing.

Chapter 7 discusses and contextualises the simulation results in light of the four research questions. Furthermore, learning from the modelling process as well as learning about the modelling process, i.e. the implications for modelling practice, are discussed. Learning from the modelling process includes important findings about the discrepancy between how different entrepreneurial activities are treated by both policy makers and academics.

8.3 Contributions

This thesis makes several theoretical, methodological, and empirical contributions in the areas of entrepreneurship and management science and operational research (MS/OR), which will be discussed in the following.

8.3.1 Theoretical Contributions

This research makes two theoretical contributions to the field of entrepreneurship. In particular, university ecosystems are defined in new way that provides a basis for synthesising existing and guiding future research (T1) and a simulation model is developed that can be applied in different contexts (T2).

Contribution T1: A novel conceptualisation of university ecosystems.

The first contribution is a novel conceptualisation of university ecosystems that clarifies some of the tensions and overlaps between different territorial models of innovation and entrepreneurship and the role of universities within them. Existing mapping exercises have either simply focused on with whom the university interacts, but not the type of interaction, or looked at a particular subset of the university's ecosystem. The conceptualisation in this thesis is independent of particular activities, industry sectors, or university characteristics. The aim is not to replace concepts such as innovation or knowledge ecosystems when studying the external engagement of universities. Instead, it is hoped that this conceptualisation will help synthesise findings, provide a common understanding for the role of universities in these different settings, and a basis for future empirical research and theorising.

Contribution T2: Development of a multi-actor, multi-activity simulation model for academic entrepreneurship.

The existing literature on academic entrepreneurship has been dominated by spin-offs and licensing, which has "reinforced the single-minded emphasis on easily measurable outputs" (Norn, 2016, p. 8). Furthermore, the majority of existing studies has focused on individual activities and universities, hereby neglecting the feedback effects between different activities and how universities are linked through an overlap of their ecosystems. This thesis has addressed this issue by developing a novel multi-actor, multi-activity model building on the university ecosystem concept in contribution T1. This has led to insights starting with a more representative categorisation of universities by considering a wider range of measures to being able to more effectively capture partnerships between the same partners through different activities. These are crucial insights into dynamics such as the evolution of these partnerships; how universities can influence their ecosystem and, by extension, other universities; and the co-evolutionary dynamics of these interactions. As knowledge in entrepreneurship is growing cumulatively, the model represents an intermediate step between individual studies and a more comprehensive theory (Shapira, 2011).

8.3.2 Methodological Contributions

From a methodological perspective, the contribution of this research to the field of modelling and simulation in management science is threefold. The contributions include a modelling process for hybrid simulations (M1), new practices for modelling the size of agent populations through different designs of stocks and flows in the system dynamics module in hybrid simulations (M2), and complex events for recognising emergent behaviour (M3).

Contribution M1: A modelling process that focuses on the triangulation of data sources for better modelling feedback across module boundaries in hybrid simulations.

First, a contribution is made to how HS are developed. Specifically, a modelling process is developed for HS that is based on a review of existing processes and is particularly suitable for combining system dynamics and agent-based modelling. While the process has been tailored to this study, it includes a number of aspects that are relevant for modelling other problems. A particular focus of this modelling process is the triangulation and how insights from different sources are integrated, particularly in the conceptual modelling stage. This is the 'least developed stage' in the modelling process for hybrid simulations (Brailsford et al., 2019). The issues addressed in this thesis, in particular, include a detailed account of why a combination of SD and ABM is required; how feedback loops cross module boundaries; an explanation of the data that are exchanged at the module interfaces; and how tools for confidence building from SD and ABM are applied not only to the respective module but the HS as a whole, where appropriate. These are important steps towards a more comprehensive guidance for developing hybrid simulations. This emphasis on the interface between SD and ABM is also related to the following two contributions.

Contribution M2: Modelling stocks in SD modules that influence the size of the agent population as a new mechanism for the interface between SD and ABM in hybrid simulations.

The second contribution of this research is showing an additional means of how different HS frameworks or designs can be modelled, particularly *integrated* HS. A review of published simulations using this type of hybrid SD-ABM design has led to three generic means of combining these two methods, namely agents with rich internal structure, stocked agents, and parameters with emerging behaviour (Swinerd & McNaught, 2012). This model has included a previously overlooked mechanism by which stocks in an SD module are not just the aggregation of agents' characteristics or actions ('stocked agents'), but are used to dynamically influence the size of the agent population. This enables a new form of feedback that goes beyond using information from the SD module to affect the agents' decision-making or shape their environment. This mechanism will be applicable and useful in a number of different contexts. In diffusion models, for example, a stock in an SD module that captures aggregate diffusion measure can dynamically alter the number of influencers among the agent population.

Contribution M3: Introducing complex events as a means for capturing emergent behaviour in hybrid simulations.

The third contribution of this study relates to the issue of emergent behaviour as a form of emergent properties. Traditionally associated with ABMs, this issue is also highly relevant for developing HS as well. Part of the rationale for developing a hybrid simulation was the need to be able to examine aggregate dynamics at the university level and the activities of individual firms. A key aspect was partnerships, i.e. the repeated interaction between a company and a university, which can neither be observed in the SD structure nor from state aggregation of the company agent. Complex events were introduced and defined as a means to detect this kind of emergent behaviour. In this thesis, they are only used *a posteriori* to answer the research questions and demonstrate the value of the concept. Complex events provide a new basis for incorporating emergent behaviour into HS and advances the ability to model feedback between different modules of a hybrid simulation and, therefore, different levels of aggregation.

8.3.3 Empirical Contributions

Lastly, this research makes two empirical contributions to the field of entrepreneurship. Through triangulating primary and secondary data, this research shines a light on the dynamics of academic entrepreneurship (E1) and that universities can partially overcome a low research prestige to increase academic entrepreneurship (E2).

Contribution E1: The simulation model has demonstrated how universities interact with businesses and their internal behaviour.

The simulation model allows one to *see both the trees and the forest.* It strengthens the notion that entrepreneurial activities should be seen as "mechanisms" and means of knowledge dissemination and exchange as opposed to targets in themselves. Experimentation with the simulation model has shown that significant investments are required by universities to grow their ecosystem and enable more long-term partnerships. However, these investments must be made as part of a holistic strategy that also considers the current state of the university ecosystem. This has been widely overlooked in the academic entrepreneurship literature. This focus on mechanisms also has implications for attempts to measure ecosystems, which has eluded researchers so far. A sole focus on simple count measures of spin-offs created or income generated will lead to similar shortcomings that other territorial models of innovation and entrepreneurship have suffered. Measuring ecosystems needs to incorporate

Contribution E2: The entrepreneurial reputation of a university can, to some extent, offset a lack of research prestige, which is the most powerful single signal to the ecosystem.

The final contribution is in the area of universities' reputation and prestige. The model has shown the extent to which research-intensive universities ('Alpha') benefit from the halo that is based on their reputation and research prestige. However, there are also tremendous opportunities for other universities (those that fall in the 'Beta' and 'Gamma' category) to counter this by developing an entrepreneurial reputation. The interviews have shown that universities are increasingly aware of these effects and invest in people and structures that allow for companies to have easier access to the university's knowledge base and equipment.

8.4 Practical and Policy Implications

This research has several implications for policy and practice beyond its contribution to the academic literature. From a practical perspective, this work and the resulting model have numerous stakeholders for whom it can serve three purposes. First, for universities the model serves the traditional *what-if* purpose of evaluating the dynamic effects (and potential unintended consequences) of different actions such as changing terms and processes, adding resources, or modifying the strategic focus, among others. New initiatives such as including external marketing activities of academics in their workload model have been modelled as part of this thesis. The model itself, can, however, also be adapted and parametrised for specific universities in order to test other scenarios.

Second, for the public sector, including the Scottish government, funding agencies, and local authorities, this model provides a risk-and, more importantly, politics-free environment for learning about the system, exploring a wide range of potential interventions and understanding the connections between them. These include, but are not limited to, considering a mandatory commitment to investing in partnerships and developing organisational proximity for grants and tax breaks as well as innovation and growth programmes. Furthermore, the model can support monitoring ecosystems by using new data when available. This thesis has highlighted the challenges measuring ecosystems and other territorial models of innovation and entrepreneurship. This simulation approach offers an opportunity for measuring ecosystem performance based on interactions instead of aggregated levels of capital or start-up rates.

Third, decision-makers at all levels, from the TTO to the university management and regional and national governments are reminded of Goodhart's law. Simply holding universities accountable to count measures of particular activities does not lead to benefits for the university sector, the economy in general or individual ecosystems in particular. Rather, all actors should be encouraged to explore new types of interactions and forms of partnerships. This has implications for funding policies as well as incentives and promotion policies within universities, which will be further explored in the following.

The modelling process and the model outcome carry several implications for policy at different levels. These implications should not be seen as prescriptions but as a starting point for developing new policy solutions and have to be tailored to the respective context. This includes the regional or national environment in which universities operate, existing funding mechanisms, and the prevalent culture and traditions in particular industries or technological sectors, among others.

Starting with policy makers at the regional and national level as well as funding agencies, a clear recommendation is to introduce funding mechanisms that combine research funding and R&D investments with network and capacity building (Autio & Rannikko, 2016; Cowling, 2016; Min et al., 2020). Making external engagement an integral part of research funding where appropriate or even provide a certain budget that gets added to all research funding for these types of activities would increase the connectedness of universities and the absorptive capacity of companies – two of the key enabling conditions for academic entrepreneurship. These commitments should not be tied to specific forms of interactions and are certainly not limited to, nor should they particularly encourage commercialisation activities.

This work supports the suggestions by Heaton et al. (2019, p. 16) that for an early-stage ecosystem, policy makers should focus on "workforce development or infrastructure investment", whereas a more mature ecosystem benefits from "tax credits that support technology commercialization and new business formation". There is, however, a second lever for policy and funding agencies. The amount of effort and, by extension, monetary investment that is required by universities to grow their ecosystem varies significantly. Allowing different universities to spend a varying share of grant money to support companies could be a possible solution to increase absorptive capacity among (regional) firms for medium- and long-term benefits.

At the university level, this research suggests that in order to grow academic entrepreneurship and the exchange and exploitation of academic knowledge, universities should provide more institutional support for academics. While most universities have established TTO that provide a variety of support services to academics and external partners, the bottleneck is the academics' time. Addressing this issue can take multiple forms that range from designing new workload allocation models, where academics have time allocated to engaging with external organisations in order to formalise these relationships, to new types of positions that are split between academia and industry.

8.5 Limitations and Future Research

The hybrid simulation model in this thesis was developed to provide a first step in operationalising the ecosystem concept in general and how universities can grow their external engagement with companies to foster their ecosystem in particular. No research is without its limitations. A number of future research opportunities have emerged, some to address these limitations and others that build on the contributions of this research. The main avenues are outlined in the following.

8.5.1 Expanding the Model

A key contribution of this model is its ability to provide insights into the dynamics of academic entrepreneurship across a number of activities and within a system of multiple universities. While this multi-actor, multi-activity setting is appropriate to address the research questions of this thesis, there are also opportunities to expand the model for addressing wider dynamics. These include the implementation of further entrepreneurial activities, particularly informal interactions, student placements, and other activities that are not necessarily concerned with innovation; the public sector as a different type of agent that is already frequently interacting with universities; and broker institutions such as Interface in Scotland, which create new connections and support universities in their external marketing efforts (Hughes & Kitson, 2013).

Other features that have been identified as relevant include the role of network structures for ecosystems (Shipilov & Gawer, 2020); regional characteristics and institutions (Mascarenhas et al., 2018; Zhang et al., 2016); elaborating on the quality of interactions as well as the effects of opportunities that did not materialise; industry characteristics and structure for company agents (highlighted by interviewee B43) and modelling universities at the faculty level with different characteristics and strategies (highlighted by interviewee B42); as well as taking into consideration a life-cycle model of university ecosystems (Perkmann, Neely,

& Walsh, 2011; Heaton et al., 2019). The aim is not to cram all of this into one model that tries to explain everything, but to develop adaptations of the model presented in this thesis with different features that are relevant to the respective problem at hand.

8.5.2 Data

The main limitation of this study is the inability to match data from individual companies (in this case the CBR Business Survey) to the respective academic partner (the HESA and HE-BCI data) as well as the lack of data for individual interactions. Furthermore, the CBR Business Survey includes interactions with universities from the UK and beyond, which means that companies' experience of working with Scottish universities and the resulting implications could be different from the overall experience from working with universities. More fine-grained data are required to dive deeper into the issues of partnerships, how universities attract companies, the time they spend on sourcing the right partner/technologies, negotiations or how long the the actual interactions last. This is in line with limitations pointed out in other studies that highlight a lack of "systemic data on all dimensions of technology commercialisation" (Grimaldi et al., 2011, p. 1055) and a "need for more in-depth process oriented and longitudinal studies to explore how resources are orchestrated in academic entrepreneurship ventures in the different contexts discussed here" (Wright, 2014, p. 330).

It is important to note that HE-BCI is, despite the limitations, still one of the best data sources for population-level data on universities' engagement with industry (Smith, 2015). Therefore, future data collection efforts should focus on more fine-grained data that complements the existing institutional-level data for universities. Companies are, however, not driven or guided by the HESA definitions of different activities but the fact that some activities carry tax benefits and others do not. This is an important issue to consider because the company might not intentionally engage in *contract* or *collaborative* research as defined by HESA, but invest in research that has tax benefits.

In addition to primary research for gathering new data as input for future simulation models (both for the model structure and parametrisation), there is a novel secondary dataset that will become available over the next years. The new Knowledge Exchange Framework (KEF) is designed to measure universities' performance with regard to knowledge exchange activities, increase accountability, and help companies navigate the UK university landscape and access knowledge.[69]

[69]Research England (2020). Knowledge Exchange Framework: Decisions for the first iter-

This thesis and the model are published at the right time to engage with these efforts to further understand and map the external engagement of universities in the UK. Other data sources to consult include the Time Allocation Surveys, which are filled out by individual academics and returned to the Scottish Funding Council by the universities as part of the Transparent Approach to Costing (TRAC). These will significantly improve the accuracy of 'workload allocations' and 'entrepreneurial capacity' within the model.[70]

On the industry side, new research should be devoted to shift the focus from simple count measures of interactions with universities to the time-dependent patterns of engagement. The rules are partially reverse-engineered from observed behaviour and might differ from the actual decision making of firms that caused the behaviour (Weick, 1979). This is to some extent controlled for by using literature that is based on both qualitative (rich picture and narratives of firm decision making) and quantitative studies. However, further primary research is required for more fine-grained modelling of the agent-population.

8.5.3 Complex Events

Complex events are proposed as a means to recognise emergent behaviour in ABMs. This model applies them *a posteriori* to identify the prevalence of three pre-defined behaviours. While a novel application to the analysis of simulation results, 'sequence analysis' (Abbott, 1995) or 'event history analysis' (Keiding, 2014) have a long history in social sciences and other areas. Applying insights from these areas to the development of new algorithms that can detect complex events while the simulation is running enables a new strand of ABM research. However, this also provides new opportunities for hybrid simulations. For example, it could be linked to *event-reconfigurable* hybrid simulations (Swinerd & McNaught, 2012) and support learning in system dynamics models by activating different parts of the model based on the *behaviour* of the agent-population rather than the *outcome* (i.e. state aggregation). Depending on the size of the agent-population and the diversity of the complex events that are considered, this poses a number of practical challenges such as the computationally intensive nature of such algorithms. Methodological advancements in this area that address both the theoretical/conceptual challenges as well as practical issues have far-reaching applications for complex systems simulation in socio-economic and

ation, RE-P-2020-01, available at: https://re.ukri.org/documents/2019/knowledge-exchange-framework-decisions-16-jan-2020/

[70]Further information is provided by e.g. the University of Strathclyde at https://www.strath.ac.uk/fec/timeallocationexercisetas/

socio-technical settings that require adaptive behaviour of 'intelligent' agents.

8.5.4 A Blueprint for Simulating Complex Systems

With or without the use of complex events, hybrid simulations, particularly combinations of SD and ABM, are promising approaches for the study of complex systems (Swinerd & McNaught, 2012). Complex systems consist of a set of heterogeneous agents whose interaction and adaptation lead to (emergent) changes at the systemic level. The decision-making and resource utilisation of these agents as well as the ways in which they influence other agents and their environment can vary significantly. This simulation has provided a number of mechanisms, including the aforementioned concept of complex events and a dynamic agent population based on SD stocks, among others, that can serve as a blueprint for simulating other complex systems with similarly heterogeneous agents. Potential applications are not limited to areas that are commonly addressed by MS/OR scholars and practitioners such as health care or supply chain dynamics, but also areas of computational social science such as opinion dynamics or ecological modelling. Methodological innovation and the development of archetype-like structures for different aspects and mechanisms of complex systems, regardless of the area of application, contribute to moving from case-specific models and insights to a more general theory of complex systems through the use of simulation (Lorscheid et al., 2019). This thesis has, however, also shown that further work is required to address issues like how to treat DT and to develop a set of specific HS guidelines or 'best practices'.

8.5.5 Simulations and Games for Education

Simulation studies are still rare in the areas of entrepreneurship and innovation, with the exception of diffusion studies in innovation. Consequently, the use of simulations for educational purposes is also still in its infancy and usually restricted to 'small business management for undergraduate students' as well as 'underresearched' (Fox et al., 2018, p. 81). As a result, opportunities are missed to use simulations to demonstrate the effects of non-linear relationships and feedback for a variety of entrepreneurial decision-making problems. One of these is directly related to the context of this thesis. TTO staff are usually either recruited from industry or transition from being involved in academic research to supporting the translation of research into practice. As a result, their core expertise is either on one side or the other (e.g. understanding the challenges of scientific research) with an implicit assumption, that they will be good at the respective other (in this case, identifying and exploiting commercial opportunities). This research has shown that growing a university's ecosystem requires a deep understanding of how ecosystems evolve and the position of the university with this ecosystem. Further developing this model into an educational game could provide a novel training opportunity for TTO directors and staff to gain an understanding of some of these dynamics.

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Appendix A

Interview Outline

Introduction

In the course of my doctoral research, I am developing a [hybrid system dynamics / agent-based] simulation which focuses on the dynamics of academic entrepreneurship and the impact on both the university and the ecosystem. Therefore, the simulation looks at the dynamic interplay of Scottish universities and UK businesses.

After finishing and analysing the interviews, I will share a causal model that is based on a combination of said interviews and the literature to make sure that I didn't misunderstood you. I am also happy to share the final simulation results with you in the end.

Entrepreneurial activities can generally be defined as the "discovery, evaluation and exploitation of opportunities to introduce new goods and services, ways of organizing, markets, processes and raw materials through organizing efforts that previously had not existed" (Shane, 2003, p. 4). Accordingly, Siegel and Wright (2015, p. 582) academic entrepreneurship includes all "efforts undertaken by universities to promote commercialization on campus and in surrounding regions of the university", i.e. the total of all entrepreneurial activities.

The aims of this interview are (1) to build confidence in the structures that have been derived from the existing literature; (2) to gain additional insights into drivers as well as barriers and limiting factors of academic entrepreneurship; and (3) identify particular characteristics of the University of Strathclyde to model it as accurate as possible.

In doing so, this interview focuses on five particular entrepreneurial activities as well as the interviewee's experiences and a holistic perspective. Hence, it is divided into seven parts, namely:

1. Personal Experience

2. Licensing and Start-ups
3. Spin-offs
4. Consulting
5. Contract Research
6. Collaborative Research
7. Holistic Perspective

If you feel that one or more parts or particular questions are outside your area of expertise or you have no experiences, I would be grateful if you could suggest someone else within your institution.

Personal Experience

1. Could you please briefly describe your position in the university, the responsibilities you have and for how long you've been doing this job?
    - How would you describe your experiences/expertise with regard to entrepreneurial activities?
    - Strategic or operational/practical, broad overview or specialised in a particular area

Licensing

Licensing, in this case, is the act of granting a company the legal rights to use and commercialise university intellectual property (e.g. patents, MTAs) in exchange for a licensing fee or royalty payments. Start-ups are "companies created by licensing an early-stage invention to an independent entrepreneur (who is not necessarily a faculty member), with the goal of developing the company around the growth and commercialization of the technology" (Bradley et al., 2013, p. 587).

2. How does the licensing process work from invention disclosure to finalising the agreement and potential post-licenses activities?
3. Does your institution have a particular licensing strategy?
    - How are the terms determined?

- Do you focus on “homerun” technologies or a more industry-friendly approach to get as much technologies out as possible?
- Do you license for royalty only or shares in start-ups as well?

4. What happens to the income from this activity?
5. Would it be desirable to increase the number of patents and licenses?
    - IF YES: How could this be achieved?
    - IF NO: If we think about this more generally and regardless of your previous answer, how could this be achieved if intended?
    - Would more industry-friendly licensing terms attract more companies or entrepreneurs?
    - Are there any trade-offs or unintended consequences with regard to an increased licensing rate?
6. What are the main limiting factors (e.g. bureaucracy, hard terms, resource constrains such as time)?

Spin-offs

Spin-offs are defined as “new companies formed by individuals (faculty members) related to the university or university research park to develop a technology that was discovered in, and is transferred from, the parent organization” (Bradley et al., 2013, p. 587).

7. Does your institution have any programmes in place or offer support for faculty through the spin-off creation process?
    - What is the typical process?
    - How do these programmes look like?
8. Does the university always take equity in spin-offs by default?
9. What happens to the income from this activity?
10. Would it be desirable to increase the number of spin-offs?
    - IF YES: How could this be achieved?
    - IF NO: If we think about this more generally and regardless of your previous answer, how could this be achieved if intended?

- Are there any trade-offs or unintended consequences with regard to an increased number of spin-offs?

11. What are the main limiting factors (e.g. bureaucracy, hard terms, resource constrains such as time)?

Consulting

Consulting can be defined as "advice and work crucially dependent on a high degree of intellectual input from the HE provider to the client (commercial or non-commercial) without the creation of new knowledge. Consultancy may be carried out either by academic staff or by members of staff who are not on academic contracts, such as senior university managers or administrative/support staff" (HESA, n.d.).

12. How are consulting activities organised within the university?
    - How does consulting emerge?
    - Is there an overall strategy and support mechanisms, e.g. through a centralised organisational unit?
    - Are they arranged and executed solely on the departmental/individual level and depend on existing networks and links?
13. What happens to the income from this activity?
14. Would it be desirable to increase the number of consulting projects?
    - IF YES: How could this be achieved?
    - IF NO: If we think about this more generally and regardless of your previous answer, how could this be achieved if intended?
    - What factors attract companies to seek consultation from your academic staff?
    - Does the industry-friendliness of the contract terms play a role?
    - Are there any trade-offs or unintended consequences with regard to an increased number of consulting projects?
15. What are the main limiting factors (e.g. bureaucracy, hard terms, resource constrains such as time)?

Contract Research

Contract research describes a form of university-industry collaboration in the course of which the university (or a university research centre, a department or a single academic) performs research under a contract for monetary benefit (Lee & Win, 2004). In line with this, HEFCE (2014, p. 15) defines contract research "as a more simple transaction, where the benefit is assumed to be primarily on the side of the external partner, rather than the mutual gains obtained by collaborative research."

16. How are contract research activities organised within the university?
    - Is there an overall strategy and support mechanisms, e.g. through a centralised organisational unit?
    - Are they arranged and executed solely on the departmental/individual level and depend on existing networks and links?
17. What happens to the income from this activity?
18. What makes your university attractive as a provider of such research services?
19. Would it be desirable to increase the number of contract research projects?
    - IF YES: How could this be achieved?
    - IF NO: If we think about this more generally and regardless of your previous answer, how could this be achieved if intended?
    - How could more firms be attracted?
    - Are there any trade-offs or unintended consequences with regard to an increased number of contract research projects?
20. What are the main limiting factors (e.g. bureaucracy, hard terms, resource constrains such as time)?

Collaborative Research

In contrast to contract research, collaborative research endeavours are characterised by a mutual benefit (Lee & Win, 2004). According to HESA (n.d.), this "includes research projects with public funding from at least one public body, and a material contribution from at least one external non-academic collaborator."

21. How are collaborative research activities organised within the university?

- Is there an overall strategy and support mechanisms, e.g. through a centralised organisational unit?
- Are they arranged and executed solely on the departmental/individual level and depend on existing networks and links?

22. What happens to the income from this activity? Is it treated as a 'regular' research budget?
23. What makes your university attractive as a provider of such research projects?
24. Would it be desirable to increase the number of collaborative research projects?
    - IF YES: How could this be achieved?
    - IF NO: If we think about this more generally and regardless of your previous answer, how could this be achieved if intended?
    - How could more firms be attracted?
    - Are there any trade-offs or unintended consequences with regard to an increased number of collaborative research projects?
25. What are the main limiting factors (e.g. bureaucracy, hard terms, resource constrains such as time)?

Holistic Perspective

26. Does your university have a strategy that favours one or more of the above mentioned five entrepreneurial activities above others?
27. Does your institution provide incentives for academics to pursue entrepreneurial activities?
    - Do they actually motivate you or are there other reasons why you get involved in entrepreneurial activities?
28. Do any of the above mentioned five activities generally precede others?
    - For example: does collaborative research provide a basis for contract research or consulting or vice versa?
29. What impact, if any, do you think the university reputation has for the engagement with businesses?

- What type of reputation is it?
- Institutional, personal, research prestige, entrepreneurial (knowledge exchange) reputation?
- Is there a word-of-mouth effect?

30. What percentage of your institution's total interaction with business is with those located in the UK?
31. Do you think the HESA data collection is accurate or is there something missing?
32. If participant has a dual role (e.g. an academic who is also Associate Deputy Principal): Would you have answered any questions differently in your capacity as an academic/working with academics?
33. Is there anything else you'd like to add to any of the previously mentioned topics or any general remarks?
    - Is there anything that I have missed or did not focus on sufficiently?

Appendix B

Ethics Application Form

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Paper

Ethics Application Form

Please answer all questions

1. Title of the investigation
Rethinking the University-Industry Technology Transfer: Insights from System Dynamics and Agent-Based Modelling
Please state the title on the PIS and Consent Form, if different:

2. Chief Investigator (must be at least a Grade 7 member of staff or equivalent)
Name: Susan Howick, PhD ☒ Professor ☐ Reader ☐ Senior Lecturer ☐ Lecturer ☐ Senior Teaching Fellow ☐ Teaching Fellow Department: Management Science Telephone: 0141 548 3798 E-mail: susan.howick@strath.ac.uk

3. Other Strathclyde investigator(s)
Name: Bernd Wurth Status (e.g. lecturer, post-/undergraduate): PhD Student Department: Department of Management Science Telephone: E-mail: bernd.wurth@strath.ac.uk Name: Niall MacKenzie, PhD Status (e.g. lecturer, post-/undergraduate): Senior Lecturer Department: Hunter Centre for Entrepreneurship Telephone: 0141 548 3091 E-mail: niall.mackenzie@strath.ac.uk

4. Non-Strathclyde collaborating investigator(s) (where applicable)
Name: Status (e.g. lecturer, post-/undergraduate): Department/Institution: If student(s), name of supervisor: Telephone: E-mail: Please provide details for all investigators involved in the study:

5. Overseas Supervisor(s) (where applicable)
Name(s): Status: Department/Institution: Telephone: Email: I can confirm that the local supervisor has obtained a copy of the Code of Practice: Yes ☐ No ☐ Please provide details for all supervisors involved in the study:

6. Location of the investigation
At what place(s) will the investigation be conducted? The interviews will be conducted either via Skype or at the home institution of the participant, which are the campuses of the following universities in Scotland: ▪ University of Aberdeen ▪ Abertay University (Dundee) ▪ University of Dundee ▪ Edinburgh Napier University ▪ University of Edinburgh ▪ Glasgow Caledonian University ▪ University of Glasgow ▪ Heriott Watt University ▪ Queen Margaret University Edinburgh ▪ The Robert Gordon University ▪ University of St Andrews ▪ The University of Stirling ▪ The University of Strathclyde ▪ University of the Highlands and Islands ▪ The University of the West of Scotland
If this is not on University of Strathclyde premises, how have you satisfied yourself that adequate Health and Safety arrangements are in place to prevent injury or harm? All interviews will be conducted on higher education institution campuses throughout Scotland, for which Health and Safety plans must be in place.

7. Duration of the investigation

Duration(years/months): 17.5 Months

Start date (expected): 15 / 04 / 2016 Completion date (expected): 30 / 09 / 2017

8. Sponsor

Please note that this is not the funder; refer to Section C and Annexes 1 and 3 of the Code of Practice for a definition and the key responsibilities of the sponsor.

Will the sponsor be the University of Strathclyde: Yes ☒ No ☐

If not, please specify who is the sponsor:

9. Funding body or proposed funding body (if applicable)

Name of funding body: University of Strathclyde

Status of proposal – if seeking funding (please click appropriate box):

☐ In preparation

☐ Submitted

☐ Accepted

Date of submission of proposal: / / Date of start of funding: / /

10. Ethical issues

Describe the main ethical issues and how you propose to address them:

Participants might feel uncomfortable talking about policies or practices that make their institution look unfavourable or about personal experiences. They might feel pressured to try to make them or their institution look good. All questions are designed to simply get an idea of how certain activities are carried out and how they are implemented, without any judgement, in order to make it as easy as possible for the participants.

11. Objectives of investigation (including the academic rationale and justification for the investigation) Please use plain English.

In the course of my research, I am developing a simulation model to investigate the impact of academic entrepreneurship on both the university and the ecosystem. The structure of the model is based on a triangulation of existing literature, secondary datasets and interviews. Those secondary datasets are also used to quantify the model and run simulations. Based on the existing literature on entrepreneurial universities and various aspects of academic entrepreneurship, a first feedback structure has been developed and data will be gathered mainly from the HE-BCI survey and potentially a second dataset.

The aim of the interviews is twofold. First, the causal structure needs to be validated in a sense that it actually represents current university structures and causal relationships. Interviewees should be able to talk about practices and policies at their university and their personal experiences. Therefore, academic managers and administrative staff will be interviewed, who are involved in and influence entrepreneurial activities. Second, the interviews will also be used to identify the relevant factors that influence academic entrepreneurship (i.e. all entrepreneurial activities) and the willingness of companies and entrepreneurs from the ecosystem to get engaged. These include the research intensity/prestige of the university, entrepreneurial reputation, bureaucracy, industry-friendly terms for knowledge exchange and commercialisation, existing institutional/departmental/personal contacts, among others.

12. Participants

Please detail the nature of the participants:

Participants are academic managers and administrative staff, who are engaged in knowledge exchange / technology transfer type of roles, from all 15 Scottish universities.

Summarise the number and age (range) of each group of participants:
Number: 45 Age (range) 18-65

Please detail any inclusion/exclusion criteria and any further screening procedures to be used:

Participants should be involved in and influence entrepreneurial activities at their university. They should be able to talk about practices and policies at their particular university and their personal experiences.

13. Nature of the participants

Please note that investigations governed by the Code of Practice that involve any of the types of participants listed in B1(b) must be submitted to the University Ethics Committee (UEC) rather than DEC/SEC for approval.

Do any of the participants fall into a category listed in Section B1(b) (participant considerations) applicable in this investigation?: Yes ☐ No ☒
If yes, please detail which category (and submit this application to the UEC):

14. Method of recruitment

Describe the method of recruitment (see section B4 of the Code of Practice), providing information on any payments, expenses or other incentives.

We are using total population (purposive) sampling and approach representatives from all Scottish universities. The individuals from each institution have been identified through an internet research and personal contacts of the researchers, who are conducting this study. Potential participants will be contacted by email or phone and no payment will be provided.

15. Participant consent

Please state the groups from whom consent/assent will be sought (please refer to the Guidance Document). The PIS and Consent Form(s) to be used should be attached to this application form.

The PIS and Consent Form that are used for all participants are attached to this application form.

16. Methodology

Investigations governed by the Code of Practice which involve any of the types of projects listed in B1(a) must be submitted to the University Ethics Committee rather than DEC/SEC for approval.

Are any of the categories mentioned in the Code of Practice Section B1(a) (project considerations) applicable in this investigation? ☐ Yes ☒ No

If 'yes' please detail:

Describe the research methodology and procedure, providing a timeline of activities where possible. Please use plain English.

This study aims at developing a simulation model. The model will be based on a triangulation of existing literature, secondary data, and interviews. A pilot study will be conducted at the University of Strathclyde. Interviews will probably be conducted until the end of June and transcribed afterwards. The information will then be combined with information from the other two sources to develop the model until the end of October.

What specific techniques will be employed and what exactly is asked of the participants? Please identify any non-validated scale or measure and include any scale and measures charts as an Appendix to this application. Please include questionnaires, interview schedules or any other non-standardised method of data collection as appendices to this application.

For the above mentioned interviews, the participants will be asked mostly open-ended questions about structure, policies, and practices at their university. An outline for the interview is attached.

Where an independent reviewer is not used, then the UEC, DEC or SEC reserves the right to scrutinise the methodology. Has this methodology been subject to independent scrutiny? Yes ☐ No ☒

If yes, please provide the name and contact details of the independent reviewer:

17. Previous experience of the investigator(s) with the procedures involved. Experience should demonstrate an ability to carry out the proposed research in accordance with the written methodology.
Bernd Wurth has successfully completed the Postgraduate Certificate in Research Methodology at the University of Strathclyde, which included a course on research methods. He has also attended NATCOR courses on system dynamics and simulation in general. Prof Susan Howick and Dr Niall MacKenzie have both extensive experience in conducting academic research that includes collecting primary data and as PhD supervisors in the fields of system dynamics and academic entrepreneurship, respectively. Additional information can be found at: http://www.strath.ac.uk/staff/howicksusanprof/ http://www.strath.ac.uk/staff/mackenzieniallldr/

18. Data collection, storage and security
How and where are data handled? Please specify whether it will be fully anonymous (i.e. the identity unknown even to the researchers) or pseudo-anonymised (i.e. the raw data is anonymised and given a code name, with the key for code names being stored in a separate location from the raw data) - if neither please justify. The data will be pseudo-anonymised and participant's names will not be included in any publications.
Explain how and where it will be stored, who has access to it, how long it will be stored and whether it will be securely destroyed after use: The data will be stored on servers of the University of Strathclyde.
Will anyone other than the named investigators have access to the data? Yes ☐ No ☒ If 'yes' please explain:

19. Potential risks or hazards
Describe the potential risks and hazards associated with the investigation: There are no specific risks or hazards associated with this investigation.
Has a specific Risk Assessment been completed for the research in accordance with the University's Risk Management Framework (Risk Management Framework)? Yes ☐ No ☒ If yes, please attach risk form (S20) to your ethics application. If 'no', please explain why not:

20. What method will you use to communicate the outcomes and any additional relevant details of the study to the participants?
After all the interviews have been conducted and the data has been analysed, participants will receive feedback in the form of causal model(s) and potentially further information. All participants will also get access to the material described in section 21 (in case they don't have access otherwise but wish to).

21. How will the outcomes of the study be disseminated (e.g. will you seek to publish the results and, if relevant, how will you protect the identities of your participants in said dissemination)?
The outcomes of the study will be published as a PhD thesis as well as in several journal articles and conference papers.

Checklist	**Enclosed**	**N/A**
Participant Information Sheet(s)	☒	☐
Consent Form(s)	☒	☐
Sample questionnaire(s)	☐	☒
Sample interview format(s)	☒	☐
Sample advertisement(s)	☐	☒
Any other documents (please specify below)		
	☐	☐
	☐	☐
	☐	☐
	☐	☐
	☐	☐

22. Chief Investigator and Head of Department Declaration
Please note that unsigned applications will not be accepted and both signatures are required

I have read the University's Code of Practice on Investigations involving Human Beings and have completed this application accordingly. By signing below, I acknowledge that I am aware of and accept my responsibilities as Chief Investigator under Clauses 3.11 – 3.13 of the Research Governance Framework and that this investigation cannot proceed before all approvals required have been obtained.

Signature of Chief Investigator

Please also type name here:

I confirm I have read this application, I am happy that the study is consistent with departmental strategy, that the staff and/or students involved have the appropriate expertise to undertake the study and that adequate arrangements are in place to supervise any students that might be acting as investigators, that the study has access to the resources needed to conduct the proposed research successfully, and that there are no other departmental-specific issues relating to the study of which I am aware.

Signature of Head of Department

Please also type name here

Date: / /

23. Only for University sponsored projects under the remit of the DEC/SEC, with no external funding and no NHS involvement

Head of Department statement on Sponsorship
This application requires the University to sponsor the investigation. This is done by the Head of Department for all DEC applications with exception of those that are externally funded and those which are connected to the NHS (those exceptions should be submitted to R&KES). I am aware of the implications of University sponsorship of the investigation and have assessed this investigation with respect to sponsorship and management risk. As this particular investigation is within the remit of the DEC and has no external funding and no NHS involvement, I agree on behalf of the University that the University is the appropriate sponsor of the investigation and there are no management risks posed by the investigation.

If not applicable, tick here ☐

Signature of Head of Department

Please also type name here

Date: / /

For applications to the University Ethics Committee, the completed form should be sent to ethics@strath.ac.uk with the relevant electronic signatures.

24. Insurance
The questionnaire below must be completed and included in your submission to the UEC/DEC/SEC:

Is the proposed research an investigation or series of investigations conducted on any person for a Medicinal Purpose? Medicinal Purpose means: ▪ treating or preventing disease or diagnosing disease or ▪ ascertaining the existence degree of or extent of a physiological condition or ▪ assisting with or altering in any way the process of conception or ▪ investigating or participating in methods of contraception or ▪ inducing anaesthesia or ▪ otherwise preventing or interfering with the normal operation of a physiological function or ▪ altering the administration of prescribed medication.	No

If "**Yes**" please go to **Section A (Clinical Trials)** – all questions must be completed
If "**No**" please go to **Section B (Public Liability)** – all questions must be completed

Section A (Clinical Trials)

Does the proposed research involve subjects who are either: i. under the age of 5 years at the time of the trial; ii. known to be pregnant at the time of the trial	Yes / No

*If "**Yes**" the UEC should refer to Finance*

Is the proposed research limited to: iii. Questionnaires, interviews, psychological activity including CBT; iv. Venepuncture (withdrawal of blood); v. Muscle biopsy; vi. Measurements or monitoring of physiological processes including scanning; vii. Collections of body secretions by non-invasive methods; viii. Intake of foods or nutrients or variation of diet (excluding administration of drugs).	Yes / No

*If "**No**" the UEC should refer to Finance*

Will the proposed research take place within the UK?	Yes / No

*If "**No**" the UEC should refer to Finance*

Title of Research	
Chief Investigator	
Sponsoring Organisation	

Does the proposed research involve:	
a) investigating or participating in methods of contraception?	Yes / No
b) assisting with or altering the process of conception?	Yes / No
c) the use of drugs?	Yes / No
d) the use of surgery (other than biopsy)?	Yes / No
e) genetic engineering?	Yes / No
f) participants under 5 years of age(other than activities i-vi above)?	Yes / No
g) participants known to be pregnant (other than activities i-vi above)?	Yes / No
h) pharmaceutical product/appliance designed or manufactured by the institution?	Yes / No
i) work outside the United Kingdom?	Yes / No

If **"YES"** to **any** of the questions a-i please also complete the **Employee Activity Form** (attached).
If **"YES"** to **any** of the questions a-i, <u>and this is a follow-on phase</u>, please provide details of SUSARs on a separate sheet.
*If "**Yes**" to any of the questions a-i then the UEC/DEC/SEC should refer to Finance (aileen.stevenson@strath.ac.uk).*

Section B (Public Liability)	
Does the proposed research involve :	
a) aircraft or any aerial device	No
b) hovercraft or any water borne craft	No
c) ionising radiation	No
d) asbestos	No
e) participants under 5 years of age	No
f) participants known to be pregnant	No
g) pharmaceutical product/appliance designed or manufactured by the institution?	No
h) work outside the United Kingdom?	No

*If **"YES"** to any of the questions the UEC/DEC/SEC should refer to Finance(aileen.stevenson@strath.ac.uk).*

For NHS applications only - Employee Activity Form

Has NHS Indemnity been provided?	Yes / No
Are Medical Practitioners involved in the project?	Yes / No
If YES, will Medical Practitioners be covered by the MDU or other body?	Yes / No

This section aims to identify the staff involved, their employment contract and the extent of their involvement in the research (in some cases it may be more appropriate to refer to a group of persons rather than individuals).

Chief Investigator		
Name	**Employer**	**NHS Honorary Contract?**
		Yes / No
Others		
Name	**Employer**	**NHS Honorary Contract?**
		Yes / No
		Yes / No
		Yes / No
		Yes / No

Please provide any further relevant information here:

Appendix C

University Data

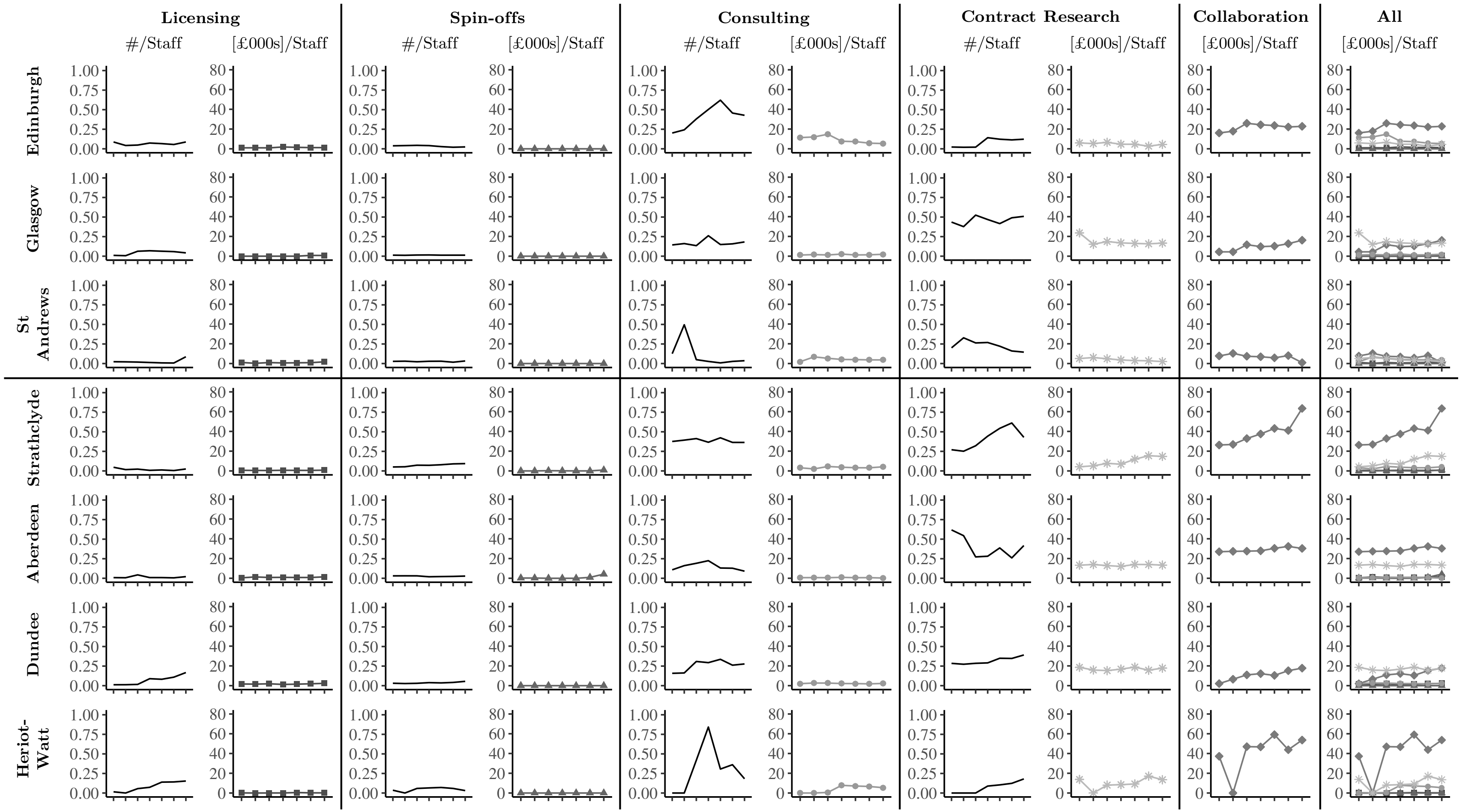

Figure C.1: Number and value (£000s) of entrepreneurial activities per research and teaching staff for 'Alpha' and 'Beta' universities for 2008/09-2014/15 (source: HE-BCI and HESA Staff)

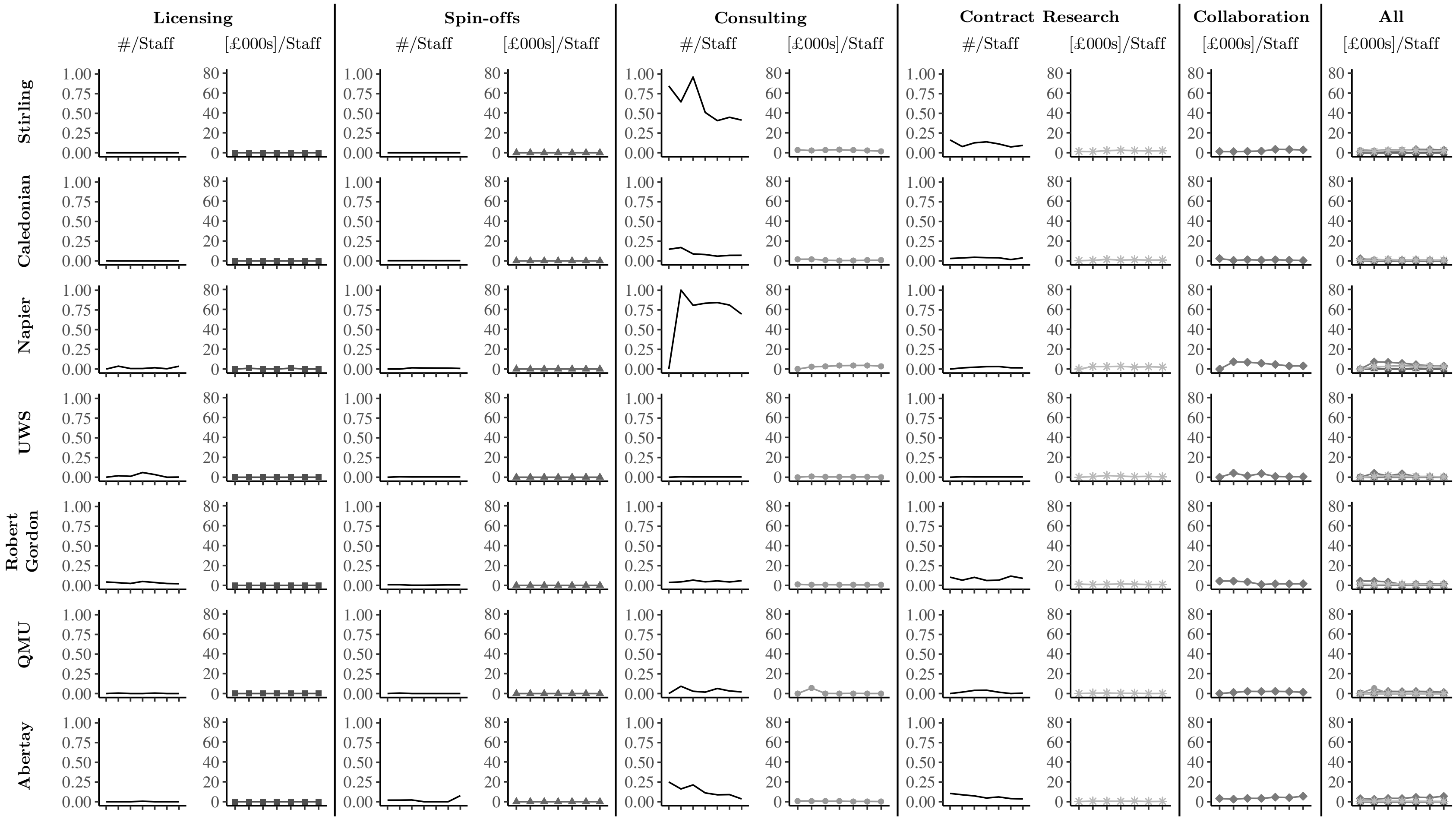

Figure C.2: Number and value (£000s) of entrepreneurial activities per research and teaching staff for 'Gamma' universities for 2008/09-2014/15 (source: HE-BCI and HESA Staff)

Appendix D

Inductive Coding of Interview Data

D.1 Influence of Policy and Government

Table D.1: Quotes and codes for the 'influence of policy and government' theme

Selected quotes	**First order**	**Second order**	**Axial coding**
"it's easier to get developmental funding for something that's a spin-out opportunity" (B41)	Easier to get funding for a spin-off compared to licensing	Direct influence on universities	Influence of policy and government
"we do find it more challenging to get support to take licensing or potential license deals forward than for spin-out opportunities" (B41)			
"a lot of the funding for that project came from Highlands and Islands Enterprise, who decided that they would put their money into Interface, instead of the unit we had" (C71)	External funding for university got re-directed towards Interface		
"To win projects, we have to be aware of what the external driver is there, you know, what political motivations are there for the government of the day to invest in its share of the triple helix, because if we can align our capabilities with our networks, with what the government needs, then we can come up with a value proposition" (B43)	Important to understand environment and government priorities to prepare an appropriate value proposition to win the project		
"Yes, you might argue, is it or is it not the right measure, but it's certainly the existing measure and that's one that appears in all the different league tables and returns and HEFCE, Scottish Funding Council, they're all really interested in those metrics." (A12)	Metrics used by government and funding bodies influence university behaviour		
"That would practically word-for-word covers the definition of this university" (A12)			
"Very different in America, someone who's a good earner and brings money to the faculty is a superstar, typically as well. We don't formalise any of industry engagement in terms of recognition, in terms of career development, maybe informally, it happens, but not formally. [...] Impact is going to have a massive addition to REF next time around and maybe we'll see the impact will reflect in people's promotional opportunities" (A12)	More recognition of entrepreneurial activities for academics' promotion must be realised at UK level in line with e.g. REF		
"Yes, that would help but it's not just something that could be done at the university level, cause the UK REF, although impact is projected to be 25% of the overall kind of score. It's still based on publications essentially." (B42)			
"There are external demands and drivers out there that tend to push you in one direction as opposed to another. So a few years ago, people were focused on spin-outs and licensing and there were metrics associated with that and funding flows were on the back of it. It's very much now about partnerships, it's about collaborative R&D, so, you know, in terms of our external profile, I think we're pushing that much harder than, say, pure licensing." (B43)	Universities are adapting to the shift in focus from licensing and spin-offs to more collaborative R&D-focused activities		

“And recently, politically, the environments moved to be more supportive of that type of applied research because of the increased focus on higher education being an engine for economic growth. So it’s not just about problem solving, it’s not just about taking graduates and giving them a job, it’s very much about how do we take the know-how in a university and have it applied so it can be, you know, traditionally applied to existing organisations or take the IP you might have developed in research programmes and try and get that commercialised in some way, spin-out, licensing, or whatever.” (B43)	Political environment increasingly focuses on HEIs as engines for economic growth through various mechanisms	Government goals and expectations	
“Scottish government would like that economic activity, especially for SMEs, to be in Scotland. And I think there have been agreements, so for example, we have an agreement with the Korean government to support projects, that’s with Korean companies. But one of the aspects of that is that we’re doing it because we would like to attract more Korean companies to do an investment in Scotland.” (B41)	Scottish government wants economic activity in Scotland, but agreements with Korean government for increased interaction with the goal of more Korean investments in Scotland		
“there is a tension here, which is worth reflecting on, because licensing might be out to companies, which are, for example, outwith Scotland and obviously a lot of the Scottish government funding is designed to produce economic benefits for Scotland. So they are more neutral about licensing opportunities outside. Of course from the university’s point of view, it’s all good if it’s generating funding” (B41)	Scottish government wants to support the Scottish economy, so neutral about supporting licensing which is open to companies outside Scotland, whereas universities just want to generate income		
“European funding is good, so hopefully we won’t lose that. Those SMEs do quite well out of European funding, so Brexit could be a problem for that. A lot of our early stage spin-outs, who have managed to get into European funding and then eventually maybe started to lead some of the funding themselves. That’s really good money for them. That could be a problem.” (B21)	Access to European funding might become and issues for universities, spin-offs and companies	Indirect influence on universities	
“you can also look at the HMRC guidelines, which distinguish R&D, which is tax deductible, from consulting, which is not. Okay, so for the company that’s the most important thing that they’re going to be interested in.” (B41)	R&D is tax deductible, consulting is not (HMRC guideline more important than HESA classification for companies)		

"Prescription is not the answer. We are an international business. We're in most countries, we're not a Scottish university. We are, but the way to look at it is we're exporting people and knowledge all over the world and that has consequences, because you have links and that could be beneficial and, mainly, the agencies in Scotland would regarded us as an add-on, so you look at your industry base, which is quite limited and then you see what the universities can do for them, rather than seeing the universities as an entity that are businesses in their own right and can bring interesting companies into Scotland." (B21)	Universities are constantly adapting to the socio-cultural-political-economic environment (beyond policies that directly target them)	
"But I think the approach of next years now with things like Brexit, I think that could really start to be shaping the universities' approaches. A lot could get changed, and obviously, the environment is going to change and the university has to deal with things, so not much to say." (B45)		
"And, you know, that partly recognises that government has a role and that might be, you know, profession of the capital [...] A large capital investment that no single company and even group of companies would be willing to fund, generally. So there is a role for government, that the government plays its part there, and industry then plays its part in terms of funding a pre-competitive, partly funding a pre-competitive programme and then you might then have another entity, such as Scottish Enterprise or Innovate UK or somebody else, who then lowers the risk of those programmes by, again, having some other kind of subsidy attached to it."	Grants for large collaborative projects that companies and universities could fund on their own	Support programmes
"We've been slower to do it in the UK, partly, I think I can... it might be driven by central funding, the States are quite lucky there are a lot of federal funded money sloshing about for one purpose or another that allows things to happen."		
"there is a lot of interest again in supporting Scottish industry, which is why we got initiatives like the innovation centres, Scottish government innovation centres."	Innovation centres	
"maybe getting involved with innovation voucher schemes as well" (B31)	Innovation vouchers to help lower the barrier because R&D is expensive	
"When we do other things, for example innovation voucher or other sorts of things" (B41)		
"So, again, problem-solving and there is kind of voucher schemes, which help that. And that's I think for some companies important, cause they don't realise, how expensive doing research is. Research is very expensive, it's people-intensive, it's capital-intensive in some areas. So voucher schemes help them lower the barrier in some ways." (B43)		
"So, the voucher scheme that is a government-backed way of doing it." (B43)		
"there's some bits of work that could be funded through innovation vouchers or other small packets of funding" (C71)		
"we use the innovation voucher scheme to scope a project and then they moved to the KTP scheme and now they are licensing our intellectual property" (C81)		

"It depends on your sort of user, that you're looking for, you could use things like KTPs and other government grants" (B21)	Knowledge Transfer Partnerships (KTPs)	
"we use the innovation voucher scheme to scope a project and then they moved to the KTP scheme and now they are licensing our intellectual property" (C81)		
"So any company wishing to take that idea on we'd have to invest a significant amount of money in it to actually turn that into a working prototype and a saleable unit, for example. This is where we could have some more help with providing financial assistance in developing the technologies." (B31)	More funding required for entrepreneurial activities and follow-on R&D (bridging the 'valley of death')	
"Part of that is not necessarily that there isn't funding coming in, because SFC funds, Knowledge Transfer Grant, which is now being changed to the University Innovation Grant, and there's funding that goes towards core staff for that." (C71)		
"Scottish Funding Council have just, as I said, changed that the University Innovation Fund, which used to be called the Knowledge Transfer Grant, and it set up with new priorities and a large part of that is to develop entrepreneurship much more than some of these other things like consultancy or contract R&D. Entrepreneurship is becoming... and innovation together is becoming the main thrust of what they want that funding to be used for, and so we look into how we can change things and develop to do more of those things." (C71)		
"We've got a lot of experience working with Scottish Enterprise proof-of-concept scheme" (A11)	support programmes for spin-offs	
"So Scottish Enterprise are the sponsor of the high-growth spin-out program, so we deliver that including the project management on their behalf" (A12)		
"Scottish Enterprise High Growth programme and various others" (B31)		
"So Scottish Enterprise, for example, has a number of initiatives, previously proof of concept funding for creating spin-out companies but not really supporting licensing" (B44)		
"But this issue that it's easier to get support for things which develop commercialisation towards a spin-out than for a licensing opportunity is a bit of an issue, because it does mean that sometimes something that you would think a priori is more likely to be a license, you might still progress that as a spin-out because otherwise you can't do anything with it. In which case, effectively, what you're doing is, what we would do for a spin-out is we then license the IP, the university IP to the spin-out." (B41)	Due to the lack of funding for licensing, a spin-out would be created to which the invention would be licensed (if licensing is naturally the better option)	Unintended consequences

"And so there will be a spin-out and they get a license and they might not do anything other than have a license deal with somebody else, which would be a bit odd. But anyway, I mean I'm not sure that it has ever come like that but there's a couple of companies that I had a conversations with, the CEO had expressed that kind of view of, you know, a spin-out and then we just make a license deal." (B41)			
"I think the whole thing is about not being one thing. So, I think we get the pressure from agencies just to be doing spin-outs or high-growth companies or something like that and, particularly in Scotland, that happens and they miss the point that global interaction actually brings inward investment."	Government focuses on spin-offs, which can lead to unintended consequences		
"So government is interested in universities producing more spin-outs, right. So as a university, if you want to please the government, you would have maybe a policy of spinning out as many as you can and then you get into discussions about what's the failure rate of the spin-outs and this kind of thing." (B41)			
"In some ways, the financial element is necessary, because if the university is paying someone to do something 100% of the time, but they decided to spend 20% of the time working for Google, that means the university is funding Google. There has to be a financial element where Google buys out the university bit and, therefore, benefits both the university and the academic." (A11)	Commercialisation income as a means to show accountability for public money	Universities must show impact and value for or return to society	
"You've got to adopt, what's best for the university, it's public money and you've got to show that you get value for that, so that there has to be some kind of return." (C71)			
"If you're doing more deals and you're in a century driving impact, so impact for REF would be important. So getting the technology out there and getting someone else to use it rather than the university is good for impact for REF, so that's a positive." (B21)	Licenses can be used to demonstrate impact for REF		
"I think, kind of going back again to the impact of research, I think it's the great technology that amasses the potential root in order for research to be translated into real societal use." (C61)	Licensing and IP transfer as a means for creating value for society		
"I think, you know, translating research, it is always a positive. I think, it needs to be done in the right way and an appropriate timing for the market etc." (C61)			
"As I said, each deal is negotiated on a case-by-case basis, but we do have responsibility as a body that received public funding to demonstrate good stewardship of the resources that we are being asked to manage and so we can't really give stuff away, we need to be able to show that having developed this intellectual property using, in part, public funding that the return on that is being some sort of other equity or revenue of some kind. So yes, normally there is equity." (C81)	Taking equity to demonstrate good stewardship of public resources		

D.2 Current Limiting Factors

Table D.2: Quotes and codes for the 'current limiting factors' theme

Selected quotes	First order	Second order	Axial coding
"Obviously there's, you know, you got bureaucracy, the negotiations can be difficult, there are resource constraints in the sense that there's only one BDE but there's 40 researchers." (A11)	(TTO) resources to initiate and nurture relationships	Limiting factors collaborative research	Current limiting factors
"Yeah, because we're already so active in doing this anyway. It's finding the resource and time to do more of it than we already do. That, by and large, would be more people. It could be more people in a support role, admin, emails, that sort of thing or in another BDE-type activity." (A11)			
"For us, again, resources. Getting out there and meeting plenty of companies and promoting that." (B21)			
"I think from purely within this office, we can see the limited number of industrial partners that we can engage, who are actually willing to work on collaborative projects. It's quite a job to engage these companies and keep them interested in some cases." (B31)			
"Which again, some academics find that very natural and they're experts at it and they're the best people to kind of have the conversation and do the negotiation but, say the majority are not sure how to do it and do need that support and then there is probably not enough of us to provide that support." (B42)			
"Again, our resources to promote collaborative research is limited and if we have more resources to do that, we would be able to generate more and stimulate more, but then that would create problem of potentially not being able to meet all of that demand."			
"ability to draw-off capability. There is a cycle in the university in terms of what goes on when, you know, so you don't want to be approaching people in the middle of the exam season, at the start of the term, dreadful time to get anything of the ground. You know, the summer period, okay there isn't the teaching, but quite often people are not here, they are going to conferences, they're networking, which is all vale things to do. But people might not be here for you to be able to do that, so those are small barriers but, you know, maybe they add up to something quite big. The barriers for the likes of our organisation in terms of developing opportunities, is access to people, access to the movers and the shakers, you know." (B43)	Access to academics and students when industry needs them or proposals are due (e.g. travelling in the summer, exam periods)		

"limited staff, and if you have too much you would, again, shorter-term, unless you're getting contracts that are going to last long enough to employ somebody, like a two- or three-year, one- to three-year period like a KTP-type thing, it's difficult to allocate resources randomly, when they're supposed to be doing something else at the same time, so there's an issue with that." (C71)	
"I'm just thinking of the European projects in particular, that can be quite a big administrative burden if you're the lead partner of a large project. Also, the work on dissemination, which can be a bit time consuming and labour-intensive. A lot of red tape, as well, and hoops to jump through." (B31)	Administrative work and additional responsibilities and tasks for both academics and TTO staff
"The external environment is increasingly or is ever more competitive in pulling these bits together and it's become more difficult to win awards." (B45)	Increasingly competitive environment for winning grants
"the external environment, the fact that there have been cuts in public sector money which just means that it's ever more competitive in applying for research grants." (B45)	
"lack of understanding about how to cost and price for industry and, you know, in general, a lack of understanding that it's a hackling process, you know. So there's all kinds of things that we have to keep educating academics on." (B42)	Lack of understanding among academics about costing and how things work in industry in general
"But all those little things, yeah in fact that's the problem, they are all quite little things, quite subtle things, they're things that you just build up experience of by doing the job for many years. Things like don't use the label 'overheads' because, of course, they'll then say 'we don't want to pay for your overhead'. Whereas a company, when it gives a price to another company, it never expresses that, it never breaks it down in terms of overhead. But I suppose that's the problem, it's all quite subtle, nuances of language." (B42)	
"That might be financial resources. An industry partner generally hasn't devolved responsibility for R&D budgets down to a level to which you can easily negotiate with. So if you've got a piece of research that's costing you a lot of money, it critically has to be signed off by somebody higher up the chain, the food chain. And if it's not in their annual budget, it's not going to get funded and therefore it won't go forward. So, there's going to be quite a bit of forward planning, you know, to understand... So the bigger companies know that, they can build in budgets years in advance and can be a bit flexible about drawing those budgets down. Smaller companies, they just don't have that and if you're in a branch of a multi-national company, whose headquarters is not in the UK, you will find it even more difficult to engage with that. Because, again, the budget is set somewhere else and needs to negotiated, it's going to be understood why you would partner with, say, [our university] as opposed to some other entity." (B43)	Larger projects need buy-in from company senior management because they are a big investment and needs to be included in advance in their annual budget

"Capacity of research leadership is absolutely one of the main limiting factors. We can go out and talk to industry, colleagues from the faculties and also central business resources can go out and talk to industry, find out lots and lots of things that industry would like, but we have a limited resource base to deliver on that. I would say that we've got real capacity issues at research leader levels, that's research group leaders, profs. And I think we also do have challenges in recruiting. We're doing well at the moment in recruiting the up and coming people, but we need to be able to recruit and retain research talent at all levels. I would say leaders is the biggest capacity challenge, but I think attraction and retention of research talent at all levels is a bit of a challenge." (B46)	Research leadership (professors, group leaders) to successfully deliver these projects	
"but it really is down to the academics, their appetite, their capacity." (A12)	Time and workload allocation for academics and their appetite	
"I think, there's a workload balance that we need to manage more carefully, so that academics have the time and bandwidth to be able to do that." (C81)		
"small company might come in with something more like what used to be industrial liaison. They just want an answer just do that bit, they don't want anything else. That's less attractive to the academic, they want something more stimulating. Small companies tend to come with very defined little problems" (B21)	Consultancy seen as less intellectually stimulating by academics	Limiting factors consulting
"consultancy is a bit of a fringe activity" (B46)		
"difficulties that is consultancy seen as a second class activity or a lower level activity than research or teaching and that's where we were into the issue about the KE fellows. If it's having status as a KE fellow is the route for people, who want to do consultancy, maybe it will grow." (B46)		
"there's a questionable financial incentive, because either the faculty levies are a deterrent or the process for having the faculty levy waived is a deterrent" (B46)	Financial incentives are unclear	
"But that would also cross consultancy as well, where we have had instances that you'd be asked to undertake let's say chemical analyses and I haven't got a technician available to do that, or we haven't got the piece of equipment ready and it is already being used for research projects." (B31)	Having the right staff available on short notice to fit the time frame and needs of industry	
"I think it's also timings sometimes, essentially for consultancy." (B45)		

"I think there's a difficulty in terms of having the right people in place, certainly having a right research associates involved in projects quite difficult. I think that sometimes it's quite a difficult career for young people to go into because certainly in the early days, it is not a massive job security in there, they maybe go from contract to contract to contract with the current economic climate that's maybe not so bad. Making sure you got the right people in place who can carry out this activity and that goes right through from bring through good undergrads in the first instance, PhDs, we've not talked about their place here, but those are some issues." (B45)		
"For us it's resource. We've taken on consultancy and haven't added any additional resource to that. We're fitting it in with what was our economic development work and because we do more business engagement where we'd always offer consultancy to large companies anyway. In the future, strategic partnerships with companies are going to be important." (B21)	Lack of central support, a clear policy, showcasing the university's expertise	
"Limiting factors, I suppose for us personally, it would be the lack of a dedicated website for actually hosting information on who is available for consulting and their expertise. We have adopted as much as we can standard terms and conditions for consulting." (B31)		
"For us, at the moment, it's the lack of a consultancy policy that has a reward to the consultant or, at least, to the department of the consultants that they could use it for their research or other departmental budgets. Until we can sort that out, I think we'll have trouble developing consultancy." (C71)		
"I mean along the discussion over the IP terms and other times but mostly speaking we follow kind of a standard processes and since many of our partners are long-term partners, we have a framework for working together." (B41)	Occasionally IP, but standard processes and relationships prevent issues	
"Second to that, is the promotion. You need to have a very good reputation. You can't sell a duffer. They need to have credentials that says they are good at this. No one is going to pay you for poor advice, so it's not just the numbers of academics, who need to make sure that the credentials of the academics and or the institute and the university are incredibly high. People are not going to come to you or pay for advice from somebody that's average. We've got to protect that reputation very very carefully." (A12)	Reputation of university and the individual academic (both need to be carefully protected)	
"Well, academics again, with the dependency on the academics and their network and their profile, that's a key dependency." (A12)	Time and resources as part of a balanced portfolio	

"It's probably just the availability of academic staff members. You tend to find, or in my experience, you find that it's a lot of the same academics who are being courted by companies to carry out consultancy activities. These are academics who are very very busy, who have lots of competing calls on their time. So there's only so many hours in the day that these people can work. That's probably, in my experience, the biggest limiting factor, just the availability of people." (B45)		
"Time, which we've talked about in every other case, that staff perceive they have too many things to do." (B46)		
"The time and resources are always a big thing, but , you know, a balanced portfolio of research is obviously a positive thing." (C61)		
"I think, there's a workload balance that we need to manage more carefully, so that academics have the time and bandwidth to be able to do that." (C81)		
"we need to make sure it's something we can deliver and not distract from some of our other main business purposes" (A12)	Academics' time as part of a balanced portfolio	Limiting factors contract research
"I think it really is capacity. There seems to be enough demand in industry." (A12)		
"Again, it is the time. If we are looking for a collaborative funded research project, you know, funded by some of the big research counsels, there is a balance of time that needs to be struck. Obviously, you can't do everything, but as I said before, a diverse portfolio is always good." (C61)		
"Again, with that and with consultancy, there's opportunity cost of doing one piece of research, contract research, as opposed to doing you're main area of research or your publication stuff rather than your commercial. There's a pressure there between which one you'd focus on." (C71)		
"I think, there's a workload balance that we need to manage more carefully, so that academics have the time and bandwidth to be able to do that." (C81)		
"I think just knowing of the opportunities for these contract opportunities. Obviously, there are very well established opportunity dissemination tools like Interface. But a lot of it happens organically as well and the sharing of those networks and opportunities, making sure that everybody is aware of them is a challenge and where we can increase that would be useful." (C61)	Being aware of opportunities (across the university)	
"There, I suppose, is not the academic staff, but there's also the administrative staff, as well, there is quite a lot of administration per project. Which when you have more projects, you need more administrative staff" (B31)	Having sufficient administrative and TTO resources available	

"Lack of interest. But by that I mean the kind of more senior academic staff. No doubt there is, and this is from the perspective of the science faculty as well, there probably are centres, where that's exactly the kind of work that they want to attract and that people are interested in doing. So that is very much kind of the senior academics that I work with in the science faculty [who] would always be concerned that contract research wouldn't stimulate them enough." (B42)	Lack of interest from (senior) academics due to perceived lack of intellectual stimulus	
"and also technicians to actually operate the technical specific equipment around the university to undertake engineering projects are very valuable, as well. And in some cases there is quite a short supply in the university." (B31)	No call-off R&D resources or academics, ultimate decision is made by academic whether they have time and are willing to engage	
"I mean the limiting factors, we don't necessarily have call-off R&D resources, cause an academic has got a career to do, he or she has got teaching to do, they've got their own fundamental research to do, they've got admin to do, you know, they've got their own career to manage. I can't manage their careers, I don't manage an academic's career. So if a company's coming in here and wants access to an academic, who has definitely got the skills to address their issues or problem or I think they would form a good partnership, the academic doesn't want to do it, that's the end of the story, you know. So that's a limiting factor, they're not line managed. We're not an R&D organisation that says the bottom line is important. So the decision-making is down to the academic and the academic has the freedom to say yes or no." (B43)		
"The other thing is, quite often, you need access then to, you know, RAs, research associates, people to actually do the work. Now, they get churned out, people go through a PhD programme or something. Quite often at the end, it's at that end point where the money's run out and the individuals are looking for something else to do. The department or the supervisor values them, thinks they could develop the person if they had, you know, some external funding from somewhere. So if those two come together, it's ideal, but it might not be. So you might have a requirement coming in from an industry partner or a group of industry partners, university says 'right, you know we've got the academic capability here to do it', but the academic capability in itself isn't enough, because you need the capacity then of the workforce attached to that academic, who they will direct, and you then have to recruit these people. And recruiting these people is very hard. Getting good quality people at the right time for the right collaboration, that is the fundamental problem that collaborative R&D definitely has and contract R&D, because it's a shorter time period, it's even worse cause you can't give somebody a one-year contract or a two-year contract if the contract R&D is for a two months project. You don't have somebody to pull off the two months contract. So unless you have a technician and they can do it." (B43)		

"Some of the issues that are in contract research, that's similar to consultancy, is availability of staff time to do it. It's short-term, but it's quite often the industry wants people to be spending most of their time on that, so that the staff and the scheduling of staff to have somebody available to just go and do that may be limiting." (C71)		
"I think it's probably the staff availability to do the projects. I think what we could get... if we did more demand stimulation, I think we'd very quickly get to the point, where we couldn't take any more on, because we wouldn't have enough staff to do all in the time frames required of industry." (C71)		
"We don't promote it." (B21)	Not actively promoted externally	
"To us, it's not really a priority to do that. I think it shouldn't be our main concern, giving access where it's needed is fine. And so your ability to maybe make people aware of what you've got, so Interface is a good vehicle for that. But I wouldn't put our staff onto marketing services, there's just far more gaps than that." (B21)		
"I think part of it is price. I think there's still a perception at times from industry, from businesses that universities are expensive to deal with. I mentioned earlier on about the full economic costing, even that has been in place for ten years now and still, I think, it's had a lack of understanding outside the university sector as to what this means and what prices are." (B45)	Price and companies' understand of how the price is calculated within universities	
"I've known situations where I've dealt with a company and they've said that in the past they've not approached universities because they just know that universities are expensive to deal with, and if they went to a contract research organisation overseas or whatever, then they know they can get it for a lot cheaper" (B45)		
"the ability of you to sell those or to others to bring them in contact with others outside" (B41)	Ability to market and sell inventions to companies	Limiting factors licensing
"Resources, definitely. You need people with a large travel budget. And by people I mean commercial business development managers." (B42)		
"Finding licensees." (B46)		
"You then have your constraints in your own teams, the IP team for example, they've only got a capacity to handle so many opportunities and ideas." (A12)	Conversion rates from disclosures to patents to licenses due to TTO capacity	
"The problem is the conversion of those patents to license deals." (B42)		
"Where I see the difficulty lying is with the translation of those patent applications, for example, into deals, into license or spin-out deals and that, I think, is a reflection on me, lack of resource, or the smaller resource available in the commercialisation team" (B44)		

"Because we're only commercialising round about half of the opportunities that we protect, there are 50% of those opportunities that we still could do something with, had we more resource." (B44)	
"cost of the patents but ultimately we cope at that." (B21)	Cost of IP protection to create a pool of opportunities
"Over the years, my experience has been that there have been less of larger organisations looking to license in technologies from universities, less investment, which makes it very difficult for us to growing prior to be chased business. If we're seeing the open hands in their pockets it's... if they're doing more and more internal R&D, then the opportunities out there for us to be able to take those forward." (B45)	External demand for licensing in technologies by (large) companies
"Academics, who see it as an opportunity and want to participate, because they're the ones are the source of the ideas. That, therefore, is based on number of academics and also academics that are actually doing research. You've got a fundamental dependency there, which is them and the number of them and the number of them that want to participate, that's a fundamental dependency." (A12)	Inventions and disclosures from academics
"ability of your academics to produce stuff" (B41)	
"your ability to identify them" (B41)	
"To an extent, we'd like to be more strategic in the way that we deal with our licensing opportunities but to a larger extent, it's driven by the opportunities coming through from the academics themselves. It depends very much on the technologies which are coming out of the academic base." (B45)	
"the fact that we've had the REF over the last couple years, academics' time tends to be taken away then from summer activities and focus on having publications in place and whatever else to support the university's improved REF performance. Those are probably a flavour of some of the biggest challenges and hindrances to licensing technologies over the last few years." (B45)	
"one of our constraints in that if they're spending the majority of their time teaching, they're not spending the majority of their time doing research. And if they're not spending the majority of their time doing research, then we have a limited amount of ability to develop intellectual property." (C81)	

"There are more mechanisms, funding mechanisms, available for the creation of spin-out companies. So Scottish Enterprise, for example, has a number of initiatives, previously proof of concept funding for creating spin-out companies but not really supporting licensing. And licensing is a process like creating a spin-out company, it doesn't just happen automatically, you don't just put an advert on your web page and you find a licensee. You have to build that relationship, you have to develop the technology and work it up. And there are relatively few pots of cash for carrying out that kind of work. So that is a problem, that's not something I know so much about but if Catherine hasn't articulated that, it's probably worth having another chat with her about it. So that's, I would say, a significant problem as well." (B44)	Less external support compared to spin-off creation	
"on another note, there is still an element of 'I don't get involved with'. Getting involved with industry is a grubby thing. We don't find it so much in our school, but there are some people, some academics in the school that just don't want to be involved in industrial partnerships. They want that pure research. If it has an impact at some point, great, but they're not actively seeking any kind of industrial licensing" (A11)	Limited industry engagement of academics	
"In order for what we do to be useful, it needs to be informed by industry and, once again, when academics are busy teaching, perhaps even busy doing research, they may feel some constraints around their ability or their time to engage with and spend time with businesses. And yet, without doing that, we have the danger of being an enclosed ecosystem that doesn't have a useful application." (C81)		
"Probably staff resources and it's difficult to recruit experienced staff. [...] No, for our office. Academics, the university has a good reputation and we're very lucky with the staff that we've got and that opens doors for you in terms of industry. But in terms of staffing the technology transfer office, so the experienced staff, is quite difficult. And if you lose staff and have to start again, you lose time. I think even Cambridge is finding it difficult to recruit experienced staff, that's what we've heard." (B21)	Recruiting good and experienced TTO staff to support the process	
"the reticence, an understandable reticence on the part of the academics to leave academia and join the spin-out company. And that's completely legitimate and completely fair, some do wish to take a break from academia and do something different and are very successful in creating the spin-out company and then having some function within that spin-out company, whether that's a chief technology officer or a chief scientific officer or chief executive, but a lot of the academics don't wish to become involved, they like doing research and they're happy to create the technology, they're happy to see it licensed into the spin-out company, but they don't want to join the spin-out company as such. And that can mean that the technology is licensed, rather than spun out or nothing happens to it at all." (B44)	Academics apprehensive to join the spin-off, which might result in the spin-off not moving forward	Limiting factors spin-offs

"Now, if the academic doesn't want to become involved in the development of that technology within a spin-out company, that spin-out company may struggle to develop the technology and ultimately be successful. Now, it may well be that they can find somebody who is an expert in that technology and make it work, large enterprises and existing SMEs tend to do better at that because they have the technology base and they have a broad range of personnel to help translate that early idea into a product. But new spin-out companies might struggle with that, if they don't have the academic involved who was involved in the creation of the idea in the first place. So that is a key limiting factor." (B44)			
"Again, no matter what the opportunity is, we work very close with the academic to identify what their personal aspirations are. Sometimes, you have an academic, you want to be very, very engaged, very involved in it, particularly obviously if it's a spin-out company. They might have a long term desire to leave the university to pursue the opportunity or they might have a desire to remain within the university but provide support to the company and there are academics, of course, they just want to have the technology going out there." (B45)			
"There's so many anecdotal stories about the big difference between the UK and the US being people's different approaches to success. People across in the States have had three or four failures before they make it big, and nobody sees it bad and across here if a company failed... Money always helps, as long as it's used correctly, but also the overall approach, the overall mindsets of people to set up new companies, as well, has got to have a place." (B45)			
"It's resource for us. The amount of time that we could help somebody, so limit how much we could spend on consultancy services [to support the spin-off]." (B21)	Financial resources, particularly for IP and external experts with commercial expertise		
"I suppose it depends which sector you're working in. One of the limiting factors would be funding to build your spin-out company or your enterprise, attracting the right team of people to take your company forward. It's not always the academic founders who are the best people to take a company forward; a research group that is employing maybe a hundred people requires a different skill for being an academic. Funding and building and managing team." (B31)			
"one thing we used to have, which we miss, is funds to employ executive director designates. And that was really useful, because then we could bring in an external expert with commercial experience into the project early on to kind of pair them up with the academic. We still manage to do that, it is just a lot harder cause we are scrabbling around for what funds there are or relying on individuals, who are happy to spend some of their time working for free, basically." (B42)			

"Yeah, definitely the ability to pay for good commercial champions, if there are any funds for that. And that makes probably all the difference to something succeeding or not." (B42)			
"Our issue is we have no budget again. It's not that we have a fund, that we're rich, just waiting to invest in spin-outs. It has to be scrutinised and it has to be seen to be making good, to be making money, not just doing it for the sake of it, for the numbers, or for the potential. We need to see a real value in it in terms of a return." (C71)			
"budget to turn development support internally. Also, that budget would be also used for or help develop awareness. Raising awareness of those opportunities and the fact that there's other things besides research and papers that researchers could be doing." (C71)			
"Probably the main limiting factors across the sector would be having the right people to drive the businesses forward, because quite often, certainly after the very, very initial stages, you need to have somebody who's got the right experience and the right expertise to take the technology forward, the right connections and, more often than not, academics either don't have that or don't want to have that role. So having a sufficient pool of experienced business people who can manage a team and take the technology and the opportunity forward is one of the keys." (B45)	Having the right people to grow the business (which are often not the founding academics)		
"I would say access to the right type of management skills is a limiting thing." (B46)			
"I think the things I've said about, you know, it's... we need to reinvigorate our focus, we need to renew our focus and decide if that is something we want to and we'd really should be involved in." (A11)	Institutional support and a clear commitment to whether this is something that should be prioritised		
"I mean yes, in terms of resources, my impression is that there's less company formation-type, company creation-type activity out there. We still, as far as I know, have proof-of-concept from Scottish Enterprise, although, my understanding is the process is far more vigorous than it once was and there's less money available as well. If we had access to more company formation type funding that could potentially buy an academic's time for a period of time, not necessarily 100%. In fact, we spoke to an organisation this last week that was looking to raise some money to invest in companies, they prefer to be a VC but they were also talking about the potential for them to fund company formation, company creation type activities, so that's 'we think we've got something here but we need to do 12 months of X to get it to the stage to actually say yes or no'. And that's a very appealing prospect, but there's not enough of that. Those little funding mechanisms." (A11)	Investments (and Scotland is behind the rest of the UK)		

"Investment. Big gap, institutional and other venture capitalists, etc., are quite risk adverse and, of course, start-ups and their need for money is very, very high risk. Yes, there are sources of grants for translational awards. It tends to favour the bio-sciences, medicine kind of areas, and can be potentially very large amounts of money in the future, but that's actually a very, very small number of businesses, really, when you look at the opportunity. So investment for high-risk early stage businesses is a key key dependency. We see that as our biggest challenge in the the next few years, is to raise the funds for investing in new businesses. There's a huge gap in Scotland and north of England in that area. [...] Out of almost 1,000 businesses on AIM and any size of business can go to the AIM market, there's less than 20 in Scotland. That emphasises that we're really behind the rest of the UK quite significantly in this area. Investment was a real gap of investment funds for these early stage ideas and turning them into new businesses and sustaining them till they're ready to actually go to second round of investment, which then you do have funds and other type of institutions to call upon, big gap area." (A12)			
"I think for us it's resource, for the companies it'll be management and ability to get investment in Scotland. You get angel investment but beyond that, it's quite tight. There's that early stage gap when they're really quite small and vulnerable when they, you know, they don't really have the sort of accounts that would pass audit for some of the government grants. So they're excluded from that. There's a certain people that need the grant but they can't get it because they're not stable enough to get two-year grant. KTP is going to be difficult and yet there are a good thing for small companies." (B21)			
"In terms of small scale-ups, early start-ups, spin-outs, which we are going to look at, obviously, whether the economy is being aghast the last number of years, it's been more difficult at times for spin-outs and start-ups to get off the ground at a certain level, for them to secure initial investments. There has maybe been less activity in this area the last few years for the universities to be able to tap in and take technologies forward." (B45)			
"Scotland is quite a small place and so that's one thing, lack of competition among equity investors in Scotland is quite a big issue. It's better than it was. There is a reasonably good network of angel groups and angel networks, but there is very little sector specialist investment in Scotland. You can probably say, what are they called, Epidarex, the life sciences investor, is based in Scotland and, I suppose, there is a specialist life sciences and healthcare investor, but there aren't very many organisations like that." (B46)			
"Again, it's down to the volume and the quality of the ideas coming through." (C71)	Limited by the ideas that are coming through		
"As I said, I think it's the number of ideas coming through that are of quality" (C71)			

D.3 Entrepreneurial Academics

Table D.3: Quotes and codes for the ‘entrepreneurial academics’ theme

Selected quotes	First order	Second order	Axial coding
“I think they’re really important. I think, you know, collaborative research takes a while to develop, it’s not problem solving. So, you know, you need to have those networks, they need to know what your capabilities are, who you are, you would have to go out and present at conferences yourself, you would have to know what the main drivers are in certain industry sectors at a given time, how you could position yourself, you know, it is very important in developing those networks” (B43)	Academics’ personal networks and links to industry are crucial	Characteristics	Entrepreneurial academics
“I think it would be fair to say most of it comes through academic networks and relationships, your previous work and contacts base.” (C61)			
“I think some, yes, some people are entrepreneurs and some people aren’t” (A12)	Not every academic should necessarily be entrepreneurial		
“They just don’t want to get involved in other things and there’s this space for everybody, there should be.” (B45)			
“Also, there’s times when you wouldn’t necessarily want to put an academic to a business, to work with a business, if they’re not going to deliver or be interested, enthusiastic about it, and they’d only be doing it because they felt like you forced them to. It’s not going to work.” (C71)			
“I think what often happens though is that the individuals who are really good at research and teaching are just inherently good at knowledge exchange anyway.” (B45)	Small number of academics that naturally excel at research, teaching and KE and naturally get involved in the latter		
“But our best do both, so quite often you’re a smart person, you’ve got some good IP, on the back of that you’ve developed some good papers, you’ve developed some relationships, you do collaborative R&D with... you’re ambitious to start your own company, who then licenses some of the technology to your collaborative R&D partners. I can think of a number of individuals, who are doing that, but again, back to what we were saying previously, the pool of these people are actually quite small.” (B43)			
“I think you’d always get some academics who would get involved in everything, no matter what the infrastructure was, what incentives were there, just because you get some people who are like that.” (B45)			
“Last year, say, about 300 academics out of 4,000 and something, who would be eligible for consulting. It’s quite a small percentage.” (A12)	Small number of entrepreneurial academics that are very active		
“I think, natural entrepreneurs are actually quite a small percentage of total populace.” (A12)			

"If you shake it down, it doesn't come down to a huge number, really out of the whole academic population, it's not a lot and those people are phenomenally busy. And so you don't get access to them, or you can't get access to them." (B43)			
"a lot of invention disclosures from a relatively small number of academics. [...] So, there seems to be a bit of a polarisation, it's not as if you have everybody in the research base generating one disclosure a year or half a disclosure a year or 0.1." (B44)			
"you find that it's a lot of the same academics who are being courted by companies to carry out consultancy activities. These are academics who are very very busy, who have lots of competing calls on their time." (B45)			
"I think they have that mindset anyway, and that they actually want to work with industrial partners." (B31)	Motivation varies hugely from scientific curiosity to potential financial benefits (personally and for future work)	Motivation	
"I mean they vary hugely. So, some of them it's pure scientific curiosity, really is, and if interacting with a company is going to get them that, then they'll go down that route. Of course, there are some that are motivated by sort of financial rewards, although they're the majority they want money to come into their university-held accounts, so they've got the flexibility to spend it on post-docs that are coming out of contracts, travel to conferences, laptops, you know, rather then the ones who are only motivated by being able to take home more money on top of their salary." (B42)			
"there is still an element of 'I don't get involved with'. Getting involved with industry is a grubby thing. We don't find it so much in our school, but there are some people, some academics in the school that just don't want to be involved in industrial partnerships. They want that pure research." (A11)	Some academics still think of industry engagement as an unfavourable thing and prefer pure research		

D.4 Internal Marketing

Table D.4: Quotes and codes for the 'internal marketing' theme

Selected quotes	**First order**	**Second order**	**Axial coding**
"create an enterprise culture within the university sector and also linking up with enterprise hubs around Edinburgh was considered, enterprise activities within Edinburgh itself, various incubators, universities, science parks and getting everybody to come together to drive entrepreneurs forward." (B31)	Create an entrepreneurial culture (together with external partners) that values research outcomes beyond publications	Create reinforcing loops through culture and future hires	Internal marketing (supply stimulation)
"I think we need to change the culture within the university and within our academic partners to see other outcomes to the research besides publications and open up the opportunities that researchers can have beyond those kind of outputs, beyond papers and publications to look at other opportunities and other benefits that they can get from their research." (C71)			
"Culture. Culture is everything. If we can develop, not just here, but across the universities sector, a stronger entrepreneurial culture, it will have have booster effects on all the five elements that you mentioned." (C81)	Culture underpins all entrepreneurial activities and should be a main focus		
"We're not doing them yet, but we're planning to be doing those in the next year or two, developing things like a Virtual Entrepreneurship Institute and trying to get entrepreneurship into every course, those types of things. But, as I said, we're not there yet." (C71)	Establish 'enterprise-for-all' to foster entrepreneurial culture		
"Revenue sharing probably helps some people, you have to put a lot of effort into it, but an awful lot of academics aren't doing it for the money, they would do it anyway, and kudos is usually more important" (B21)	Kudos for working with innovative or reputable companies		
"And they do get sort of kudos for it, I think, if they can say to their colleagues 'oh yes I'm working with this company' that is seen as being a good thing." (B42)			
"We're trying to recruit academics, because fundamentally, if you don't have academics, who do networking, who promote themselves and their capability, capacity, we're stuck. We're also trying to recruit academics who want to then proactively go and develop a network, to then be offering themselves as consultants to that network. We're working on that as well with them." (A12)	Recruit academics that are entrepreneurial and are proactive at developing a network		

"I think there is a university culture, which supports commercialisation of any kind and this is a bit of a chicken and egg question, which I'm sure you were aware since you're doing system dynamics. The fact that all of our academics love doing it forms the culture, that also reflects the fact that it's in our promotion processes, which strengthens the culture again. So I think there's a bit of a sense amongst, you know, a lot of the engineers and scientist that if you're a really successful professor, then one of the things that's part of that is having formed a spin-out company." (B41)		
"That's fundamental, if they are not doing research and having inventions as it were, we're unlikely to see many opportunities for new companies." (A12)	Capitalise on the research base and increase knowledge and skills of academics	Develop skills, awareness, and ambition
"I mean I think Stirling, as a research-led university, so I think there's lots of kind of drive to pursue the world-leading research as I'm sure that's true for many universities. I think, simply providing the kind of knowledge and skills for academics to spot opportunities for licensing, and, you know, the translation of the research is always a positive." (C61)		
"But separate to that, we're trying to make it easier to engage with, by having digital front ends to each of our varied processes. And we'll also be marketing that internally. We're promoting and sign posting that to academics that the service exists and you can engage with it in these different ways." (A12)	Demonstrate knowledge and support in the university to show opportunities for academics	
"But a key dependency is the recruitment of academics, academics wanting to play, as it were, in this space. So we're doing education, we're internally meeting with academics, we're educating them. We're trying to make an easy-to-use service, so marketing of it, so it's easy to know where to go to find it, easy to understand the value and benefits of it, digitising the front end, as I mentioned. All of these things are trying to make sure we both sign post, promote and educate about the service, because we have a key dependency, academics have to want to do it." (A12)		
"This is a very similar answer to the licensing thing. I mean, just showing the knowledge and experience and support that we have here in the university to really open up doors and opportunities for academics to see the opportunity to translate the research." (C61)		
"Of course, it's services, it's not just IP, there's other basis of companies. So we're doing internal marketing, we're doing education, we've got our business development service which includes people embedded within individual schools and institutes who are going hunting for opportunities. So things that we can actually translate into business or into spin-out businesses." (A12)	Increase awareness among and capabilities of academics	

"we work very closely with our academic staff, to first of all educate them about intellectual property, what it is, what it means to them, an academic, the risk of publishing, make them aware of the university's policies on IP, and how we can help them, so we have quite a few informational training sessions, we are eager to raise the profile of licensing and knowledge exchange mechanism." (B31)		
"We're all very keen on entrepreneurial training, enterprise activity and, actually, that is an area that my team is to look at over the next six months. We have a new Deputy Principal for Enterprise and Business arriving in October and so we're looking to putting together enterprise activities, undergraduate, postgraduate, and early-career staff and senior staff, providing additional training in enterprise and to be able to be thinking more entrepreneurial and thinking about what their research could be used for as well as education and so on." (B31)		
"I suppose it's raising awareness within the academic community of the value of consulting, of the knowledge exchange mechanism, in addition to licensing and various others. If it was for the academic side of things, if you're working with a company on an interesting project, there is potentially quite a lot of learning in there. You can then transfer back to academic work and vice versa." (B31)		
"From my point of view, just increasing the awareness of routes to assistance for and support for translating potential research ideas into businesses or products or services. You know, really, from my point of view, I'm trying to increase the skills and understandings of those that come through our student enterprise program, but just offering that support to researchers or to anybody with ideas that could potentially go on to be businesses, then that's always a positive. But as I said, it's the mix of support that we're really looking to promote here." (C61)		
"entrepreneurial development of our academics, so that they have the desire to take something forward into company creation." (C81)		
"the more entrepreneurial education we deliver, the more appetite there is for people to do company creation." (C81)		
"I think academics are attracted to the idea that they may have some control over some of the revenues that are generated in order to pursue their particular areas of interest. So I think they are attracted by that." (C81)	Autonomy at the individual level regarding some of the revenues	
"We're not an R&D organisation that says the bottom line is important. So the decision-making is down to the academic and the academic has the freedom to say yes or no." (B43)	Autonomy to decide which activities with which partner to get involved in or not	Enable and nurture intrinsic motivation

"I mean at the moment, they just do it on the basis that it's collaborative research with the companies that is very interesting. You know, they maybe get to see their technologies developed in a way that they won't be able to purely in-house, they get a different perspective on things, when you have the companies viewpoint" (B42)	Collaborative research often driven by curiosity of academic because it offers new perspectives	
"Again, looking at what universities do, commercialisation is just one of the factors, academics have got very strong competing cause of their time, they are expected to be able to teach, to carry out research, knowledge exchange, producing publications, carry out administration, to come up with commercially potential technologies. From that side of things, freeing up some more of academics' time would potentially be useful as well. It's difficult because if you could magically do it, it would be great, but unfortunately it's not." (B45)	Include entrepreneurial activities in academics' workload model and free up some of their time	
"when academics are busy teaching, perhaps even busy doing research, they may feel some constraints around their ability or their time to engage with and spend time with businesses. And yet, without doing that, we have the danger of being an enclosed ecosystem that doesn't have a useful application. So finding time and the ability to engage robustly with industry is another constraint, not one we can't overcome, but it's a very important one." (C81)		
"I think financial incentive is always going to be a strong one, but I do think that if we have a significant chunk of academics here in school that enjoy working with industry, they enjoy solving problems that industrial partners face, so it's not just the financial reward" (A11)	Intrinsically rewarding process to see research being deployed in the real world and exploring new opportunities	
"And often for academics, it's not money, it's not money. We need to find a way of linking their interest to participation in industry engagement. Impact, I think, is one, but also but also increasing the range of research opportunities that academics use to recognise, that's a great opportunity for them." (A12)		
"it's usually people that want to progress their career and get their technology out there." (B21)		
"I think it's more about impact, it's more about getting the research out there, being seen to be entrepreneurial, be seen to have an applied technology base, to be a place of useful learning, I suppose, to quote the maxim of the university." (B44)		
"it's intrinsically a rewarding process for the academic to go through, I think, it's nice for the academics to see their technology out there and being deployed" (B44)		
"one of the unintended consequences is the loss of academic talent in the university. In many cases, the spin-off requires one of our academic members of staff to join the company and in which case we lose them to the university. Maybe not permanently, they might be on secondment, but it's still a brain-drain." (C81)	Brain-drain when academics join spin-offs (even if only on a part-time basis)	

"it tends to lose the boundary between the lab and their... you know, especially when they're working just across the road. Things become merged and they employ people in their company but suddenly they appear in their lab in the university, all sorts of things happen and it's really all over of the world, that's a problem. Sometimes it goes wrong, because of that and they could be accused by other members of staff. [...] There's a tendency for our life sciences to like the company to be in the school and we don't really like that although we see all the advantages of that. They're not really running independently, they are not learning. So when they go out, they have much more problems, so just having it literally across the road, the incubator space, but they would use facilities in the university but, formally, rather than just walking in and out. These are constant problems of spin-outs conflict." (B21)	Conflict of interest from academics staying partially involved with spin-offs
"Well, I guess, we're increasing risk to the university and the risk takes lots of forms. So, reputation risk so it might work for a company, which that company proves to be not reputable or does something inappropriate with the advice that we do... We've got reputation risk, we've also got financial risk. The more agreements we have, the more liabilities we have. There's financial risk. [...] That's just something to keep a watchful eye on and try and manage and have mitigation and contingency for." (A12)	Entrepreneurial activities come with risks (reputation, financial, etc.)
"we can't afford for it to cost us our reputation or otherwise" (A12)	
"They'll come with the same exposure to risk, reputational, financial, etc." (A12)	
"I don't think we actually do it to the point where the university's central purpose will be compromised and that's about research and getting it out of there, but there is always going to be a trade-off. That agreement with the large, very large multinational was... I don't think the net benefit to the university was there at all." (A11)	Entrepreneurial activities should not compromise the university's other missions
"And also time. We often laugh when we deal with some of the academics. When you actually look at how many industrial collaborations they have and an industrial partner will buy 10% or 20% of their time. Then when you look at everything and maybe they've got their 50% commitment to the school and so and so. They're 150% committed, but that's not realistic and it's also not honest, because the basically saying to the company 'I'll give you 10%' but that company is actually getting 5% of their time. There are only seven days in the week, academics have a number of different responsibilities, because fundamentally they're academics at the end of the day. And it's that tension between the academic research and the industrial collaboration is a difficult one to manage." (A11)	

"Of course blue-skies research is important, blue-skies research has a place that... it may not be this year, it may not be next year, but at some point that research that was in astronomy has implications for medicine. You can't anticipate that sort of thing, you can't identify an industrial application in that context. It is a good thing, but the attention is always going to be time. Freeing up enough of the academics time to do that." (A11)		
"We've got a long way to go before we would potentially be interfering with our teaching and learning capacity. But yes, that's something to watch and manage, absolutely something to watch and manage." (A12)		
"And then you got to protect against capacity to also sustain our research commitments, our teaching commitments, etc." (A12)		
"It now doesn't have a limit. In theory, you could do lots of consultancy but, of course, that's not the answer either. If somebody is not research-active enough, and they're not applying for enough grants, but they're paid as a researcher and they're spending all of their time doing consultancy, then that balance would be wrong and that would be judgemental to the university because we wouldn't have the research income. [...] that's probably the worry for the university, it's always about balance. We're not here to do one thing." (B21)		
"There still has to be enough room for blue sky research and that's where the REF ratings come from and it's that reputation. You have to have the research before you can do the engagement with industry, you have to still be leading in your field. So balance, same as everything else." (B21)		
"Again, that would be diverting, well potentially diverting people away from their academic day-to-day work." (B31)		
"You need a lot of resource, it takes a lot of time to do licensing and those things aren't compatible with sort of academics' ability to progress their careers nor with outcome agreement targets that we're signed up to." (B42)		
"There is a fundamental flaw with encouraging licensing and, you know, all the other things that a university is expected to do." (B42)		
"There is other reasons for that as well, because... what's your staff? I mean, are they academics then? Are they technicians or glorified technicians of some kind, who are not publishing, who are not teaching? The are not parting new know-how to the next generation. To me, that resides probably outside the university at some point." (B43)		
"For spin-out companies, if you're taking staff out of the university into spin-out companies, you could maybe see a negative impact for the university's ability to generate primary research there." (B44)		

"Again, another potential downside, as I've said before in licensing, is distracting academics from the fundamental activities of supporting students, carrying out basic research, and that sort of things." (B45)			
"Yes, they are time-intensive for the individuals. Probably, spin-outs are more time-intensive for the academic staff and the research assistants than licensing would be or very often they are more time intensive, which obviously can have knock-on effects into the other parts, particularly of the academics staff's work. They have the potential to steal time from other important activities of academics" (B46)			
"Clearly, consulting takes time on the part of the consultant, so it's the same as the other activities that we've talked about. There's a trade-off in relation to the way that time is spent." (B46)			
"Well, as an opportunity, I suppose, the cost. If you do it right, you're not doing something else, depending on resources that you have. We have limited resources in terms of staff at the moment, but if we did more licensing, it would also generate income. It's kind of a chicken and egg thing" (C71)			
"Again, it's all about balance. If the university buys expensive equipment, it's got to be maintained and the maintenance costs can be high, so having external income is helpful. On the other hand, having something running 100% capacity means there's less flexibility for the university and clearly the equipment won't last as long and it's got to be replaced. There's a balance between all of these things, mainly we are here to, obviously, provide the facilities for research but if there's down time on it then, of course, it's a good use of time." (B21)	Having industry use equipment is good, but also increases maintenance and reduces lifetime		
"Cause they have to publish. And we can't say to them 'no don't do that for two years'. So the best we can kind of do is say 'okay, we'll file a patent application and then you can go ahead and publish'. But, like I say, then that leaves us very short on time to identify a partner." (B42)	Tension between publishing and patenting for academics		
"It's a difficult task, because their careers are focused on, as you know, on publications and this can be a distraction for a lot of people. But I think that we need to try continue on our sort of slow drip feet that the opportunities and chances that you can do well with your research and prove that you could, if you just published it. That's through examples, case studies, seminars, workshops, that sort of thing." (C71)			

"Academics, especially research-active academics, are dually keen and likely so to publish, because in publishing they raise their academic profile, they become... it helps them in their academic progression, they're more widely recognised in their field, but there can be some contention between the publishing related to intellectual property and our ability to protect it. So there can be some constraints in an academic to withhold publication in order to protect intellectual property that's been developed." (C81)		
"I suppose at some point you may run out of academic staff and that they have all gone off to run spin-outs. But I think, no. There will always be the desire, I think, for them to be entrepreneurial. The only real trade-off is that being entrepreneurial does in some cases conflict with the academic mission as well. There is the balance between having an academic career or doing an extra-academic enterprise or taking that link out of the university to a spin-out company for however long. There are quite a lot of processes around where academics can buy out their time to be able do that as well. There are various secondments, various other things available for them to do that, there are the enterprise fellowships and other institutions." (B31)	Any incentives must not compromise on research and teaching responsibilities and trade-offs must be balanced	Limits and challenges to internal marketing
"One of the things, if you're looking at increasing royalty rates and return back into university, you've got a potential of creating academics who are generating more income in that area which maybe then distracts them from undertaking some of the other activities. So we need to ensure that whatever incentivisation programme is put in place for academics that it's got the appropriate buy-in on the academics side of things, because you wouldn't want 95% of your academics chasing commercial funding, when, at the basic level you've got an obligation to students across the university and the student experience is what drives the university's base." (B45)		
"I think we would like people who are not naturally entrepreneurs, who would still to be incentivised to participate in industry engagement. Impact might be important, but we do need to think about how do we motivate and reward those people, who are not naturally entrepreneurs." (A12)	Incentives work to a degree, but personality and mentality of academic play and important role too	
"We do need to find a way to incentivise others, because we can't grow our objectives and outputs, if we don't have participating academics. Academics need to be incentivised to want to play." (A12)		
"I don't think, if you want to spin out a company, if you would only do it if you were released and paid full-time there, you're probably not going to get too far, you've got to have a bit of hunger and feel a bit of pain, really to do spin-out companies." (B21)		

"I think the best do have it, naturally. They're personality-wise, just maybe the way they've developed their career, you know, they might have been mentored by somebody who's got that as a... how they get about doing things. You know, you can incentivise to a degree, the inclusion of impact within the research assessment exercise I think has had an important bearing in terms of how academics perceive what they are as academics, but generally people get promoted on the basis of, you know, four star research. That's going to be your number one driver, the number one driver are research excellence drivers as opposed to impact and research collaborative/entrepreneurial drivers. They are different." (B43)		
"I think, sometimes we try to push incentives at people, who really... they feel as if they should be doing it, but actually, they are probably better off not doing it and focusing on something else. So, I think, you can incentivise something and then you get perverse behaviour on the back of it, rather than it being necessarily beneficial." (B43)		
"I think, the key is to finding the right incentive for people because not everybody's motivated by the same thing. It is a difficult one." (B45)		
"There was no incentive for anybody to do it. It made it very difficult to try to encourage people to do consultancy, when there were no rewards for it at all and no kudos really in the departments for doing consultancy either. [...] None of that goes to the consultants themselves, or their... in any way, either the consultants or the departments. There's a real lack of incentive that we need to try and overcome. I think, if we can crack that, we should be able to increase the consultancy." (C71)	Individual motivation is not enough if there is no support and no incentives at all	
"We're working towards that, we don't have them. There's been one or two attempts at it, but we don't have a formal policy yet." (B21)	Benefits (financial, career, etc.) of all activities must be clearly outlined	Provide the right incentives for academics
"so then you can't incentivise them and they don't know if they got a particular activity, should they do it as a consultancy or as industry or collaborative research or as.. You know, what is more valuable to them in terms of, what financially, but in terms of their career. None of that is clear, so it's not possible to incentivise people. That's a big problem, but we are working on it." (B42)		
"I think simplifying the financial treatment of consultancy would be desirable, so that it is much more transparent. I think making it work, if you like, the new guidelines of consultancy actually making them work somewhere or another as opposed to them just sitting there and nothing really having changed" (B46)		
"For individuals, the PI would take 50%, but ultimately the purpose of the idea is that in the event that it's licensed the financial return to the academics is relative to that percentage split. That's an incentivisation." (A11)		

"There's an incentivisation, this much I do know about consultancy at [this university], there's a direct financial incentive for the academics, who consult and, as far as I know, the split is still 70/30. [...] The 70% of the academics can be taken in two ways, it can either go into a pot in the university for conference trips, or employing a lab assistant, or whatever. Or the academic could take it in their salary, but if you take it in your salary, then they get taxed. But they still benefit. [...] In a very short period of time, you get a financial benefit back, whereas a licensing could be three years before anything is negotiated and it could be another three years beyond that for them to see any financial return." (A11)	Financial reward from licensing and spin-offs as well consulting probably the main incentive		
"My understanding is that the deal would be the multinational would pay X and the amount that would be dispersed between the inventors would be X minus what the university would take. Let's say the university would take 10% as an administrative charge, the remaining 90% would then be split accordingly 50%, 25%, 25% between the academics." (A11)			
"Yes in that we provide support to them and they've got the opportunity to have an equity in a company, which may be very, very valuable. Likewise we give them 60 days to earn consulting, 60 days, a thousand pounds a day, where they keep the majority of that money is quite healthy increase to your salary, which is often already a very generous salary and benefits package. There are all those kind of incentives." (A12)			
"So it brings incentives and to academics to do more impactful work because they get a reward, but we're not charged with sort of making a really high income from licensing." (B21)			
"We're trying to encourage them to do it because it adds to their academic career rather than about making money, but some people would only do the extra work if they get bigger payment." (B21)			
"We have a few academics who are driven by financial return in terms of licensing" (B21)			
"That will, of course, be motivated by money, reward, I am pretty sure that if I have the potential to develop a multimillion pound spin-out company that could interests me." (B31)			
"Well the are also eligible to get money from the funding back from the licensing deals that are done." (B41)			
"Yeah, so obviously, if they're spinning out a company, they can hold equity, they also do, as inventors, get a share of royalty and that is set, that is one that is transparent and clear, you know what an individual will receive based on the royalties coming in from a company" (B42)			
"I think the reward structure for commercialisation income is an incentive" (B44)			

"primary incentive is probably money in the pocket at the end of the day, whether that's directly to the academic or whether they chose to divert those funds into their research accounts or whether it's a more indirect benefit, because money has been received into their department." (B44)		
"There are some form of incentives in terms of, I've mentioned it a couple times, the resource allocation model and the way which money flows through and support activities." (B45)		
"Yes, we have both in our intellectual property policy and also in our consultancy policy a provision for our academics to take advantage of some of the revenues that are generated." (C81)		
"In the past, if it's one of our big academics, one of our stars, they've had maybe 50% of their time, still paid, still salary, still pension and they've gone into their company maybe for up to two years and then they come back in again. And that's because we want to keep the academic, because they're very important to us. Obviously, from our junior stuff, you don't get the same kind of deal, but you still get something." (B21)	Flexibility in terms of sabbaticals and other arrangements to pursue entrepreneurial activities	
"I think one of the things, which the university is very good at, it's very people oriented. For example, if an academic wants to take a sabbatical to look at a particular area of activity then, this university puts systems in place which can support those. The flexibility that an employer like Strathclyde shows, I think, is also a very good way of incentivising academics." (B45)		
"And then likewise, their promotional opportunities are enhanced if they're contributing more to an institute in terms of the revenue and sustainability of an institute. The institute should recognise that and they probably do informally but I think it could do with being more formalised." (A12)	Reflected in promotion and annual reviews (reflecting the university's priorities)	
"The incentive the university would look at is really in recognition and promotion, and others, and those are the things, the softer things, that we've not done yet. We've done it for one or two people where they perhaps wouldn't have been a professor but hadn't been because they've been so entrepreneurial, because their papers and everything else weren't pushing them in that direction, but because they've spent time doing something that's really made a big impact, but it's been a bit more ad hoc, we need a bit more." (B21)		
"There is our rewards and promotion process in place for all members of staff in the university, not just academics. I'm not exactly sure how it works, but there is a promotion process linked to personal development, I think, in everybody's job plans with the university." (B31)		

"And then within our promotion processes, and I mean the yearly assessment, then you see also the academics, sorry the commercialisation activities are things, which are... which form a core part of the knowledge exchange element of academic assessment. And indeed, if you go and look at the professors, you can get the professorial descriptions cause we're going though a zoning-process the moment, where academics are zoned into four different categories. And in the descriptive of that, you have to have indicate in a certain number of areas and the knowledge exchange are is those commercialisation, is an actual part of that. So we're using that amongst other things as a mechanism to distinguish the performance of professors." (B41)		
"In the annual development reviews they do have to, you know, say what their KE targets are for the year and how they've delivered them, but I think it's still possible for, I think for career progression, you have to be good at two out of the three of research, teaching and knowledge exchange. So at least it features, but you could still be... if you're really good at research and teaching, you wouldn't have to do any knowledge exchange, but that's a reasonable." (B42)		
"the inclusion of impact within the research assessment exercise I think has had an important bearing in terms of how academics perceive what they are as academics, but generally people get promoted on the basis of, you know, four star research. That's going to be your number one driver, the number one driver are research excellence drivers as opposed to impact and research collaborative/entrepreneurial drivers." (B43)		
"I think that's probably recognised as well within the university structure, certainly patents are given I think a similar weight to journal publications when it comes to assessing the performance of the academic. So it's a good thing if they have patents to their name." (B44)		
"it boils down to priorities, what the university sees as more important, the academic recognition of publication or the commercial realisation of the intellectual property." (C81)		
"So that's very much target based, so some of the rewards would be an annual bonus of x in return for them [generating] income of however many millions pounds." (B31)	Targets set by HODs or Deans, which academics have to consider when managing their careers	
"There is an agreement made as part of the spin-out agreement, we would usually have an agreement also signed of by the head of department, which would agree to an arrangement, whereby the academic puts time into the spin-out. As part of the university duties. That would be acknowledged under citizenship, basically." (B41)		
"Citizenship or knowledge exchange, you could put that into your ADR that you got the spin-out company, that you spend so much time supporting it. And that would be fine, that would be something that we accept as being a good thing to put into our idea." (B41)		

"Now they might come under pressure because, you know, head of department might be saying we need to do more of this type of stuff, generate more income, we need to develop more relationships, in which case that might be an incentive. So, you know, they're managing their career." (B43)			

D.5 External Marketing

Table D.5: Quotes and codes for the ‘external marketing’ theme

Selected quotes	**First order**	**Second order**	**Axial coding**
“Again, using our academic colleagues, if they are away at conferences and they’ve got a portfolio of patents then they are certainly free to go ahead and to take the discussions forward. What I said here is, my experience is that some institutions take an approach where it’s very much driven by the administrative and professional services, which here at [our university] is very much a partnership between our office and the academics. We don’t drag them in a direction, they don’t drag us in a direction. It’s very much a partnership. Quite often it might well be that an academic has been having discussions with companies in the first instance and they bring the opportunity in whereas sometimes, it might be our office has been out or somebody else at professional services has been at it and brought the opportunity in. That’s the way the system works here.” (B45)	Combining efforts from TTO and academics (e.g. when attending conferences)	Centralise coordination, de-centralise execution	
“I think we absolutely need a more organised face, in terms of going out and talking to business and at the moment, it is a bit of a mesh mash, so that our staff in here as we talk to businesses, there are people like Professor [...] who talk to businesses, there are people in the faculties who talk to business, there are people in the industry centres, who talk to business, it is not as well organised as it could be, but I think, in terms of talking to business there are enough bodies, they’re just not as well organised” (B46)	Coordinate the promotion of expertise and capabilities centrally		
“Well, if we could get an agreement across the board that it was a positive thing to do and to be encouraged, we could then try and centralise the service, so that we could have consultancy agreed through one portal, one point, and it could be promoted and managed centrally, which would hopefully mean more consultancy projects coming through as a result. It could be marketed and promoted more as well, as a cross-university thing rather than individual academic partners.” (C71)			
“It means you’ve got to try to be a bit smarter on how you use resources. It’s more online activity, try to piggyback on certain events. If somebody is going out to meet a company to discuss a potential research opportunity, then trying to bolt something on the back of that as well. That is somewhere where we can be proactive.” (B45)	Requires smart use of resources and utilising the existing network		
“I don’t think it is good to run through ‘We want to have more investment’, but you need to be worthwhile, because it’s easy to go out, jet around the place and say, ‘I’m doing this, I’m doing that’ It needs to be worthwhile and targeted and actually making a difference. Meeting the right people at the right time at the right place.” (B45)			External marketing (demand stimulation)

"Also, developing better channels, either through the people, who are... or the companies, who are members of our industry centres or through the likes of our [...] global community that we're going to try to create, developing linkages with people, who can articulate us to the right markets." (B46)		
"It's kind of looking at the opportunities, we have to make sure that these relationships aren't kept between an individual and a business, share these knowledges and these networks" (C61)	Share and expand academics' networks internally	
"Well, as I said before, a lot of the opportunities for consulting do happen organically and, you know, happen through networks. So I think anything that we can do to increase those networks between colleagues can really alleviate any of the limiting factors of opportunities coming through" (C61)		
"So, again, it is just broadening the networks and keeping those strong." (C61)		
"Partly, we try to be more proactive here, so we were trying to identify industry needs. And trying to demonstrate how the university can solve industry needs. I would say there is a greater degree of proactive marketing in this space in terms of trying to generate the industry contracted research. And when we say industry, we also mean the public sector, so like NHS, etc., who are big customer of ours if you like, when it comes to contracted for research as well as other parts of government. It's not just industry, we include public sector in that definition of industry." (A12)	Demonstrate that the university is an attractive partner	Demonstrate attractiveness and expertise
"There seems to be enough demand in industry. I would say capacity, probably, the presentation or marketing of that capacity, because sometimes businesses wouldn't think to work with a university, which can be really, really beneficial because we've invested massively in facilities and assets so they can leverage that. Sometimes that doesn't seem like an opportunity to them and I think it should be an obvious opportunity. There's probably a marketing challenge there, that they don't more readily think about coming to universities with a question. I mean, some industry people do, absolutely, and understand that. I would say, in general terms, there's probably a lack of awareness by industry of the opportunity to engage with universities and leverage all of that, not just brain power, but assets, which includes facilities and things like that. It's hugely beneficial to businesses, I think, so yes, probably too many areas there that need effort." (A12)		
"I think raising awareness of the benefits of working with a university. I think from my own experience, you tend to work with science and engineering-based companies because there are science and engineering-based technologies which have been developed from the university. It's more difficult to work with companies in the humanities and arts side of things, management sciences is a different sale, you can say, to engineering." (B31)		

"the argument there is if you look at the quality you're getting from Scottish academics. It is very much a quality against price argument and sometimes they come to you and they'll say how much are you going to cost and you quote a price and that's just undoable, we could appoint people for that. But again, the argument there is you don't have your own people to do that, again the quality of the Scottish academic base." (B45)		
"thinking about advertising our consultancy capability would be something that I think would certainly be worth thinking about, because I think we've obviously got industry centres now with the Advanced Forming Research Centre, Power Networks Demonstrator Centre, the all have company members in them. These should be almost captive markets that we can sell consultancy to." (B46)		
"All that sort of thing just really getting ourselves out there, getting the connections made and showing the willingness to be involved in collaborative projects." (C61)		
"Show how we can be an attractive partner in these kind of endeavours." (C61)		
"it's stimulating demand" (C71)		
"Another limiting factor would be industry understanding and knowledge what universities could do for them, the majority of businesses will go about with what they do without any reference to universities, not knowing that there is something available to them that might be useful. There is an awareness-raising in industry that there is something useful here that they can take advantage of." (C81)		
"You know, so a company that has never worked with a university before might actually read something in the press and think that was a good place to interact with." (B42)	Effective PR for companies that have never worked with a university	
"With company formation, you can have a good PR head at the start, probably a better PR head at the start than you get it from licensing, which is good for the university's reputation. You have intermediate opportunities as well, to crow about the success of the company and now with our investment powers, which I mentioned earlier on, we can invest commercially in some of this companies and get commercial returns. I would say that probably we have, over the last four or five years, probably we've focused more on spin-outs for exactly those reasons, but I think what has happened as a result of that is that clearly, we dined out on PR and we've had returns from spin-outs, but they're not at the high end of what you might get from a license." (B46)		
"I think that educating industrial partners on usage of intellectual property development in university's and the actual value of it and the benefit of working with the university to develop new products and processes." (B31)		

"The challenges probably, the companies, who just don't get to that point because they assume that the university's going to ask for ridiculous terms. So I often find, you know, when you do get companies that are interested in funding a piece of research, and so they may have an interest in licensing the output but they don't know what that output is going to be, but they often do want to reassure right at the start that when it gets to that point, we're not going to ask for ridiculous royalties. And we manage to assure them that we can even put a cap in the upstream research agreement to that effect." (B42)	Grow reputation for being accessible, having expertise, and being a reliable partner and have more transparent contracts and processes	
"it is the reputation and the expertise and our kind of accessibility, if you like, the appreciation that we are the skills base to come to for questions to be answered and that we are a positive partner in relationships like that." (C61)		
"what you could do, is make it easier to understand what the contracts are, make them simpler and probably more uniform across the university sector. That's something that's being worked on at the moment. Those template contracts for Scottish universities for various different activities and other things like KTPs or working with an industrial partner, where there's a common contract that all the Scottish universities have signed up to. So you don't have to try and negotiate separate contracts with each university, you work with people who come to see that it's as simple as possible, hopefully, and easy to understand. I think there's a preconception maybe that university IP is difficult to work with and complicated and to try to demystify a little bit and make it as simple as possible and that it's uniform across all the Scottish universities, hopefully will help that." (C71)		
"I mean often, we might often be competing for a piece of work with a CRO and, you know, we would make our case on the basis that we were providing more than the CRO could, more intellectual input than the CRO could. So we're kind of used to always arguing actually 'yeah you're right, we're not CRO but it's better that we're not'." (B42)		
"Yes, so back to what we were talking about earlier, one of the things we do very well is the due diligence and freedom to operate. Of course, that to do extensively, particular something that might be global in its applicability, does take time, that could be months, so you want to do a deal quicker, that's one of the things you might compromise on. But compromising on that might expose you later to your patent being challenged. It's not suitably rigorous enough, so there is a real issue and the real balance to try and find there. I think there's a real skill involved in terms of your patent filing, which is heavily influenced by that due diligence and freedom to operate." (A12)	Quick responses and processes in general often come at the expense of diligence, which need to be balanced	External trade-offs
"Obviously, you want to minimise the number that do that. But the unintended consequence, if you go for a pure numbers game, you're looking at quantity, not quality. If that's the road you take, then you run the risk of things dissolving into nothing." (A11)	Simply focusing on increasing numbers can dilute quality	

"It's not the numbers, as I said before, it's the quality and value that we're interested in increasing. Now numbers is a part of that but that's not the end game. The end game for us is the quality and value." (B41)		
"One of the ways to increase the rates of spin-outs is to reduce the threshold by which university would support a spin-out going through, maybe have riskier spin-outs going through. The potential downsides there would be having more failures, having reputational risks for the university, which is always in mind. If the university has 20 spin-outs a year and 10 to 12 of those are failing does that look bad in the eyes of the public? That's one potential downside." (B45)		
"Yes, so we do events. One is coming up in the next few weeks, which is called an AIM day, which is focused on the construction industry. If you look online, you'll actually see the details of that, but what we are actually looking to do is we try to get industry partners to come to an AIM day which is a workshop type event, where we have questions from industry, which during workshop type activity between academics and industry, we're looking to try and solve. But the idea is that out of those workshop type of activities through an AIM day, which is focused on a particular sector or challenge, we give or we create a list of new project or collaboration opportunities. That's proving to be very, very effective way of generating new ideas in addition to the traditional opportunities that there are. Yes, it's working very well. Soon, we're certainly planning to do more AIM days but they got to be focused, they got to be thematic, construction, energy, offshore, renewables. They will be quite focused." (A12)	Dedicated workshops and events to initiate interactions	Initiate and maintain relationships at the personal level
"We're also sort of looking at mechanisms for bringing companies in on problem-solving days, where they come to talk to an interdisciplinary section of the university. So we're not just talking scientists or technologists, but design and psychology and other areas, addressing the whole spectrum of manufacturing and everything training. More engagement in a much more holistic way rather than one-to-one piece on that, although I know that it says research collaborations, but in general strategic partnerships is a good way to increase a beneficial relationship." (B21)		
"the university does things like Engage with Strathclyde, which is specifically designed to bring academics together with people from industry" (B41)		

“The effort that we put in and where we’re trying to recruit staff into is the marketing and going out, more external facing than we’ve been for the last few years, actively engaging with companies, so therefore the licensing income. Number of licenses will go up and the collaboration will go up just because of the network. That’s where the effort needs to be. I mean the academics can do it themselves, but not everybody does them. We tend to need footsoldiers going out and being really close to the companies and picking up what they want.” (B21)	Demonstrate efficiency and understanding industry requirements through personal contact	
“Universities raising awareness of what they could do, as well.” (B31)		
“coming in and meeting the group that’s going to do the work and getting a general impression that they are efficient and understand industry requirements.” (B42)		
“We used to have here a team, it was a project, it was a SEEKIT project that was funded through the Scottish government initially, and then we got ERDF funding for it. It was designed to not only to do this for research, but consultancy and commercialisation, licensing and everything else. We went out, tried to promote externally to businesses, what we could do, we’d organised sector-specific events, where we bring experts from UHI or from other universities even into the local area and talk about something that was relevant to the businesses there, and try encourage collaborative research and contract research.” (C71)		
“I think doing more of what we had done in the past, which was organising the regional and local promotional events to tell businesses, because quite a lot... the majority of businesses in our reach don’t consider universities as a business resource. They don’t see that, and it’s quite a revelation to many of them that the university would do this kind of work and help businesses, even small businesses, and so there’s a big job to be done there. [...] You find a lot of other agencies around entrepreneurship and innovation, who are all trying to reach businesses, but from our region, which is bigger than half the size of Scotland’s landmass with all the highlands and the islands as well, it’s a difficult area to get to. Unless you go out and do things locally, people will not... If you say you’re going to put event on in Inverness to cover the highlands and islands region, that could be a couple of days of travel to get to. You need to go out to where the people are, if you really want to get across and get to all remote rural, isolated areas, which is a large part of what our region is. If you want to peg those down and get those businesses engaged, you have to go to them.” (C71)		

"We do promote our licensing opportunities on the university website. We also promote them through universitytechnology.com, which is a pan-Scottish technology licensing website. I think, in all honesty, that web-based services haven't been very successful for us. We don't really tend to generate a lot of licensing enquiries from these web services. And we've had the same experience with the free ones as we've had with the ones that you pay for. I don't think they're great at attracting would-be licensees." (B46)	Online platforms do not work well for attracting licensees	
"I think they'd also be very happy to travel with, you know if we had a travel budget, to come out and meet the companies as well. Which maybe be the ideal kind of pairing of an academic with a commercialisation person to go out and meet the companies where they are. You know, demonstrate some sort of commitment and everything like that, that's needed to build up the trust and everything." (B42)	Pair commercial manager and academic and visit companies to build relationships and trust and show commitment	
"Well, you know, the people transfer is probably how to do it. You have come across programmes such as the Knowledge Transfer Partnership programme, that's one of these, which capacity is developed in academia and then translated into an industry environment. Having more sponsored PhD students around the likes, I talked to you about the doctoral training, having more companies engaged in sponsoring of that activity, I think would be good. Embedding those types of interactions in undergraduate degree courses used to be common, people moved away from it, we need to move back to it again. I think that's important as well. So, the people transfer bit is certainly the way to enhance understanding of both parties, but it's... there are barriers there, because, you know, if somebody from industry wants to spend a period of time in academia, then they're taking out the job for a while and that might not feel like a good thing if you're trying to progress through your organisation, you might become invisible for a year when you don't want to become invisible. Likewise in academia, if you're taken out of front-line research in terms of publishing papers, for a while then you might feel as if your career prospects are going down." (B42)	People transfer (KTPs, sponsored PhDs, integrating industry in UG studies, etc.) to build relationships and enable collaboration	
"So again, that's in pharma cause that's at least where my experience comes from, you know, you never secure a deal via a cold pitch to a company that hasn't previously known you. It works because you have a dialogue with them for like I say three to five ears, long enough to kind of build the trust that you've got something of value to them. So, more university staff in general, I think, need to be having more of that dialogue, more frequently, for a long time and if you want to increase the levels and then I suppose some of it will come about just because Strathclyde has a higher profile." (B42)	Starting a dialogue with companies and nurture a relationship over years	

"Work, work with industry to understand industry's needs. On the kind of five, ten and 20 year time scales and then develop propositions. Working in partnership with industry and with public sector funders like Innovate UK, Scottish Enterprise, the research councils, to come up with propositions that can then become centres of the future and that's absolutely, you know, a really big part of what we do." (B46)		
"Of course, international companies are geographically far away from here and, therefore, you have to try to find ways to get the companies on the hook. I regard soliciting of licensees as quite an inefficient, hit and miss type of process that's greatly enhanced by having an academic, who really knows the marketplace that they're interacting with." (B46)	Hard and resource intensive to start conversations with geographically distant companies	Limits and challenges to external marketing
"we don't have any resources for pro-active marketing, by which I mean going out and about, which is what you need to do, is to travel internationally and speak to companies frequently, you know keep that dialogue going. We got no resource to do that, the exception to that is for pharmaceutical technologies, where we've kind of historically had a profile in the pharmaceutical community that we've regularly attended, they have bio-partnering events, which are very efficient. So over two, three days you meet 20, 30 companies and most of our licenses in that space have come from attending those events." (B42)	No resources for (international) active marketing	
"But, as far as I can tell, they are very specific to the pharma sector as well, as it seem to be anything like it for technologies within physics or, you know, software packages or anything like that. Probably because the applications are too broad, but that's kind of the problem, the resource. You need a lot of resource, it takes a lot of time to do licensing and those things aren't compatible with sort of academics' ability to progress their careers nor with outcome agreement targets that we're signed up to." (B42)		
"Yes, I think anybody would say that marketing activity is great when you've got the resource base to follow up. Once we are proactive in terms of giving online presence, working with other Scottish universities through ut.com, where it is a shop face for Scottish universities' technologies, we would always like to be more proactive in that area, but unfortunately, in the current environment, that's not something which we're able to do." (B45)		
"The system that we had before worked a lot better than it does now, but we had a lot more money, so we had a budget to promote and to stimulate demand from businesses. It won a European Structural Funds award for best practice, so it did have an impact. I don't think that what we've got now, has fully replaced all the things that that unit did." (C71)		

"One of the things that we've often talked about is basically getting out on the road, identifying cohort companies that... Much the same way you do as a sales executive, you've got your existing customers but you want to grow the business, so what do you do? You need more customers and the quickest way of growing your customer base is non-organically in the sense that, say an institute, you can have ten customers, do you just keep besetting around that institute to get another five or do you start talking to a completely different company and get another ten? So that kind of business development side of things that we just don't have time for, by and large, we don't have time to do. For the BDEs to get out on the road more and identify new companies to work with and new opportunities within those companies. We talk about it but it very rarely happens." (A11)	Active scouting of new opportunities for collaboration and engagement	Proactively identifying new opportunities
"We are proactively marketing, and there's different parts to that. Proactive also means trying to identify what our credentials, capability and capacity comprises. And once we've identified, what the capacity comprises, we proactively market that to targeted businesses. Which means we need to do quite a bit of industry analysis to understand what the demand is and how we can connect with that demand. But we have resources that are dedicated to that." (A12)		
"The sort of things that we're doing, you know, by working with the academics finding out, where their expertise is, where they're leading and promoting that to industry, engaging in different ways with industry as well as standard partnering and using IP as a leverage." (B21)		
"I think there is a job for the universities in the reach out activity to companies, making ourselves more approachable, and not just be seen as centres for a teaching undergraduate students and also post-graduates. Making ourselves more open to working with industry and the actual benefits of working with a university department." (B31)		
"at this university, because we spend a lot of time bringing our academics in contact with industry that also, in principal, increases their awareness of industry challenges and, therefore, should increase the number of potentially commercialisable ideas that they are producing." (B41)		
"we're also looking for opportunities to get involved in external networking and relationship building and kind of open opportunities for collaborative research" (C61)		

"I think we could do more in terms of promotional activity, going to various workshops, trade fairs, sit at conferences, where the people who are looking, businesses looking for our expertise would be, for example, All-Energy or Marine Renewables in Glasgow. We could be doing more of those kind of events or promoting, what our expertise is to companies. We could also be doing more locally, with local companies and, generally, just within our region, getting our message out that we have this expertise and it's available. At the moment, we tend to be more reactive rather than proactive, because of funding issues. We tend to rely on things like Interface, which I don't know if you're aware of Interface, but for enquiries coming through and we'd react towards that rather than trying to stimulate the demand ourselves, which requires budget to do that." (C71)			
"Again, I mentioned earlier on about the likes of Interface and these other matchmaking type industry organisations. A lot of work is going on identifying for them from the university base what activities are being carried there, so the themes and the areas of technology, so they can be cascaded out to the industry base and the business sector as well, to kind of sell some universities' offerings I guess for them. [Our university], a lot of work is being done again at the ground level identifying strategic thematic areas which tie in with real-world problems, the themes that Strathclyde has: future cites, energy, medical technologies, these sort of things, trying to really bring into a cohesive approach, so that we've got a more complete offering for industry." (B45)	Identifying areas of expertise to feed into intermediaries such as Interface		
"We also have a number of relationships and agreements in place, where we share our IP portfolio ongoing with a number of partners, who are looking at 'well, is that investable, is that early stage start-up business that could be worth investing some amount of money in, taking equity in for a future payout' and university would have equity within that as well. And we're looking for the value to grow and at some point in the future, get some value for our equity in those opportunities." (A12)	Share IP portfolio with partners to identify commercial opportunities		

D.6 Reputation

Table D.6: Quotes and codes for the 'reputation' theme

Selected quotes	**First order**	**Second order**	**Axial coding**
"I think it's a combination of all of those things. So the university's undoubtedly got a very strong reputation. There's been work very focused on collaborating with industry and that leads to interest, natural interest from larger companies in particular in engaging with us." (B41)	Combination of different types of reputation, institutional reputation attracts larger companies, partnership are based on individual performance alongside institutional support	Combination and compensation between different types	Reputation
"So the fact that they are more likely to come here and knock on the door is one thing that follows from the institutional reputation. Once they started the project, they would continue and they will expand that, depends obviously on the performance of the individuals and their relationship they build up with those individual academics alongside the continued institutional support. Again, there's some nice cycles there." (B41)			
"I suppose it's both of those. I think, Strathclyde is a place of useful learning, it's an applied university, it's not doing so much basic research, it's much more at the problem solving, industry-engaged end. And you see that with some of the long-standing collaborations and research centres that the university has, AFRC for example, where research is being carried out, sponsored by industry and sometimes those ideas that are being generated are quite basic and are quite far from market, but often, they're a little bit more downstream and developed and you're solving specific problem. But if I had to place Strathclyde within a continuum of basic research to applied, it would be definitely towards the latter and I think that's what it stands out" (B44)			
"Yeah, absolutely. Yes, I think our entrepreneurial reputation still has some way to go to meet our own aspirations, but I think we are such a strongly known as our research-intensive areas. Certainly, what we would like to do is grow the reputation that we have in terms of the innovative way that we can influence projects to make them a little bit different." (C61)			
"And like you say, in terms of sort of top lists of companies worldwide and Strathclyde doesn't feature really, so it's got to emphasises that it's entrepreneurial, practical abilities, but I think that message actually is getting across." (B42)	Compensate research prestige with entrepreneurial reputation		

"But beyond RKES, I'm not so confident, but I would be pretty confident that RKES is seen as a good place to do business and that we facilitate these interactions and we do it fairly well and we're flexible, which a lot of universities aren't. I mean, in a sense, because we're relatively small, I suppose, we have to be competitive, we have to be flexible. Perhaps your Oxford's and Cambridge's can take a much harder line in commercial negotiations, because of the kudos, because of the extremely high, world-class research base that they have that is not being pejorative about Strathclyde but those universities are arguably in a different tier. So I think Strathclyde has to be a little bore carny, a little bit more flexible and keen to do those deals. But as a result, we've build up a very good understanding of what works for industry partners and what doesn't." (B44)		
"If you'd ask the principal, he wants all of those. (laughs) So, I think, it's hard to pick one in this. Every principal is got to say, you know, I've got research excellence and dot dot dot." (B43)	Universities strive for excellence across all types of research	
"Yes, I do think it makes a big difference having an entrepreneurial culture within the university." (B31)	Entrepreneurial reputation and connectedness with industry is recognised externally	Entrepreneurial reputation
"Also externally, in the community, that is recognised as well. Maybe the tag line is not, but it is very much seen as a... I knew somebody who went to Strathclyde, who's now working for British Rail, or, you know, British Rail at the time, Virgin or whatever it is these days. Anyway. So it is seen as a very locally, well-connected, engaged university. So Strathclyde definitely has that." (B43)		

"Huge. I would say that, I can only speak for ourselves, I think Strathclyde has a long-standing reputation for being industry friendly and industry engaged, we have a good reputation for being entrepreneurial. Since Jim MacDonald became principal in 2009, we've had someone at the top who very much is an embodiment of those types of values and who has projected Strathclyde onto the UK stage, particularly with a great deal of success. That makes a huge difference. I don't think GSK, for instance, we have got two of these strategic partnerships with indefinite industry centres, I don't think GSK would have had Strathclyde in the top 20 UK places they would want to interact with in 2006, but we're firmly in the top ten now and I believe that a huge proportion of that has has been to do with the way the university has projected itself as industry friendly, willing to try things maybe the other people aren't, which comes back to the kind of the entrepreneurial and innovative piece. So, for instance, you may have spoken to Billy Kerr in your exercise, I don't know whether you have or not, but he's an Associate Deputy Principal. There's a joint PhD programme with GSK in sort of medicinal chemistry, that's now extended to biological chemistry, so it's an up-scaling, up-qualifying for GSK staff. Strathclyde did that and we wouldn't, as I said, in 2006, we probably wouldn't have been on GSK's shopping list, now we are a central partner in something like that. So reputation is huge." (B46)		
"I think being Entrepreneurial University of the Year was, yeah that was used as way to bring companies in." (B42)	Entrepreneurial reputation from Entrepreneurial University of the Year	
"I don't think people come without that, past experience and reputation in being able to do business. Companies saying that we're easy to work with and we're industry-friendly is important." (B21)	Entrepreneurial reputation from past interactions	
"I think that if you get a reputation for being easy to deal with then companies will come back. If you carry out a piece of activity with a company and, notwithstanding what I said before about having great academics, then if the company finds the university difficult to deal with contractually, they will go elsewhere. Or they find different ways of doing it rather than going through the university, so we need to, again, reflect on what the requirements of a piece of consultancy are, it's not about generating new intellectual property for the university, it's about getting out there helping the client with their problems, helping the client resolve their issues. It's a very different approach to research and the terms and conditions need to reflect the requirements of the client." (B45)		

"I think that certainly Strathclyde has a are real can-do type of reputation across the business world. I think that people know, industrial partners, or business partners, or external partners, see Strathclyde as being someone who's easy to do business with, someone who's pragmatic in approach, somebody who delivers when they say they going to deliver. And I think the reputation is key. To an extent, it's a reputation the academics drive but also courses and institution. Strathclyde's got personality that people like doing business with Strathclyde." (B45)		
"And, obviously, if people have experience with working with you, then, of course, reputation is going have some sort of an impact in terms of identifying you as a potential collaborator." (C61)		
"the networks and experience of how people work together, that will obviously kind of feed into it as well, the experience that people had working with you in the past." (C61)		
"I hope that the Innovative University, that Reuters thing, will make us more interesting for people who haven't known us, but we had to see that, (laughs) that's new." (B21)	Awards that signal innovativeness and excellence	Research prestige
"Then I think it has been a good strategy to partner with some of the more prestigious, you know, from that point of view, universities like New York University, that's been a good thing to do as well. So I don't, I mean I don't know how it's perceived internationally, you know which people in what countries would know how we're read before." (B42)	Collaborations with prestigious international (research) universities	
"I think, you will obviously be known for your experience in a particular area." (C61)	Reputation in certain scientific areas	
"I think it does have an impact. I think that a lot of businesses like to use a university because it gives them that independent input, at least seen to be an independent, more kind of critical eye on something that would help them justify what they're trying to prove. Any university, in that respect, would be good, but then there's also specific universities that have high levels of expertise in certain areas and certain disciplines, and the kudos of that is important for companies." (C71)		
"The university has a fantastic reputation globally. There's enormous amount of brand recognition. We in Informatics Ventures benefit... Let's say, we go outside Edinburgh, go to London and start talking about Informatics Ventures... 'Alright, okay, that's interesting' but you drop the University of Edinburgh in the conversation, 'all right, okay'. So that kind of brand recognition. It's also because industry recognises the quality of the research that is across the road. That would be the primary driver in those cases, the research reputation of the School of Informatics benefits the university and the university benefits the School of Informatics. It's very mutual." (A11)	Research prestige and REF, recognised by industry; although basic research poses other challenges	

"excellent research, the challenge there with industry, of course, sometimes is fundamental research is a long way from being applicable, but that varies across the university. Within the School of Engineering, we've got institutes that are doing some really good applied research and therefore it's easier to engage with industry with those particular institutes. But first and foremost, it is reputation, but our reputation varies from being world-leading, world-class research, all of our colleges appear on that category, which is fantastic for reputation purposes, but fundamental research is a long way from being transferable to industry, it is a long way from being applied. That becomes more of a challenge for us in that regard but reputation is hugely important." (A12)		
"Academic reputation's really important." (B21)		
"I think it would be the overall reputation of the university in our cases, specific parts of the university. For example, if people are looking for expertise in lasers, I hope they would generally come to Heriot-Watt, same thing for chemical engineering as well where we are ranked number one in UK after the last REF exercise." (B31)		
"REF performance and skill areas, and things like that, I think that's kind of how businesses may identify you in the first instance." (C61)		
"Those that work with us tend to come back time and time again and work with us again, because we typically provide a very good collaborative research delivery experience, if that makes sense." (A12)	Word-of-mouth effect and learning among companies from past experiences	Word-of-mouth among companies
"We get lots of repeat business with that and those companies have gone out and spoken at tech transfer type conferences and other industry conferences and said that Dundee model works in terms of engagement with industry. It's simple, you get good business support as well as academic support that's trustworthy, negotiating the contracts and if you have any issues, you get good follow-up and so reputation for being good at collaborating with industry helps, obviously, particularly in the pharmaceutical sector." (B21)		
"Yes. As I say, people like GSK advisers have stood up at international companies and said Dundee's really good at this, at working with industry, not just the science, but just the doing it. Dundee knows what they're doing, and they've brought pilot schemes to us because they say if it won't work in Dundee, it won't work anywhere, because they're flexible enough to do this. That kind of reputation really helps. If you're able to say to somebody we've done all this before, we've managed to work with six companies in a consortium, everybody signed the same agreement and yet, there were Chinese walls between them, and we kept them, delivered them, yeah, just like an industry. If you can do it and other people say you can do it, it makes a difference." (B21)		

"I think that it also has a lot to do with working with industrial partners as well, if you got a good reputation from working with industry, generally, you get more work with industry as well if you can prove that you work together on collaborative projects. Success breeds success and this can lead to further reputation." (B31)		
"And I think, there is some sort of word of mouth effect in the sense that, you know, a good amount of companies will say that heard that Strathclyde was good to work with." (B42)		
"I mean, from where I sit within RKES, we're known to be flexible in the way we do business. We're known to be, I think, good at licensing a technology, good at spin-out creation. We understand what companies need, we understand the limitations that companies might have and we work with companies to gain a position that is mutually beneficial. We know how to do that, we've got lots of experience doing that and I would be surprised if that wasn't widely known and self-reinforcing." (B44)		
"Yes, absolutely. You see it sometimes when you get feedback from innovation centres on projects you have done through them, where a company will come back and say to the innovation centre, not to us, 'That was great, that went really well.' Or maybe that didn't go so well, it comes back to us that way. Certainly, you do hear a thing going on about, sometimes with maybe start-up companies, there's a perception that universities should make intellectual property free for them, free of charge. There's definitely a community around that does talk to each other, outwith the university. They do discuss the approaches that universities take. Again, that's why we need to be very careful of our reputation. In short, we can see it's about delivering taking things where we say we're going to." (B45)		
"Yes. I think... obviously bigger companies, especially the kind I've been mentioning, have very many operating divisions and sometimes even the operating divisions inside the company don't talk to each other very well, but within a given community, for instance the pharmaceutical manufacturing community, they do talk across companies. So, for instance, with CMAC, I would say the fact that GSK and whoever else it was, Novatis were in, probably as a fact an AstraZeneca and all those companies." (B46)		
"And I think, as I said before, the networks and the expedience that others would have had in contracting with us or being part of a project with us and the reputation that we have as being good to work with and the solutions that we provide." (C61)		

"Yes. I think, inevitably, there would be those that have a great experience with working with us hopefully, and, you know, which will be willing to recommend us on to others. Certainly, that would be true for collaborative partners, etc., so certainly, that would play in. I'm afraid, I don't have any personal examples to bring to that, but certainly, word-of-mouth is always powerful tool and that's why we would be keen to be positive partners in relationships that consultancy, in collaboration, etc." (C61)		
"I think it's a big one, back to the idea of raising businesses' awareness of what's available to them from the university. If they don't know any about the university or worse, if they heard bad things about the university, then of course they're not going to take advantage of what's here. So, I think reputation is a big one." (C81)		
"Potentially, I don't have a great deal of evidence to back that up but intuitively, it does sound like something that you could take advantage of. I mean I know, the businesses we deal with enjoy the experience and I'm sure the share that with others. Not enough, they could some more but yes, I think that's a factor too." (C81)		
"If there is it's probably only as a result of staff moving between employers, so they would carry information with them, you know, 'when I was at such and such a company, we worked with Edinburgh University, now I'm in this company and we thought about working with Edinburgh University'. I imagine that happens. In terms of people between companies, suggesting 'we work with Edinburgh, you should work with Edinburgh', remember, businesses are hugely competitive organisations, so if they are doing something, which is giving them a competitive advantage, they are unlikely to really promote it to other competitors. But if they do, maybe they do, I don't think so. But then having said that, we've got maybe 20 different industry partners coming to our next AIM day. In that effect, they are actually open and sharing to a degree and we've organised the event and we've invited them to the event. I think, it's a generalisation, but it's probably unlikely other than individuals moving around and sharing contact information and past experiences with new employer. Definitely happens." (A12)	Word-of-mouth enabled by people moving between companies, not companies actively sharing what gives them a competitive edge	
"Yes, I do think that that makes a difference as well, especially within a small country like Scotland. We have got a lot of sort of micro-climates almost, also micro-networks, I think, so if you have a good experience of working with a university... or if one company has a good experience of working with a university and has a positive outcome from it, then, I suppose, it does get round the business community quite quickly. The same can be said for negative experience, as well." (B31)	Word-of-mouth works very well in Scotland	

"And definitely, the word of mouth thing does work very well in Scotland. Plenty of cases of companies saying that they did just go to I don't know Scottish Enterprise or whoever and were pointed specifically in Strathclyde's direction as being easy to work with. Maybe they say that to all universities they end up with." (B42)			

D.7 Partnerships

Table D.7: Quotes and codes for the ‘partnership’ theme

Selected quotes	**First order**	**Second order**	**Axial coding**
“What has been said to me is the fact that there is so much support here for university-industry collaboration, means that it’s more of an expectation in the UK than possibly elsewhere that industry will get it at low cost whereas industry elsewhere is sometimes prepared to pay more for that. You may be aware also, I mean it’s just a private digression, that there are people in Scotland, who really believe that actually we should give away, universities should give away all their IP to Scottish companies. [...] Of course that would be illegal under European Union law and national competition law. So that’s not something that’s going to happen.” (B41)	Expectation that IP is given away cheap or for free and universities are too greedy	Developing the cultural aspect of organisational proximity	Partnerships
“And as far as I can tell, I think that’s where that stems from, is the people in the companies who think that universities have no business in, as they see it, defending IP, just flowing into their company. But of course, what they often sort of fail to realise is that even if universities did allow flow of IP into companies, why should it be their company versus any other that gets it? So there’s still a problem of who do you decide to make that transfer to.” (B42)			
“what sometimes happens is that organisations are maybe having a bad experience across sectors somewhere else they come sometimes with pre-conceived ideas and to be honest, we all have had that certain experience with a certain group or a certain type of company, it can be easy to go in there being somewhat blinkers. Sometimes, some people feel that because universities are seen to be publicly-funded, then the university has got an obligation to make the technologies available free of charge which is maybe slightly an unrealistic expectation. Universities do their best to make technologies available at very reasonable terms. Again, as I was saying, commercial money coming back into universities is the type of money that we... or one of the very few sources of money that we have flexibility on how we can allocate that and supports. So if we’re saying universities should be making technology free of charge because they are publicly funded, I think it’s slightly disingenuous.” (B45)			
“there’s been a perspective that universities are very difficult to work with in terms of licensing” (C71)			

"So that's definitely a useful thing to know, what are the sort of political/philosophical views of the person in the company, cause that affects, I think, how you start the negotiation. Basically, you have to do a lot more explanation of what our role is and the fact that the IP does have value and you don't try and not to over-inflate that value but we still should have a discussion about what we receive in exchange for it." (B42)	Important to know the other side and their political and philosophical worldview in negotiations	
"I suppose I find it increasingly odd that, you know, you can have two companies that sort of on the surface don't seem particularly different and yet, they can have widely different views of how the university's going to behave. You know, for some, it's not a problem at all to negotiate with us, as they would any other company and that case others... yeah, either assume that we're going to do something that we would have no intention of doing or like I say, they are the ones that think they should be able to have the IP for free." (B42)		
"I do think, there's a lack of understanding of how expensive research is. If you're depreciating equipment, they cost many billions of pounds, if you're having to put up buildings to house that equipment, if you've got academic staff, who are, you know, they're not in the banker's (laughs) levels of pay but they are by and large reasonably well-paid. It quickly adds up to quite a sizeable bill and, you know, companies typically need make calculations about whether that's going to take them to the next step in whatever they're doing." (B43)	Lack of understanding among companies how expensive R&D is	
"You always hear commentators out there and they've had a bad experience for whatever and maybe that's because expectations were too high on their part." (B43)	Research takes time and does not follow a linear path, so managing the company's expectations during contract research is crucial	
"So by the very nature of research can take a long time to come to any conclusion. There will be times when the research project might go into a direction that the company is not happy about but that's the way the research goes. I think trying to balance the company's priorities of time and money, just the nature of research being as it is" (B45)		
"It's quite a cyclical kind of thing, and it's all based on relationships and experience." (C61)	Experience and relationships are key, activities are cyclical	Developing the social aspect of organisational proximity
"Generally, the research comes first, then there might be a patent that comes out of that and there might come a spin-out company, that spin-out might do more research with the university. So it's maybe circular, if we're going to look at it that way, but I think definitely the search activities come first." (B31)	Not a linear model, interactions and relationships form in many different ways	
"I mean it's not a linear model of engagement, you know, you don't go from a contract R&D to spin-out and it's a nice progression. There is all shades, basically, so yeah." (B43)		
"There's definitely not a linear flow between each of the activities, it's not as astounded." (B45)		

"I think, consultancy could, but it doesn't for the reasons that we've talked about. It's relatively recent that people have been asked not to do private consultancy. I don't think the links are that strong, I think if you did research collaboration then you might license something else from the university, but generally, no." (B21)	Relationships are build on trust, which can be developed in many ways	
"Things can go in any order." (B41)		
"The point is that activity with companies is driven by personal contacts and by personal trust. And that personal trust can be build up in lots of different ways." (B41)		
"Yes. Yes, definitely. We often sign, particularly in collaborative deals with industry, that may not be for a lot of money but it's part of a bigger picture of what may happen down the line. It can be a pre-stage to larger deals further down the line." (A11)	Collaborative research leading to further interactions	Examples of temporal order of activities
"so we're very much focusing on collaborative research, and contract research as well. But, I suppose, through those two things we can also leverage the other aspects as well because they're all linked to some extent or another." (B31)		
"collaborative research leading to licensing is one. I suppose that's the main connection, isn't it" (B42)		
"bilateral collaborative R&D, which will take you so far but once that over, that's it, it's over" (B43)		
"you typically see IP being generated from collaborative research. That happens quite often and when that happens, the institution, if it's a company that has been collaborating, will quite often become the licensee of that technology. Often within those types of collaboration agreement, the company will be given an option to evaluate that technology and ultimately acquire a license under the technology. So in terms of a chronology, you often see licensing coming after collaborative research." (B44)		
"for me, where I sit, is between collaborative working and then license opportunities. And there's a clear causal link there, I would say." (B44)		
"collaborative research that would then lead onto consultancy, possibly also to contract research." (C71)		
"Once you've engaged with a company through, say, contract research or a collaborative research, they're more likely to come back and work with you on other things, including consultancy, for example, but with your additional contract research as well." (C71)		
"Some of the collaborative work can lead to patenting as well and go on to do spin-outs or licensing as well." (C71)		

"The other thing that's good about consulting, consulting is quite strategic, so it's a small piece of work with a potential industry partner. It gives us a relationship and the idea is, we might be able to nurture that relationship so we can achieve a bigger collaborative project in the future, and so that's the other strategic reason to be very interested in consulting." (A12)	Consultancy leading to further interactions	
"Well, consulting, as we talked about, strategically we see consulting as a good initial step in terms of developing a new relationship with an industry partner and we would hope to nurture that relationship, such that it becomes more strategic and higher value, potentially a big collaboration project over time. Yes, often consulting is a first engagement with people. Yes, that's probably... if that were to precede anything its probably consulting." (A12)		
"Consultancy generally is very much a transactional process. I think there would be opportunities to convert these to much larger, longer term consulting services or teaching as well." (B31)		
"And presumably there is as much consultancy then lead to collaborative research or consultancy demonstrates the need for something that then can be realised by setting up a spin-out company." (B42)		
"Although, you will occasionally see companies maybe come through to the university for small-scale consultancy contracts, maybe through one of the innovation centres or through Interfacing and one of the voucher schemes to maybe carry out a small, 5000 project at the university. Goes very well, so slightly larger consultancy project, then through to a piece of collaborative research and then there is some technology here, which is available for patenting, goes into licensing." (B45)		
"I don't think I'm setting there necessarily categorising, you know, the interaction, I'm trying to work out what is best for both parties at that particular time point, the motivations of both parties, you know, from an academic's perspective you might start of a project where it's predominantly contract research, but that then allows you to build trust with the other partner, which then might hopefully lead on at some other point to a more substantive, a longer lasting relationships." (B43)	Contract research leading to further interactions	
"I think they are good in terms of establishing relationships and, you know, that is essential. But if you're starting eating into another organisation's business, whose primary function is that type of interaction, then I think you're moving a bit too far away from your core business and into somebody else's." (B43)		

"Contract research tends to be more closed off, in the sense that the company has approached the university with a well-defined problem to solve, the IP will be delivered to the company as a term of that contract. So it doesn't necessarily create licensing opportunities. It might create further consultancy" (B44)			
"Once you've engaged with a company through, say, contract research or a collaborative research, they're more likely to come back and work with you on other things, including consultancy, for example, but with your additional contract research as well." (C71)			
"I've got a recent example of having done a KTP with a company in which we developed some intellectual property, which we subsequently licensed to them. So yeah, there is an example of an initial, in fact we use the innovation voucher scheme to scope a project and then they moved to the KTP scheme and now they are licensing our intellectual property. There is a consequential process there." (C81)			
"If it's kind of what I'm saying, we tend to be more thinking of IP as the leverage. So if our strategy is anything in terms of licensing, it's that IP. We're not here just selling pieces of IP, we're really more interested in collaboration. We will do a license just for technology and no relationship, but they're much less frequent than they used to be. It's much more about a relationship and that's beneficial to both sides, so that would be our base strategy. That's how we approach it that we look to kind of market the expertise alongside the IP, rather than IP alone, because usually they're very early stage and you still need the person." (B21)	Licensing leading to further interactions		
"for the university, if you think of the size of the university and the finances of the university, the amount of money we're likely to make in licensing doesn't hugely disrupt the university finances. So it brings incentives and to academics to do more impactful work because they get a reward, but we're not charged with sort of making a really high income from licensing. It's much more about how do we use that, much better for the university, in terms of finances as well as actual outcomes from the research, is having a collaborative, fully-funded with all the overhead recovery and, you know... So it is much better than something kind of a 50k license or something like that." (B21)			
"patenting can, in some cases, help that with an interesting technology to work up a research collaboration and use that licensing deal [unclear] at the moment about patenting and maximise the value through to building a patent portfolio." (B31)			

"you get a company who comes in because they've seen we've got a technology, take a license for that technology, like the academic, like the university, all things go well and take more research with you, let's take some directly funded contract research that's gone really well. Okay, let's put in a bid for a bigger collaborative piece of work, involving three or four other institutions throughout, for a big piece of money. You see movement throughout the whole lot and anyone time you can have an organisation to work with on four, five different types of activity." (B45)		
"In my early career, we did a lot of work for the Royal Institute of British Architects in the university. It was very applied and in the end, it didn't work within the university, we had to spin it out, because it was getting into that territory of, you know, we're servicing one organisation, rather than developing a capability and knowledge base that can then be widely disseminated." (B43)	Spin-off might be the result of intense interaction with a single partner	
"Spin-outs lead to licensing" (B42)	Spin-offs leading to licensing	
"What we're interested in doing is adding value for the companies while increasing our own knowledge and understanding and research base around innovation." (B41)	Creating value, increasing research and using what works, independent of the entrepreneurial activity	Focus on relationships rather than activities
"I think we've got a view that there's a kind of creative mixture of things that you provide to companies and what's important is the overall outcome, not the particular mechanism that you use to achieve the outcome. So, what works might differ between one company and another company, depending on their own internal culture and their ability to take forward research within a company. But we're interested in what works and what the outcomes are. So that means that we don't have a specific preference. Except in as much as it goes to a university, always our core mission is going to the research commission, the research income is going to be larger than, much larger than the consulting income." (B41)		
"And that's what really what makes us as a university distinctive I think, more than us saying that we're going to prioritise consulting. And I think that's a bit of an artificial distinction." (B41)		
"Okay, so the key question is whether we're talking about work done with university partners or not. So, when you look at AFRC, which is kind of a model for how we do it in other areas as well, as much as we can, we basically have a joint industry research programme, where the companies are funding a lot of the research that goes on in here in AFRC and that's part of a contract with them. The contract that we have with those companies says that they will get royalty free, non-exclusive licenses to any technologies, which are developed under that contract. Okay, so effectively, what we're doing, we're exchanging the potential of future licensing income for the definite industry research funding now." (B41)	Engage partners in research centres, guaranteed research investment rather than negotiating licenses	

"This thing about whether universities are charging too much for IP is something that comes up a lot and our view as a university is that for us, the relationship and the partnership is the thing we're most interested in rather than necessarily the price. And that's reflected in the fact that we effectively give away the IP for those things where there is a strategic partnership." (B41)		
"Yeah, we're interested in engaging with these companies and external organisations and we'll select the mechanism on a case-by-case basis to make the partnership work. And we do want to have partnerships rather than let's say stand-alone things where we're not engaging with companies, that wouldn't normally be our preference. And it may be that the character of, obviously there is range of different types of research projects that we do, some which would have more or less engagement from company." (B41)	Selecting mechanism on a case-by-case basis to make partnership work	
"So things like knowledge transfer partnerships, increasing the connections there with opportunities for future development for future partnerships." (C61)	Strengthening and expanding existing relationships	
"I said KTPs and the contract research and the consultancy, I think it's just strengthening those relationships and building them further and being involved in other collaborative projects where we can show the value of the relationships, that we can provide and the skills that we have." (C61)		
"We work very hard to make sure that the relationships work and that we deliver on things that we agreed. And we're very open right through the highest level in the university to construct strategic engagements." (B41)	Working hard as a university with top-management support to make relationships work	
"Right, so when you're doing a negotiation you got to realise that on both sides there is a commercial proposition. Companies may well complain whatever price they pay, anything above zero. But the fact is that companies need the universities as well. So again from their side it is beneficial if they view it as a partnership rather than trying to get the best deal on cost. I think if you're just having an argument about the cost of the IP between you, then it's a hopeless situation, because the fact is that it's going to be partnership that's going to work that's stronger." (B41)	Companies need universities to commercialise inventions, not just the IP, and this works better in a partnership approach	Individual, one-off interactions have little benefit for both parties

"The problem is that they might find that it is attractive but then they'll still object about price that we charge for, which is obviously considered more than collaborative research. So they kind of want the cake and eat it, but I don't think it could ever be the only model. So, suppose we have an academic and RKES might consider it as if we thought 'okay, actually if we are capable of this piece of contract research and that's what the company wants at this point in time, then yeah, maybe let's do that', but it would probably be with a longer-term view that the company might decide to do collaborative research, or, you know, might fund studentships, or, you know, sort of broaden the relationship, but just to have that without anything else, I don't think anyone would find that rewarding." (B42)	Contract research alone not rewarding, companies might want to expand relationships through other activities	
"That's how we approach it that we look to kind of market the expertise alongside the IP, rather than IP alone, because usually they're very early stage and you still need the person." (B21)	Patents alone give ownership, not understanding	
"We're not money grabbing and overvaluing and all of this stuff, we're trying to bring value through the expertise of the academics, which is much more important than just a patent. Particularly for a small company who don't necessarily have the work force to develop it." (B21)		
"I'd also say there's a huge amount of excellent universities, and although you might be taking a license to a patent in a specific area and means that the industrial partner may still need to access the entities from management or to help implement that process or to help implement that patent into the manufacturing process or they may be need to access special [unclear] expertise." (B31)		
"But it also seems to me that that is based on a fundamental misperception about the way you drive innovation forward, which is that it's good to have academic-industry collaboration, because even if you have a patent, that doesn't bring you all the know-how and the other things around them. It gives you the ownership but not the understanding" (B41)		

"And, therefore, just to transfer that from one body to another without giving any benefit to the inventor or keeping them involved is not something, which I think it's a good idea. And so what we always do, for example when we're commercialising a company... Well typically the inventor will get a deal in which they either get, they certainly get royalty payments, they get a share of the royalty which is part of the university policy. If it's a spin-out, they will typically get some shares, a portion of the shares, the university takes typically 20% of the shares of the spin-out and the other 80% remain with the founders of the company, which may well include, which would normally include also the inventor of the core technology of that company. And we are always concerned that even if that company is, doesn't have the direct involvement of the inventor, that that inventor is, let's say still has got a framework. There might not be involvement with the day-to-day running of the company, for example, cause academics are very often being academics probably, but they should still, their knowledge and know-how about what they've invented should still be available to the company to ensure that it took to minimise risks of translating that technology to a commercial product." (B41)		
"I think there is this misconception sometimes that once you've created IP in the form of a patent, that's all that a company, whether that's a spin-out or a licensee company, requires in order to practice the invention and make that product or process. The patent is a comprehensive document, but it's not the same as having the inventor there, helping with the development of the technology, productising that technology. We're often dealing with nascent technologies that require technical development, particularly the point of filing a patent. So the involvement of the academic is critical to the success of commercialisation." (B44)		
"I think a lot of our contract research comes from contacts that individual members of staff have with a range of partners that they've developed over a number of years via a whole host of different mechanisms, you know. Students go out ant work for companies, they, you know, re-contact the department or the department's had a long-standing relationship with a company just because, again, historical. So there are a lot of these relationships that are held at faculty and department level." (B43)	Long-standing relationships at faculty, departmental and individual level that were developed through a variety of mechanisms	Partnerships exist at different levels of aggregation
"They very often have the contacts themselves either from conferences, or from having worked with companies before, or whatever." (B46)		

“But it’s quite interesting, there are a lot of academics who develop their contacts early on in their career and they stick with those contacts. Quite often, you know some of them are very very productive, you know, you might talk to Billy Kerr, who has a very productive relationship with GSK over the years but he’s maintained that relationship rather than, say, developing another GSK-type relationship, which, you know, are certainly out there to be done, but the personal relationship that they developed, he’s maintained that, he’s got the reputation in GSK and therefore, you stick to that gold scene, rather than ‘okay I’ll let go and start mining another one’. ” (B43)	Many academics develop relationships early on and maintain them over the years	
“Yeah, I would say that, and I’ve already explained that, I think collaborative research is our bread and butter way of doing things, especially in the construct of industry centres. If you do a lot of that type of work, where you’re generating IP within a club and it’s shared within the club, then you are challenged in terms of making any down stream money for it. I would say that a high level commitment, particularly to collaborative research, doesn’t massively enable you to do a large amount of remunerative licensing activity, because it really is model where IP is paid for upfront.” (B46)	Collaboration with shared IP limits opportunities for commercialisation later	Trade-offs
“The other side of that is, quite often when you’re doing a lot of collaborative R&D, you’re managing access to companies’ IP at the same time. There is a bundle of IP, it’s not just the university’s IP. So we’ve got... companies have expectations on us of managing the bundle of IP, you know, and that then may restrict in some instances your ability to do work with a third party. So for example, we do a lot of work with Rolls Royce. Now Rolls Royce are very very protective of their IP, but they also recognise that they can leverage innovation, new IP from the length of Strathclyde who can then access research council funding, etc. And they see benefit from that, you need two to take the technology forward. If Pratt & Whitney turned up tomorrow and said ‘right, we want to do a contract R&D with you, we’ll pay you loads and loads of money but then we need access to certain IP’, we probably have to say no because we’ve got to also protect our relationship as well as looking at the bottom line.” (B43)	Partnerships require managing a mix of university and company IP, which might result in having to decline working with other companies	
“There are relatively few cases, where we turned a licensee away on a technology. The only time I can think that we’ve done that recently is because we’ve had other licensees already within that space and this is just an additional licensee seeking rights that would cut across those already granted to a previous licensee.” (B44)		

"we recognise that there are high value for the university, both reputationally and also providing a platform on which we can then develop collaborative, more collaborative R&D, so I would call that single sponsor R&D, as opposed to pre-competitive, which might have a number of different. And if you look at the AFRC, it's got a mixture of pre-competitive, single sponsor, contract research in one area." (B43)	Large multi-partner collaborative projects have reputational value and provide a platform for a multitude of further interactions	Utilising partnerships	
"gives us the new capacity, capability in the university that both services, collaborative R&D, contract R&D, but also as a capability that undergraduate students might be able to get access to build post-graduate programmes around it." (B43)			
"So, for us, it's a central entity, RKES, we see it as important to manage those big, strategic things so that there's a platform there so on which other things can be build upon. It is dealt with, definitely, because of that." (B43)			
"We also have partnerships. So sometimes, we're looking for translational awards. The translational awards can also come from industry and also from investors, institutional investors, private investors, and other investor types, so not just looking for grant-type translational awards, but actually potential investors." (A12)	Utilising partnerships for translational funding in commercialisation activities		

Appendix E

Sensitivity Analyses

This section provides a detailed account of the seven sensitivity analyses that were conducted to build confidence in the simulation model and the output. They are based on the baseline model, which is described in Sections 6.2 and 6.3, and only changes in the model structure or parameter values are outlined.

E.1 KE Allowance and Entrepreneurial Capacity

A key aspect of the model is the finite amount of time that researchers can allocate between conducting independent research and engaging in entrepreneurial activities (since the teaching workload is typically fixed). The parameter value for KE Allowance 'wa', multiplied by the number of Entrepreneurial Academics 'ea', determines the Entrepreneurial Capacity 'ec' of each university, which, when exhausted, triggers a negative feedback loop to limit new interactions with businesses. In addition to the baseline model, two other scenarios are tested. The values for the different configurations are presented in Table E.1.

Figure E.1 presents the simulation results of the three configurations for each university. The results indicate that Alpha's academic entrepreneurship stays within its capacity limits, whereas Beta (even under baseline circumstances) and Gamma (for a lower 'wa') are above their current capacity.

Table E.1: Configuration for 'wa' sensitivity analysis

Setup	Alpha	Beta	Gamma
Baseline	0.45	0.35	0.15
Lower wa	0.40	0.30	0.10
Higher wa	0.50	0.40	0.20

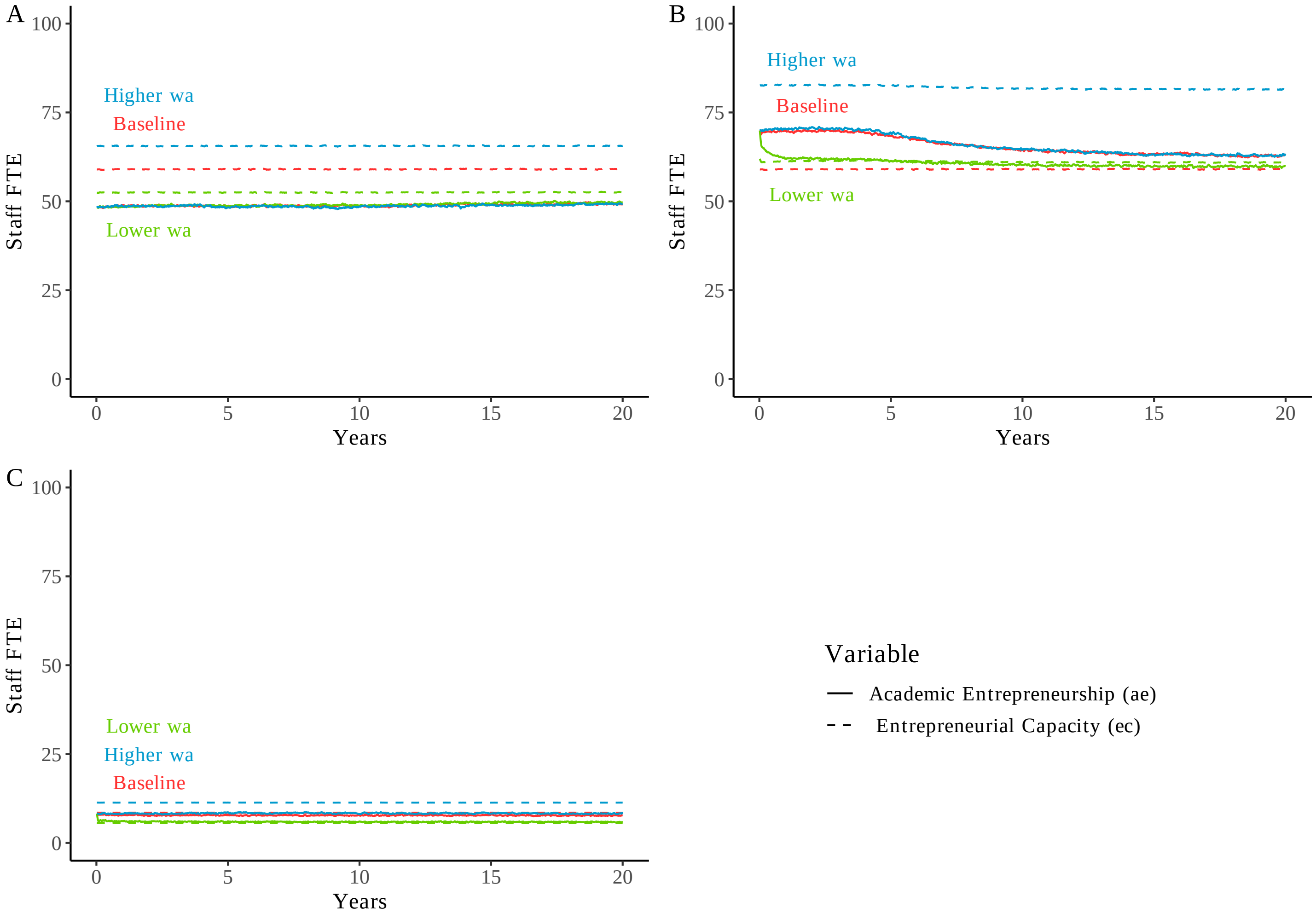

Figure E.1: Simulation output for ‘wa’ sensitivity analysis (I) for Alpha (A), Beta (B), and Gamma (C) showing the values for Academic Entrepreneurship ‘ae’ and Entrepreneurial Capacity ‘ec’

This an be further illustrated by plotting the capacity utilisation (cu), the quotient of 'ae' and 'ec', over time for the three configurations. The result is shown in Figure E.2. As a result, Beta and Gamma will have to turn away companies for potential interactions or face potential issues regarding independent research as the academics involved do not have sufficient time to publish.

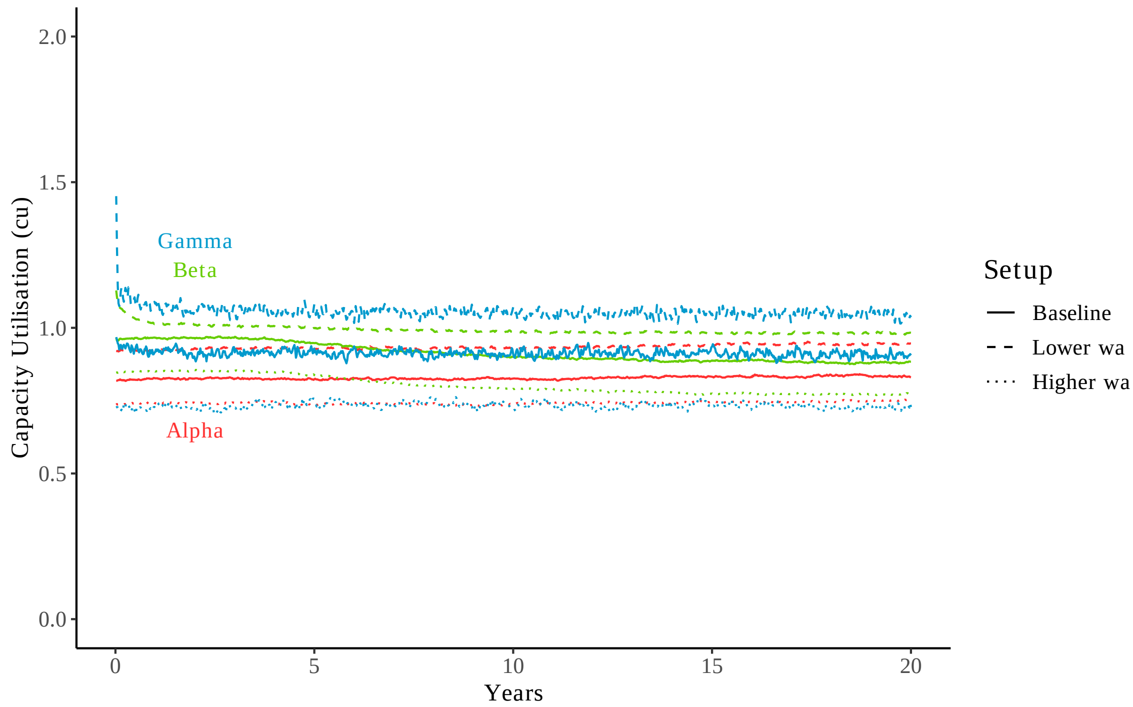

Figure E.2: Simulation output for 'wa' sensitivity analysis (II) showing the values for Capacity Utilisation 'cu' for all three universities under the three sets of parameter values.

E.2 Demand

The baseline model is parametrised to keep the stocks *COL*, *CON*, *CONR*, *LIC*, and *SO* in equilibrium. Spin-offs differ as the stock does not depend on demand from industry, therefore only the other four are considered here. The reference value for these stocks is the (see Section 6.3.1). An increase/decline in demand is proxied by an increase/decline in the number of agents, respectively, rather than changing the probabilities of each agent. This keeps the characteristics of the individual agents as close as possible to the empirical reality.

For the purpose of understanding the sensitivity of the model to the demand from industry, six additional configurations have been created, namely minimum demand with 1,000 agents (setup '1k'), 50% of the original demand with 13,444 agents (setup '13k'), 75% of the original demand with 20,165 agents (setup '20k'), 125% of the original demand with 33,609 agents (setup '33k'), 150% of the original demand with 40,331 agents (setup '40k'), and 200% of the original demand with 53,774 agents (setup '53k'). The results in the form of the Academic Entrepreneurship (ae) are presented in Figure E.3.

All universities show similar behaviour with academic entrepreneurship reducing approximately proportional to the decrease in demand, but increasing disproportional with increasing demand due to the feedback loop via 'ioccc'. In these cases, universities are above their capacity and, therefore, have to constantly decline opportunities for interacting with industry (see Figure E.4 showing the Capacity Utilisation 'cu' for each configuration).

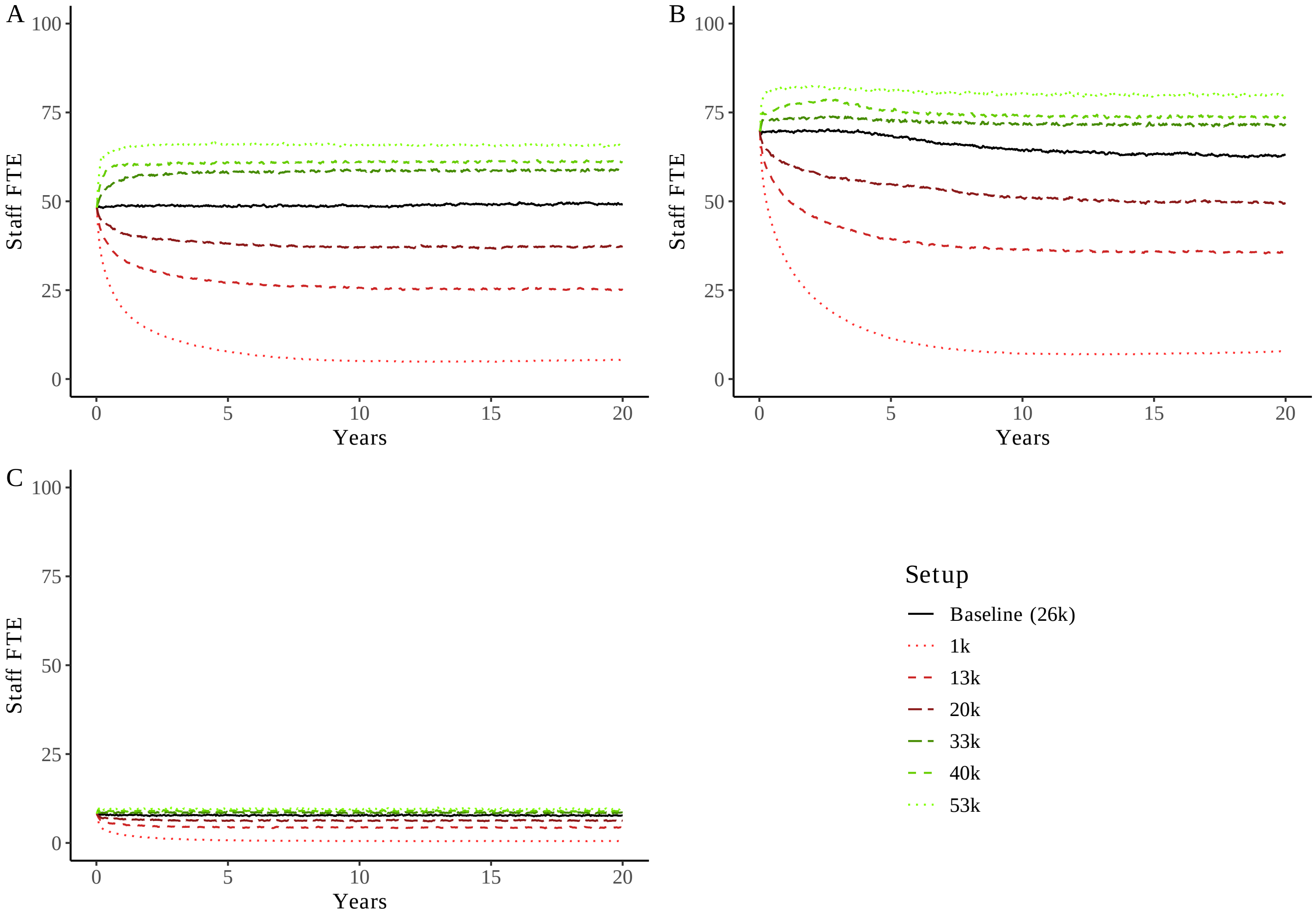

Figure E.3: Simulation output for demand sensitivity analysis (I) for Alpha (A), Beta (B), and Gamma (C) showing the values for Academic Entrepreneurship 'ae'.

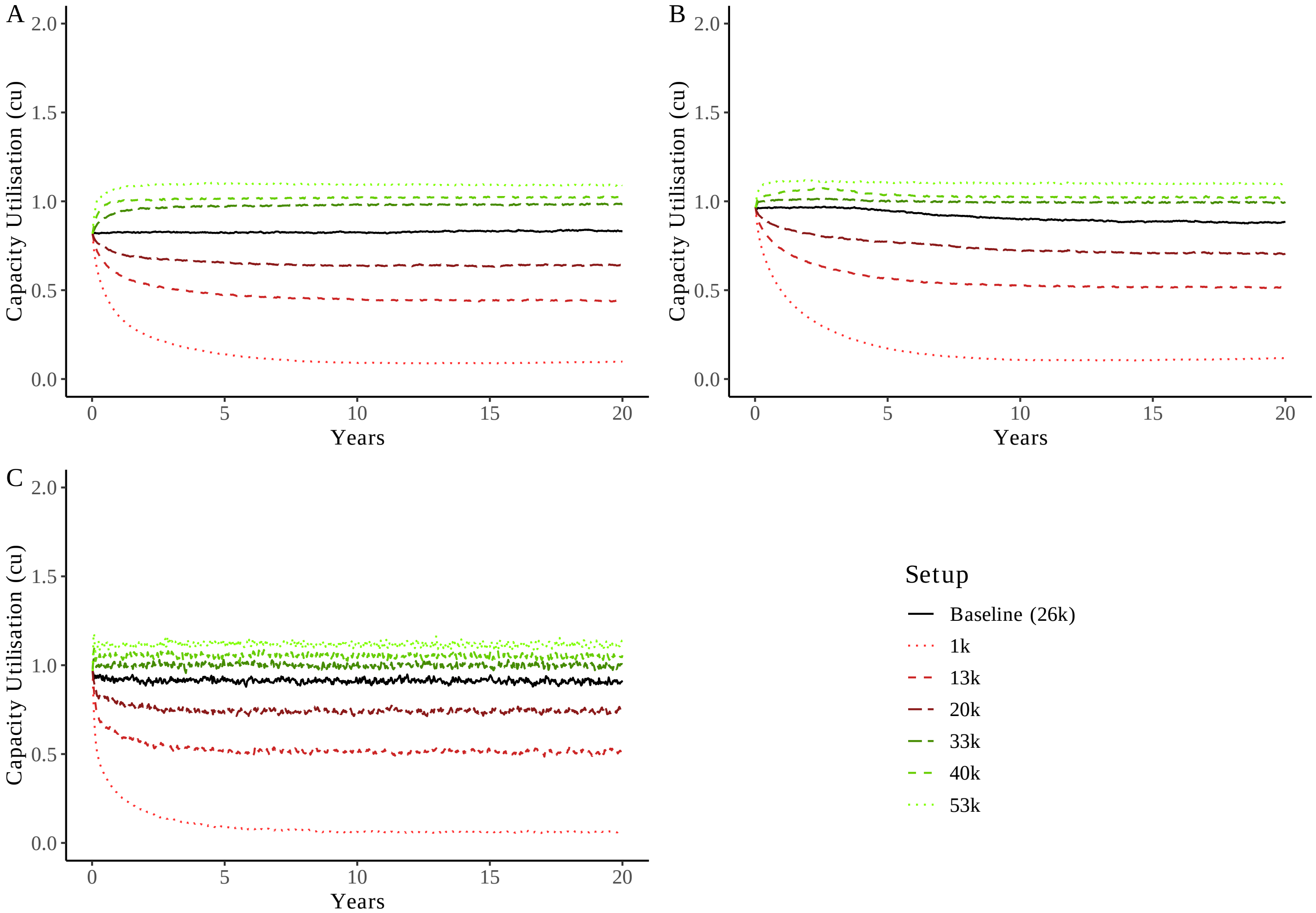

Figure E.4: Simulation output for demand sensitivity analysis (II) for Alpha (A), Beta (B), and Gamma (C) showing the values for Capacity Utilisation 'cu'.

E.3 Networking

The interviews have shown that there is a word-of-mouth effect among companies, but the magnitude of this effect is not well understood yet and hard to estimate. In the baseline configuration, a maximum of five universities network per time step, which equals 260 companies per year (i.e. 1% of the agent population). Two alternative configurations are tested, namely 10 agents per time step (520 companies or approximately 2% of the agent population per year) and 52 agents per time step (2,704 companies or approximately 10% of the agent population per year). The results in Figure E.5 show that the model is not very sensitive to networking, which is partially due to the actual number of networking interactions being lower than the previously described maximum values.

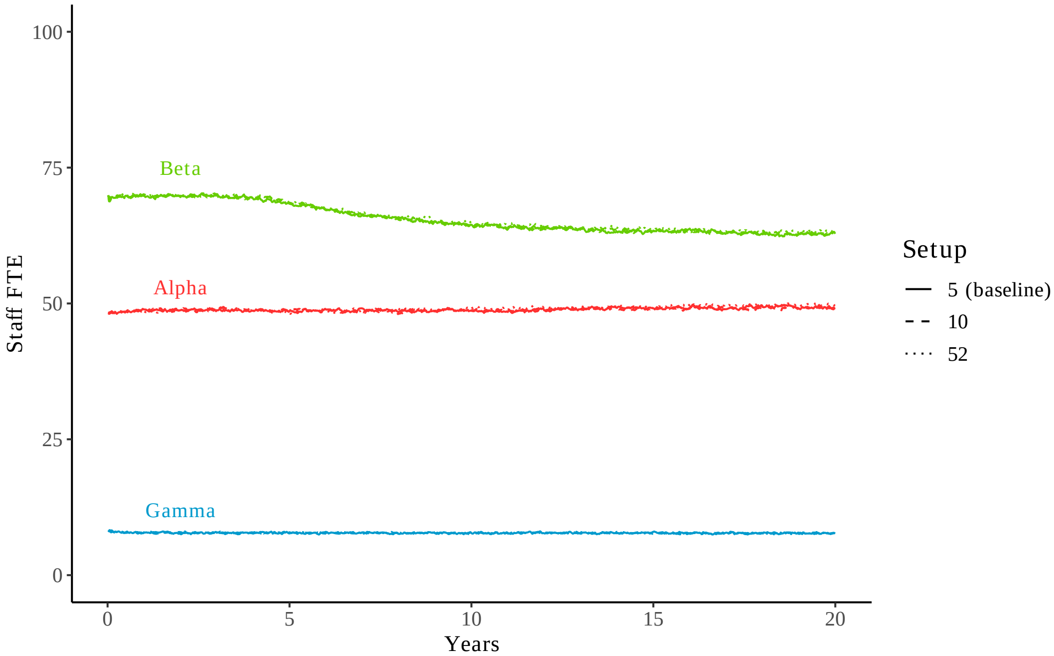

Figure E.5: Simulation output for networking sensitivity analysis showing the values for Academic Entrepreneurship 'ae' for each university under the three configurations.

E.4 Academic Involvement Collaborative Research

The baseline model is parametrised with an academic involvement 'aicol' of 0.1 for collaborative research for the duration of the project. This value is the same for all three universities Alpha, Beta, and Gamma. While this value is reasonable (see Section 6.3.2), there is a general trend towards larger, multi-partner projects. This development is spurred by the United Nation's Sustainable Development Goals (SDGs) and other 'mission-oriented' policy initiatives that aim to address grand societal challenges that require inter-disciplinary research teams. As a result, more academics are involved with increases leading to a higher 'aicol' from 0.1 over the project duration to 0.3 FTE.[71]

An crucial aspect is whether academics are able to 'buy out' some of their teaching time, which means that they have more time for research and entrepreneurial activities. This modelled as an additional structural sensitivity test by linking the costs for academic staff in collaborative research projects 'casc' to the Staff Budget 'sb', hereby increasing the Entrepreneurial Capacity 'ec' through an increase in Research-Active Staff 'ras' and Entrepreneurial Academics 'ea' (see Figure E.6 for a modified SFD).

Figures E.7 ('ae') and E.8 ('cu') show the outcomes for 'aicol=0.2' and 'aicol=0.3' as well as the option for staff to buy out time. Due to the significantly longer duration of collaborative research projects compared to consulting or contract research, an increase in academic involvement carries major capacity implications for universities. Academic involvement in collaborative research 'aicol>0.1' (with everything else being equal) pushes all universities quickly over their Entrepreneurial Capacity 'ec', which limits new interactions with industry. Engaging in large-scale collaborative projects is not bad *per se*, but must be aligned to the overall institutional strategy.

[71] A small sample of <10 projects from the authors host institution has confirmed this trend, but there is no dataset available to make generalisable claims.

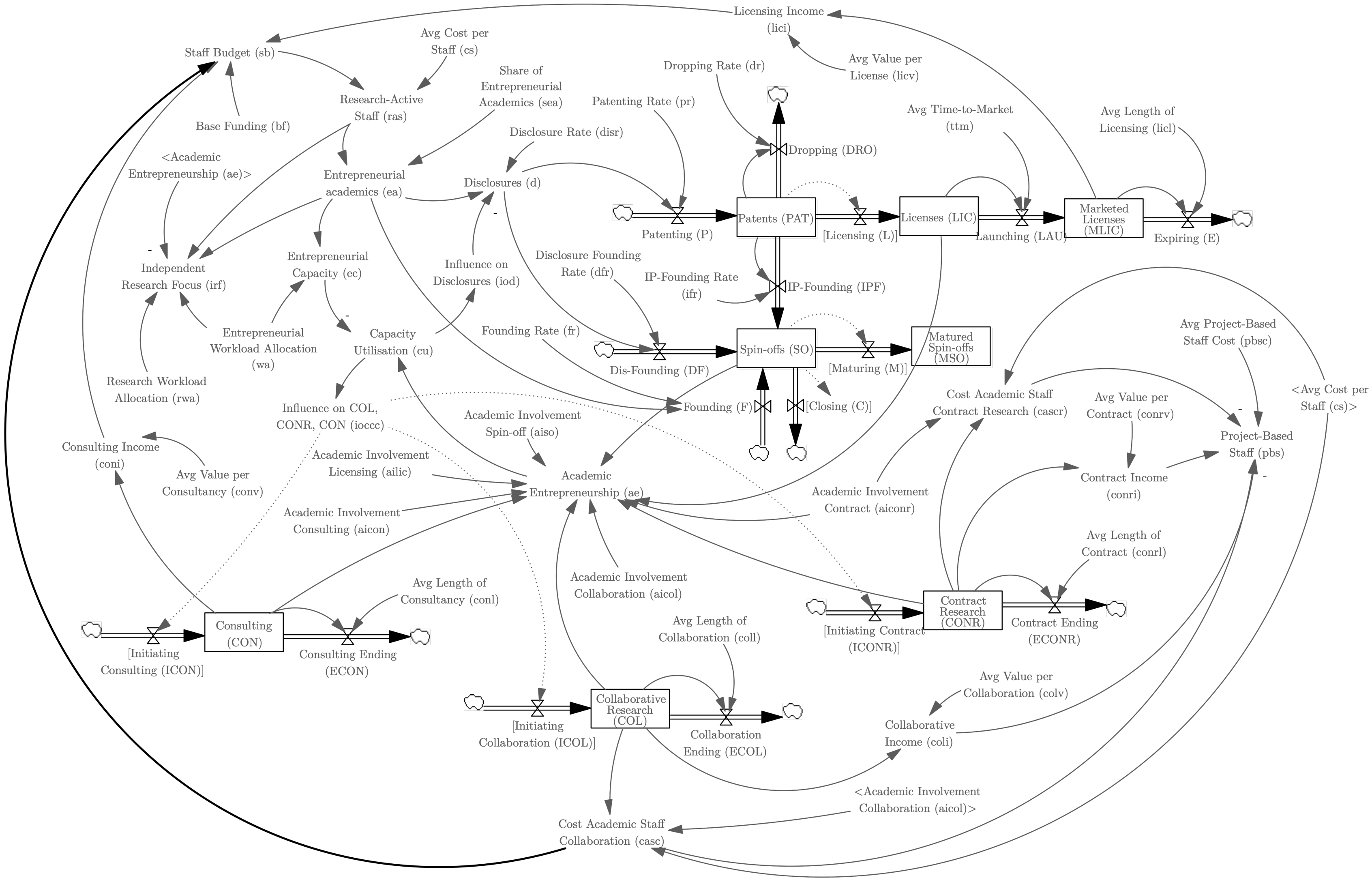

Figure E.6: SFD model for 'aicol' sensitivity analysis

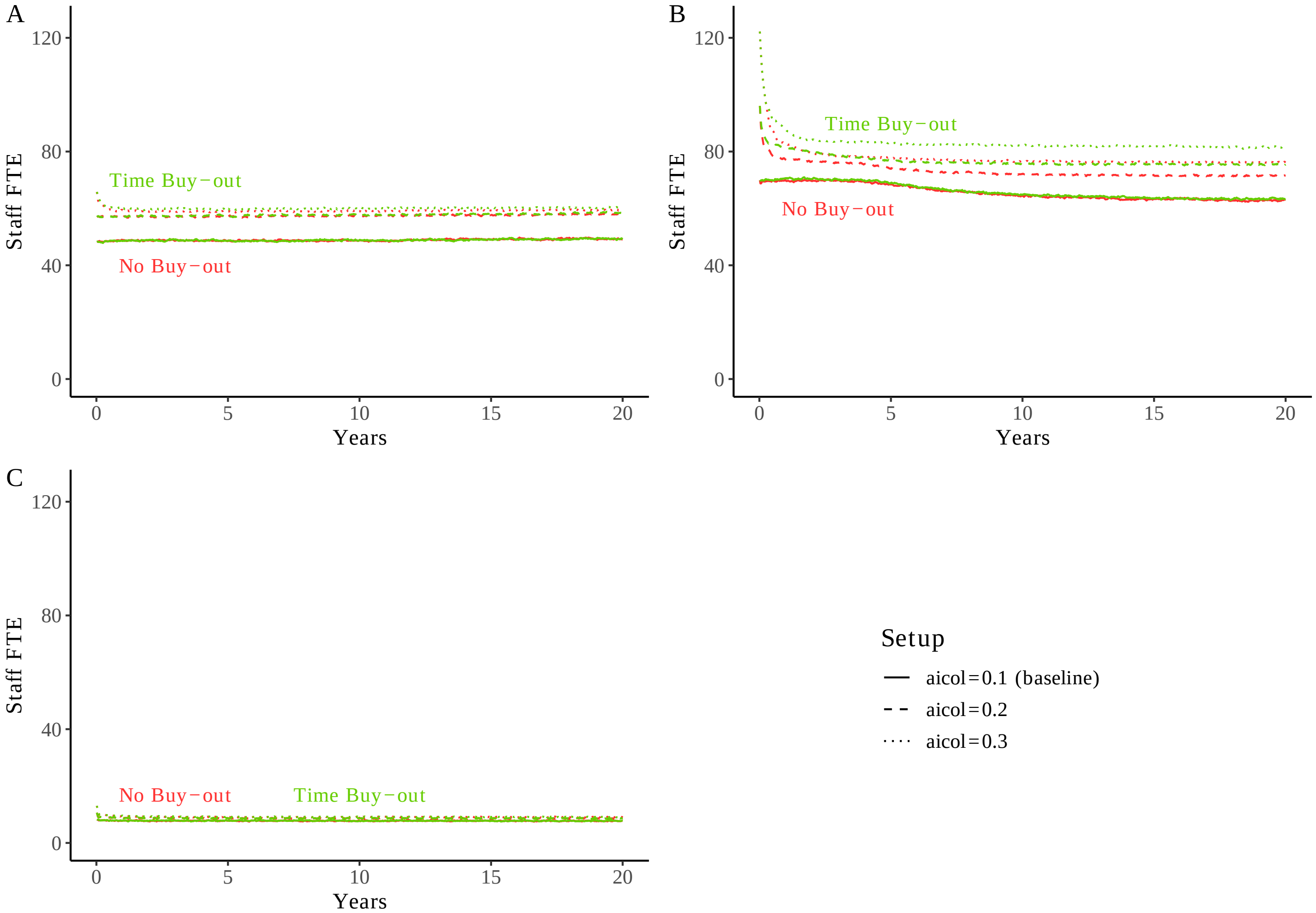

Figure E.7: Simulation output for 'aicol' sensitivity analysis (I) for Alpha (A), Beta (B), and Gamma (C) showing the values for Academic Entrepreneurship 'ae'.

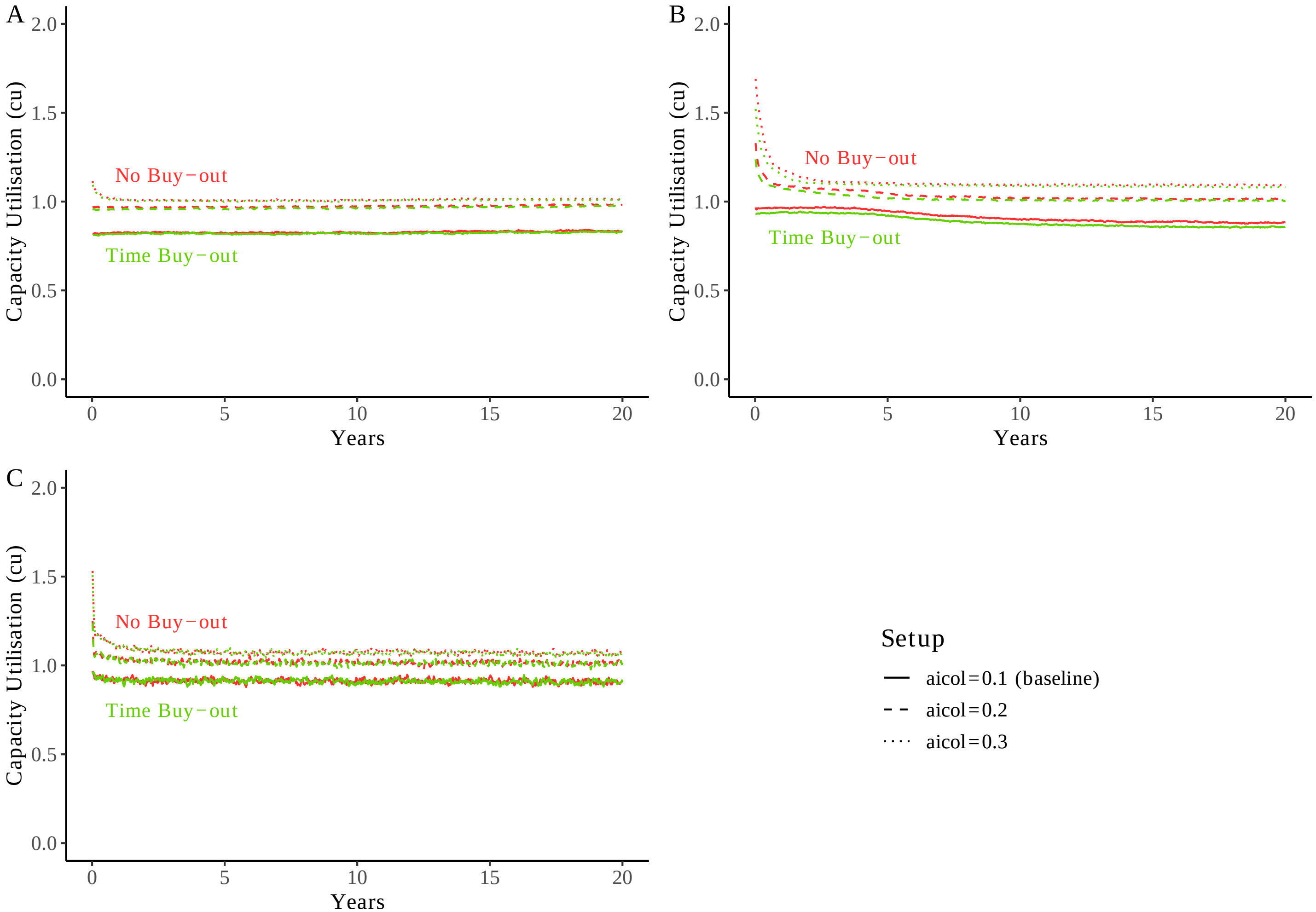

Figure E.8: Simulation output for 'aicol' sensitivity analysis (II) for Alpha (A), Beta (B), and Gamma (C) showing the values for Capacity Utilisation 'cu'.

E.5 Licensing Equilibrium

While Alpha and Gamma are in equilibrium for *COL*, *CON*, *CONR*, *LIC*, and *SO* in the baseline model, Beta's licensing activities *LIC* are not. This is cause by an average licensing rate in the HE-BCI data that is higher than the annual patenting rate, which leads to a depletion of the patenting stock *PAT* and does not allow Beta to fulfil future demand for licensing. Two alternative configurations have been developed to test the sensitivity of the model with regard to the *PAT* stock. First, the 'Patenting Rate' *pr* for Beta is set to the *pr* of Alpha. Second, the 'Disclosure Rate' *disr* of Beta is also increased to the value of Alpha.

Aggregated results in the form of 'Academic Entrepreneurship' *ae* for the different configurations compared to the baseline 'Entrepreneurial Capacity' *ec* and detailed results for all commercialisation-relevant stocks for Beta are shown in Figure E.9 and Figure E.10, respectively. While an increased *pr* delays the depletion of *PAT*, it requires both an increase in *pr* and *disr* by Beta to maintain its current patent portfolio. This might, however, not be desirable when considering the costs of filing for patents and renewal fees. Everything else being equal, an increase of both *disr* and *pr* gets Beta close to its capacity *ec*, which, in turn, requires the university to invest in internal marketing if it wants to grow any entrepreneurial activity.

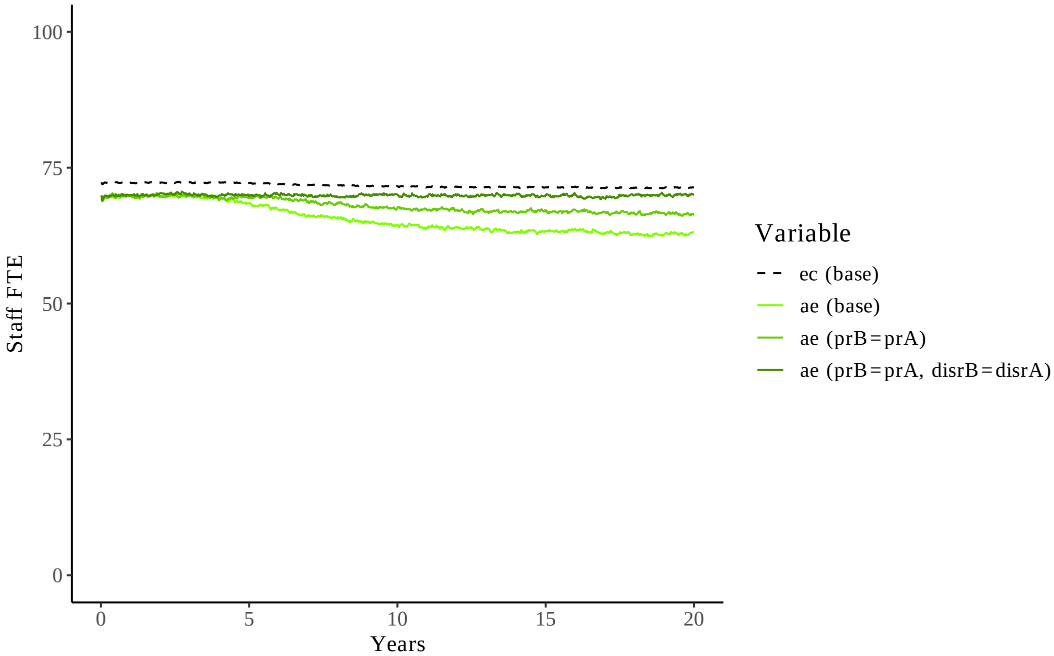

Figure E.9: Simulation output for Beta licensing sensitivity analysis (I) showing the values of 'ec' and 'ae' for the baseline scenario as well as 'ae' for $prB = prA$ and the combination of $pr_B = pr_A, disr_B = disr_A$.

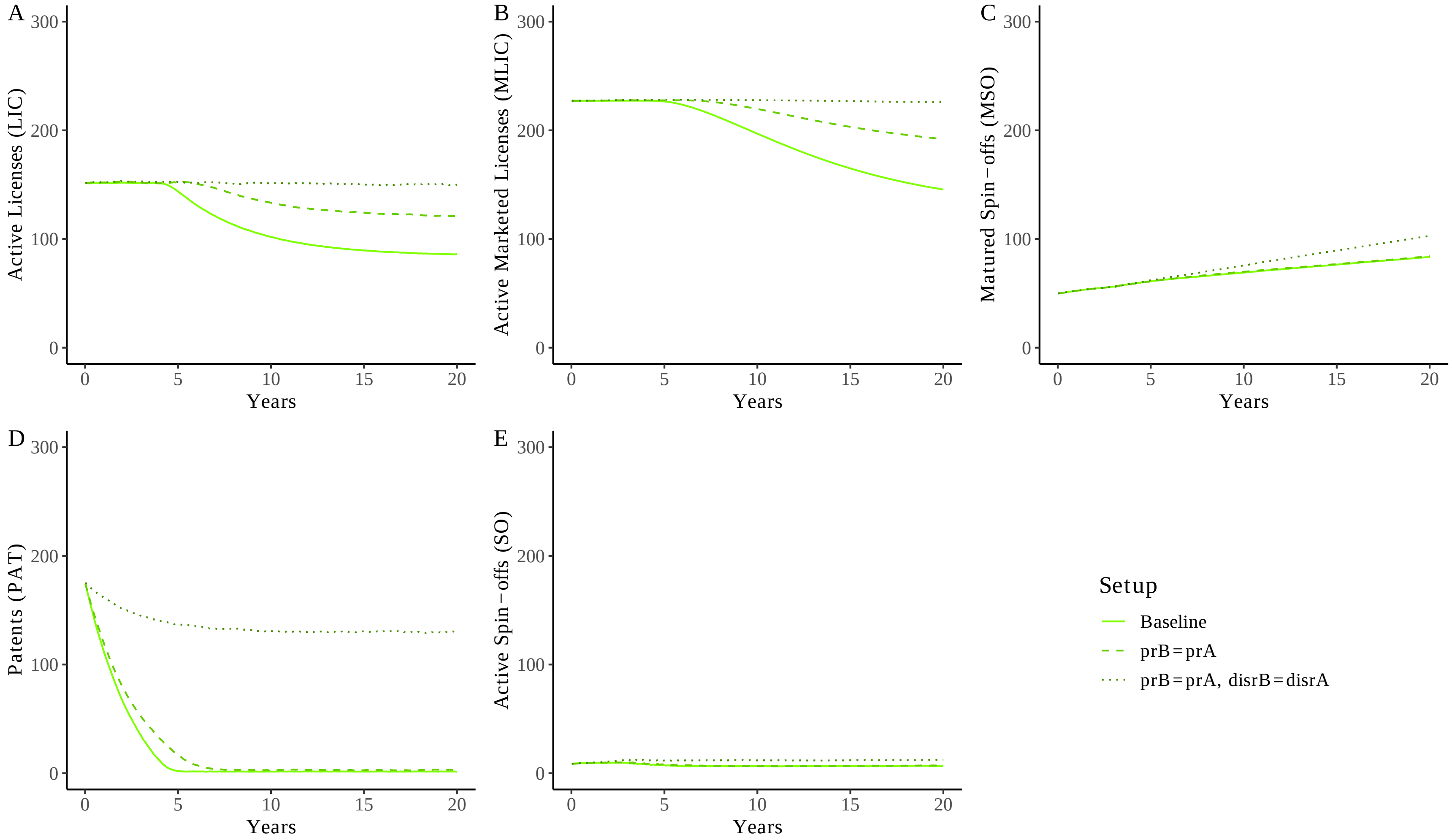

Figure E.10: Simulation output for Beta licensing sensitivity analysis (II) showing the values of the stocks of all commercialisation activities, namely LIC (A), MLIC (B), MSO (C), PAT (D), and SO (C).

E.6 Agents' University Preference

The propensity for collaboration N_i (Section 5.4.1.4) and the university preference $P_{i,k}$ for each activity k (Section 5.4.1.5) link the CBR Business Survey data (main data source for the ABM module) to the HESE and HE-BCI data (main data source for the SD modules). However, the is no data available at the required level of granularity for $P_{i,k}$, which has subsequently been used to optimise the agents' behaviour to enable the equilibrium as described in Section 6.3.2.

To test the sensitivity of the model to these parameters, three additional configurations have been developed. The basis for each configurations are the values for non-spin-off agents from Table 6.5. Then, the preferences $p_{i,k,\alpha}$, $p_{i,k,\beta}$, and $p_{i,k,\gamma}$ are increased by 10% for each scenario, respectively. The maximum preference for a particular activity for a particular university is 0.98, leaving 0.01 for each of the other two universities (which means that there is always at least a 1% chance of any agents selecting any one university). The difference between the increased preference is then proportionally deducted from the preference for the other two universities. This follows the same principle as for updating the university preferences after an interaction (see Section 5.4.2.7). The ABM module parameters for an increased preference for Alpha, Beta, and Gamma are shown in Tables E.2, E.3, and E.4, respectively.

High-level results in the form of changes in 'Academic Entrepreneurship' *ae* are presented in Figure E.11. These results can be further broken down into individual activities, which shown for the three cases in which the university preference is increased by 10% for Alpha (Figure E.12), Beta (Figure E.13), and Gamma (Figure E.14), respectively. Overall, the model is most sensitive to changes in the preference for either Alpha or Beta. This can be explained by the typically higher preference for one of these universities in the beginning. Increasing the preference for Alpha has a very small effect on Gamma's entrepreneurial activities, whereas Gamma's *ae* does decrease if the preference for Beta is increased across the agent population.

Table E.2: Parameters for non-spin-off agents ($O_i = 0$) for increased university preference for Alpha

	Firm category											
Variable	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
S_i	1	2	3	4	1	2	3	4	1	2	3	4
I_i	0	0	0	0	1	1	1	1	2	2	2	2
$n_{i,k=1}$	0.00000	0.00002	0.00038	0.00012	0.00011	0.00000	0.00013	0.00016	0.00035	0.00013	0.00053	0.00170
$n_{i,k=2}$	0.00004	0.00007	0.00025	0.00131	0.00026	0.00030	0.00038	0.00089	0.00050	0.00080	0.00170	0.00260
$n_{i,k=3}$	0.00017	0.00018	0.00145	0.00424	0.00122	0.00135	0.00149	0.00526	0.00131	0.00248	0.00504	0.01059
$n_{i,k=4}$	0.00016	0.00022	0.00071	0.00417	0.00090	0.00155	0.00183	0.00259	0.00129	0.00208	0.00198	0.00568
$p_{i,k=1,\alpha}$	0.33000	0.66582	0.66728	0.79798	0.40400	0.66000	0.91265	0.89161	0.37877	0.78255	0.90335	0.98000
$p_{i,k=1,\beta}$	0.47857	0.32418	0.32272	0.19005	0.58600	0.29750	0.07735	0.08779	0.61123	0.20745	0.08665	0.01000
$p_{i,k=1,\gamma}$	0.19143	0.01000	0.01000	0.01197	0.01000	0.04250	0.01000	0.02060	0.01000	0.01000	0.01000	0.01000
$p_{i,k=2,\alpha}$	0.01880	0.50073	0.68223	0.68616	0.02659	0.51862	0.85479	0.86198	0.21577	0.60292	0.81562	0.95695
$p_{i,k=2,\beta}$	0.90737	0.45218	0.27245	0.27153	0.89417	0.43472	0.11248	0.10602	0.72969	0.35158	0.14584	0.02554
$p_{i,k=2,\gamma}$	0.07382	0.04709	0.04532	0.04232	0.07925	0.04665	0.03273	0.03200	0.05453	0.04550	0.03854	0.01751
$p_{i,k=3,\alpha}$	0.24077	0.64206	0.74618	0.75714	0.48947	0.63012	0.87467	0.87480	0.70095	0.74534	0.87191	0.98000
$p_{i,k=3,\beta}$	0.60525	0.32214	0.22312	0.20858	0.49871	0.33857	0.09626	0.09622	0.28424	0.22421	0.09953	0.01000
$p_{i,k=3,\gamma}$	0.15399	0.03580	0.03070	0.03429	0.01182	0.03131	0.02907	0.02897	0.01481	0.03046	0.02856	0.01000
$p_{i,k=4,\alpha}$	0.01206	0.59362	0.73525	0.73952	0.33998	0.55613	0.86020	0.87719	0.56474	0.70745	0.87054	0.98000
$p_{i,k=4,\beta}$	0.69940	0.34205	0.21543	0.21482	0.50627	0.36653	0.10335	0.09315	0.32685	0.23370	0.09644	0.01000
$p_{i,k=4,\gamma}$	0.28854	0.06433	0.04932	0.04566	0.15375	0.07734	0.03646	0.02966	0.10842	0.05885	0.03303	0.01000
ts_i	0.57143	0.58333	1.00000	0.72222	0.66667	0.58824	0.66667	0.72727	0.80000	0.57576	0.75000	0.79545
$tu_{i,U=1}$	0.33333	0.14286	0.66667	0.15385	0.37500	0.30000	0.25000	0.37500	0.31250	0.47368	0.66667	0.60000
$tu_{i,U=0}$	0.00000	0.00000	0.00000	0.50000	0.00000	0.00000	0.00000	0.33333	0.33333	0.36364	0.33333	0.33333
ni_i	0.00131	0.00131	0.00125	0.00162	0.00131	0.00131	0.00125	0.00162	0.00131	0.00131	0.00125	0.00162

Table E.3: Parameters for non-spin-off agents ($O_i = 0$) for increased university preference for Beta

Variable	**Firm category**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
S_i	1	2	3	4	1	2	3	4	1	2	3	4
I_i	0	0	0	0	1	1	1	1	2	2	2	2
$n_{i,k=1}$	0.00000	0.00002	0.00038	0.00012	0.00011	0.00000	0.00013	0.00016	0.00035	0.00013	0.00053	0.00170
$n_{i,k=2}$	0.00004	0.00007	0.00025	0.00131	0.00026	0.00030	0.00038	0.00089	0.00050	0.00080	0.00170	0.00260
$n_{i,k=3}$	0.00017	0.00018	0.00145	0.00424	0.00122	0.00135	0.00149	0.00526	0.00131	0.00248	0.00504	0.01059
$n_{i,k=4}$	0.00016	0.00022	0.00071	0.00417	0.00090	0.00155	0.00183	0.00259	0.00129	0.00208	0.00198	0.00568
$p_{i,k=1,\alpha}$	0.27000	0.56682	0.56829	0.70018	0.30500	0.56769	0.81365	0.79587	0.27977	0.68355	0.80435	0.91250
$p_{i,k=1,\beta}$	0.55000	0.42318	0.42171	0.28413	0.68500	0.38500	0.17635	0.16879	0.71023	0.30645	0.18565	0.07750
$p_{i,k=1,\gamma}$	0.18000	0.01000	0.01000	0.01570	0.01000	0.04731	0.01000	0.03535	0.01000	0.01000	0.01000	0.01000
$p_{i,k=2,\alpha}$	0.01000	0.41088	0.59026	0.59368	0.01000	0.42842	0.76087	0.76800	0.13795	0.51156	0.72241	0.86268
$p_{i,k=2,\beta}$	0.98000	0.54275	0.35819	0.35804	0.98000	0.52503	0.18994	0.18283	0.82274	0.44012	0.22493	0.08487
$p_{i,k=2,\gamma}$	0.01000	0.04638	0.05155	0.04828	0.01000	0.04655	0.04920	0.04916	0.03931	0.04833	0.05266	0.05244
$p_{i,k=3,\alpha}$	0.18276	0.54872	0.65161	0.66315	0.39227	0.53606	0.78030	0.78043	0.60369	0.65072	0.77742	0.88861
$p_{i,k=3,\beta}$	0.68496	0.41213	0.31102	0.29446	0.59639	0.43010	0.17307	0.17308	0.37928	0.31225	0.17723	0.06379
$p_{i,k=3,\gamma}$	0.13228	0.03915	0.03737	0.04240	0.01133	0.03384	0.04663	0.04650	0.01702	0.03703	0.04535	0.04759
$p_{i,k=4,\alpha}$	0.01000	0.50552	0.64371	0.64739	0.27423	0.47069	0.76697	0.78297	0.48384	0.61749	0.77684	0.88719
$p_{i,k=4,\beta}$	0.77020	0.42622	0.29680	0.29729	0.58297	0.44910	0.17727	0.16900	0.40194	0.31358	0.17092	0.05653
$p_{i,k=4,\gamma}$	0.21980	0.06826	0.05949	0.05532	0.14280	0.08020	0.05576	0.04803	0.11423	0.06893	0.05224	0.05628
ts_i	0.57143	0.58333	1.00000	0.72222	0.66667	0.58824	0.66667	0.72727	0.80000	0.57576	0.75000	0.79545
$tu_{i,U=1}$	0.33333	0.14286	0.66667	0.15385	0.37500	0.30000	0.25000	0.37500	0.31250	0.47368	0.66667	0.60000
$tu_{i,U=0}$	0.00000	0.00000	0.00000	0.50000	0.00000	0.00000	0.00000	0.33333	0.33333	0.36364	0.33333	0.33333
ni_i	0.00131	0.00131	0.00125	0.00162	0.00131	0.00131	0.00125	0.00162	0.00131	0.00131	0.00125	0.00162

Table E.4: Parameters for non-spin-off agents ($O_i = 0$) for increased university preference for Gamma

	Firm category											
Variable	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
S_i	1	2	3	4	1	2	3	4	1	2	3	4
I_i	0	0	0	0	1	1	1	1	2	2	2	2
$n_{i,k=1}$	0.00000	0.00002	0.00038	0.00012	0.00011	0.00000	0.00013	0.00016	0.00035	0.00013	0.00053	0.00170
$n_{i,k=2}$	0.00004	0.00007	0.00025	0.00131	0.00026	0.00030	0.00038	0.00089	0.00050	0.00080	0.00170	0.00260
$n_{i,k=3}$	0.00017	0.00018	0.00145	0.00424	0.00122	0.00135	0.00149	0.00526	0.00131	0.00248	0.00504	0.01059
$n_{i,k=4}$	0.00016	0.00022	0.00071	0.00417	0.00090	0.00155	0.00183	0.00259	0.00129	0.00208	0.00198	0.00568
$p_{i,k=1,\alpha}$	0.29250	0.60468	0.60601	0.72424	0.36690	0.59684	0.82884	0.80753	0.34399	0.71069	0.82040	0.91861
$p_{i,k=1,\beta}$	0.48750	0.38432	0.38299	0.25787	0.62210	0.34816	0.16016	0.15287	0.64501	0.27831	0.16860	0.07039
$p_{i,k=1,\gamma}$	0.22000	0.01100	0.01100	0.01789	0.01100	0.05500	0.01100	0.03960	0.01101	0.01100	0.01100	0.01100
$p_{i,k=2,\alpha}$	0.01696	0.45275	0.61665	0.62045	0.02396	0.46893	0.77297	0.77948	0.19500	0.54512	0.73723	0.86510
$p_{i,k=2,\beta}$	0.90170	0.49073	0.32377	0.32376	0.88865	0.47472	0.17176	0.16534	0.74352	0.39792	0.20332	0.07673
$p_{i,k=2,\gamma}$	0.08135	0.05652	0.05958	0.05580	0.08739	0.05635	0.05527	0.05518	0.06148	0.05696	0.05945	0.05817
$p_{i,k=3,\alpha}$	0.21476	0.58116	0.67560	0.68514	0.44439	0.57069	0.79118	0.79132	0.63606	0.67486	0.78880	0.88962
$p_{i,k=3,\beta}$	0.61097	0.37304	0.28160	0.26646	0.54147	0.38954	0.15655	0.15656	0.34417	0.28272	0.16034	0.05770
$p_{i,k=3,\gamma}$	0.17427	0.04581	0.04279	0.04841	0.01414	0.03977	0.05227	0.05212	0.01976	0.04242	0.05086	0.05268
$p_{i,k=4,\alpha}$	0.01052	0.53542	0.66400	0.66819	0.30315	0.50081	0.77728	0.79334	0.50632	0.63816	0.78695	0.88667
$p_{i,k=4,\beta}$	0.67174	0.38442	0.26804	0.26861	0.51981	0.40443	0.16018	0.15284	0.36036	0.28287	0.15451	0.05108
$p_{i,k=4,\gamma}$	0.31774	0.08016	0.06795	0.06320	0.17704	0.09476	0.06254	0.05381	0.13332	0.07897	0.05854	0.06225
ts_i	0.57143	0.58333	1.00000	0.72222	0.66667	0.58824	0.66667	0.72727	0.80000	0.57576	0.75000	0.79545
$tu_{i,U=1}$	0.33333	0.14286	0.66667	0.15385	0.37500	0.30000	0.25000	0.37500	0.31250	0.47368	0.66667	0.60000
$tu_{i,U=0}$	0.00000	0.00000	0.00000	0.50000	0.00000	0.00000	0.00000	0.33333	0.33333	0.36364	0.33333	0.33333
ni_i	0.00131	0.00131	0.00125	0.00162	0.00131	0.00131	0.00125	0.00162	0.00131	0.00131	0.00125	0.00162

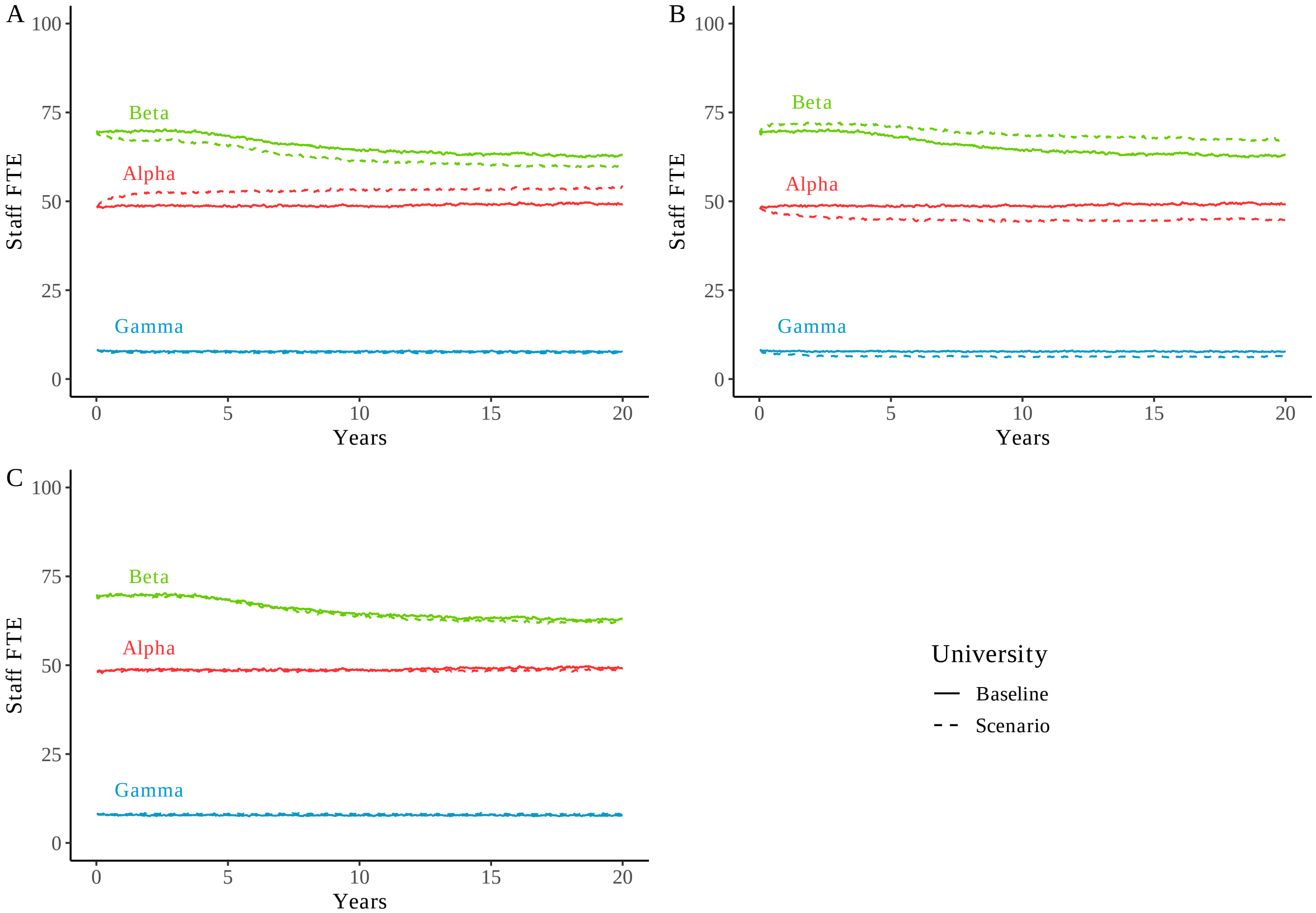

Figure E.11: Simulation output for $P_{i,k}$ sensitivity analysis (I) showing the values for Academic Entrepreneurship ‘ae’ for the three scenarios with the preference for Alpha increased (A), Beta (B), and Gamma (C).

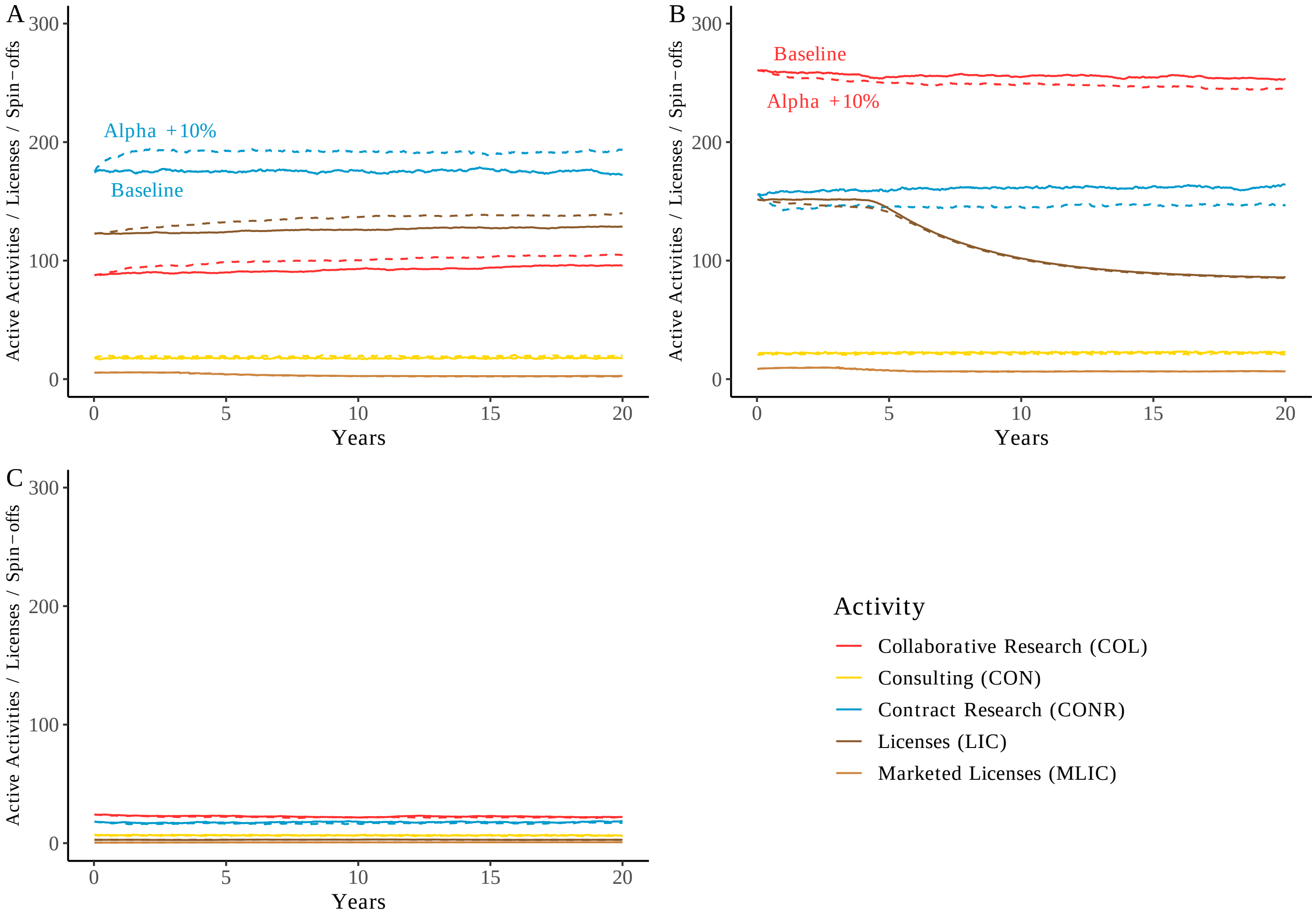

Figure E.12: Simulation output for $P_{i,k}$ sensitivity analysis (II) showing the values of the stocks of the five entrepreneurial activities for Alpha (A), Beta (B), and Gamma (C) for an increased preference for Alpha.

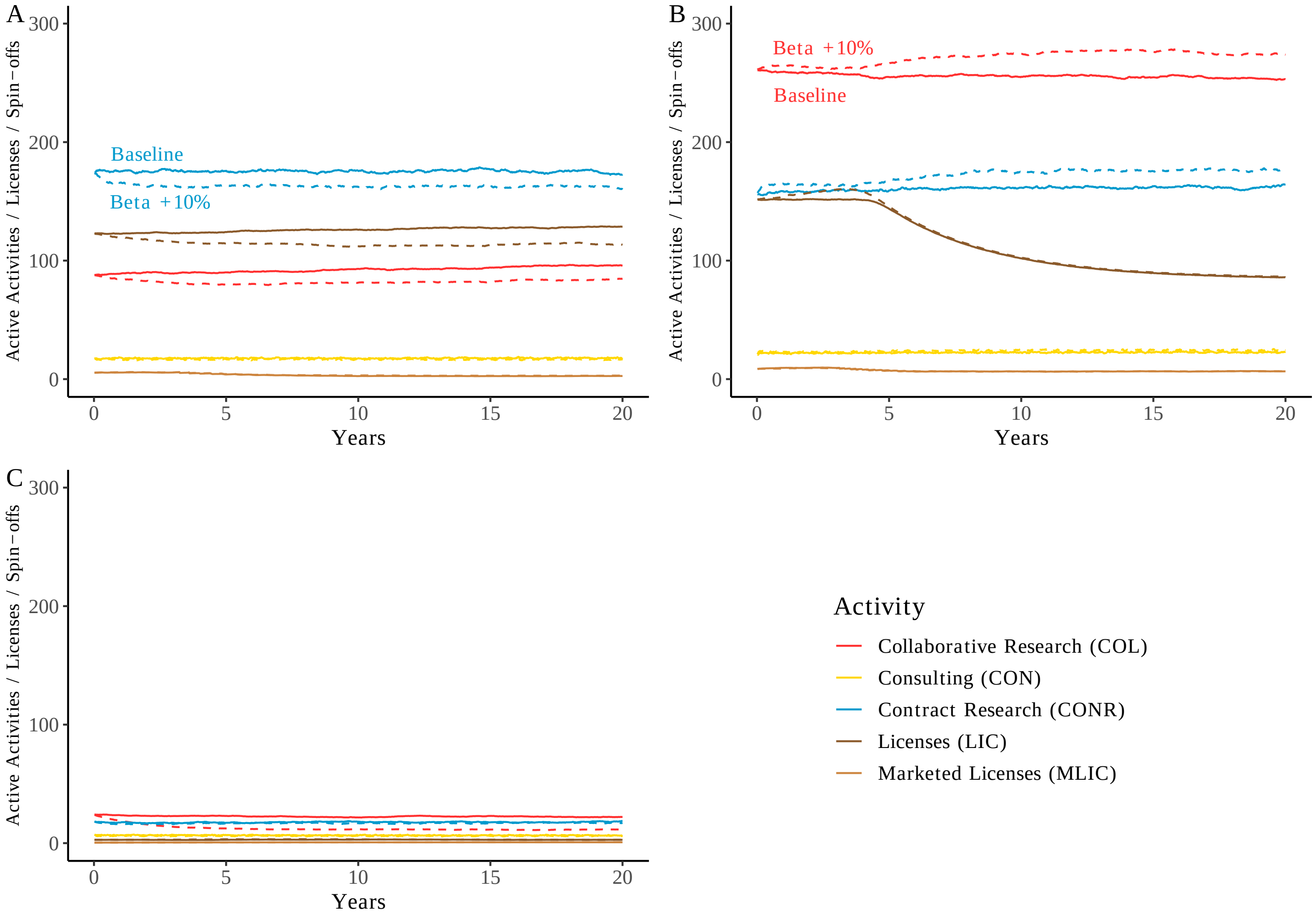

Figure E.13: Simulation output for $P_{i,k}$ sensitivity analysis (III) showing the values of the stocks of the five entrepreneurial activities for Alpha (A), Beta (B), and Gamma (C) for an increased preference for Beta.

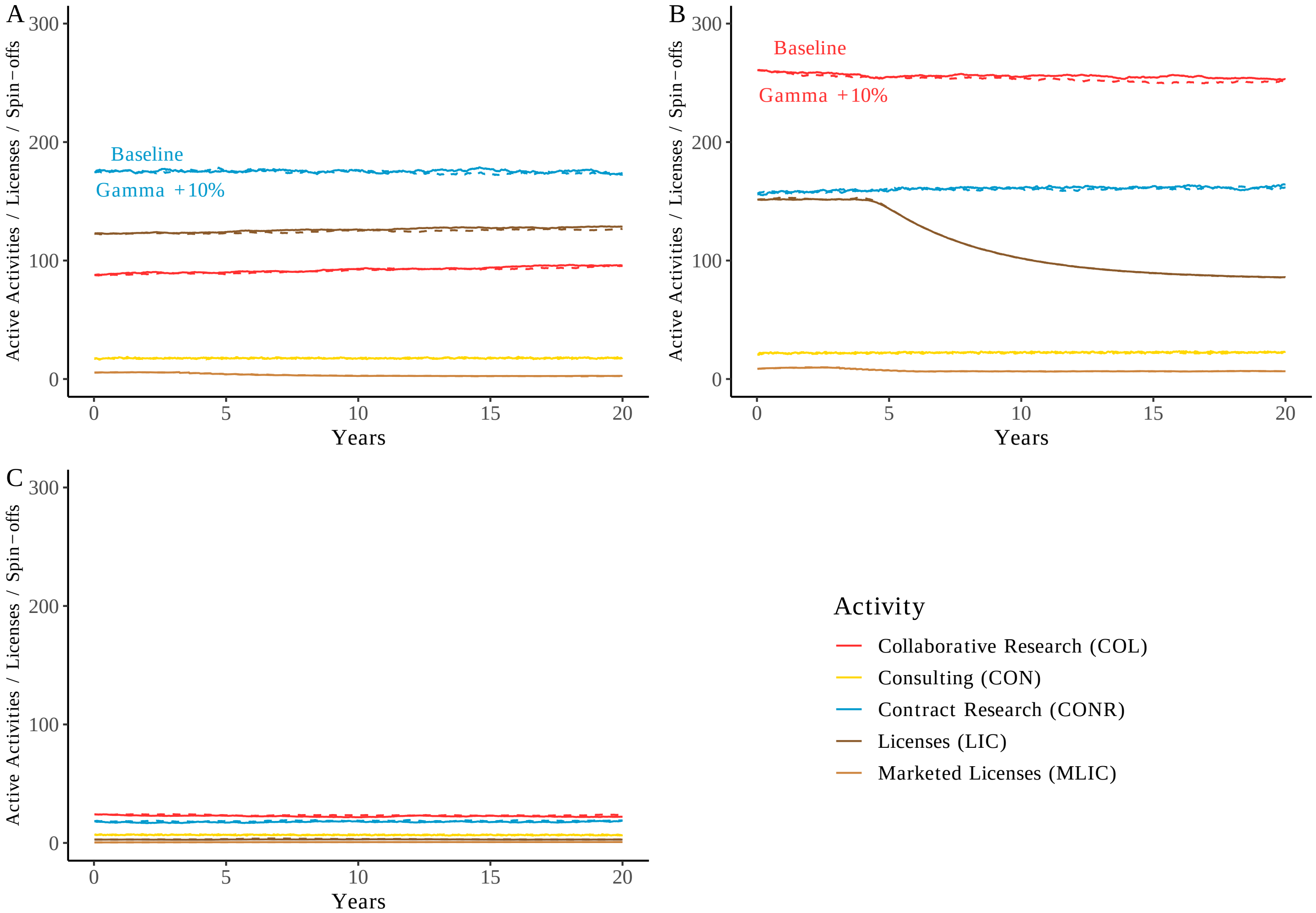

Figure E.14: Simulation output for $P_{i,k}$ sensitivity analysis (IV) showing the values of the stocks of the five entrepreneurial activities for Alpha (A), Beta (B), and Gamma (C) for an increased preference for Gamma.

E.7 Learning from Past Interactions

Lastly, company agents update their preference in the baseline model based on the update rule R_{UPPREF} (Section 5.4.2.7). The sensitivity of the model is tested by simulating three cases, namely (1) no learning from previous interactions at all; (2) using a success rate of 1.0; and (3) updating the university preference and need for additional input after every interaction, regardless its success.

The results are shown in Figure E.15 and at a first glance, the model does not seem to be overly sensitive to these changes. However, these different learning mechanisms do result in changing retention rates (i.e. the likelihood of a company engaging again with the same university) in the transition matrix for each configuration, which are lower if there is no learning (Table E.5) and higher than the baseline scenario when all interactions are successful (Table E.6) and if the university preference is updated regardless of the success (Table E.7). Because every university is increasing its retention rate, the effects cancel each other out when simply looking at 'ae'.

Table E.5: Transition matrix (I) for the 'no learning' sensitivity analysis.

	-> 1	**-> 2**	**-> 3**
1 ->	0.55	0.39	0.06
2 ->	0.43	0.49	0.08
3 ->	0.42	0.49	0.09

Table E.6: Transition matrix (II) for the sensitivity analysis that treats all interactions as successful.

	-> 1	**-> 2**	**-> 3**
1 ->	0.68	0.28	0.04
2 ->	0.31	0.63	0.06
3 ->	0.30	0.39	0.31

Table E.7: Transition matrix (III) for the sensitivity analysis that updates university preferences after every interaction regardless of success.

	-> 1	**-> 2**	**-> 3**
1 ->	0.71	0.25	0.04
2 ->	0.28	0.66	0.05
3 ->	0.27	0.35	0.37

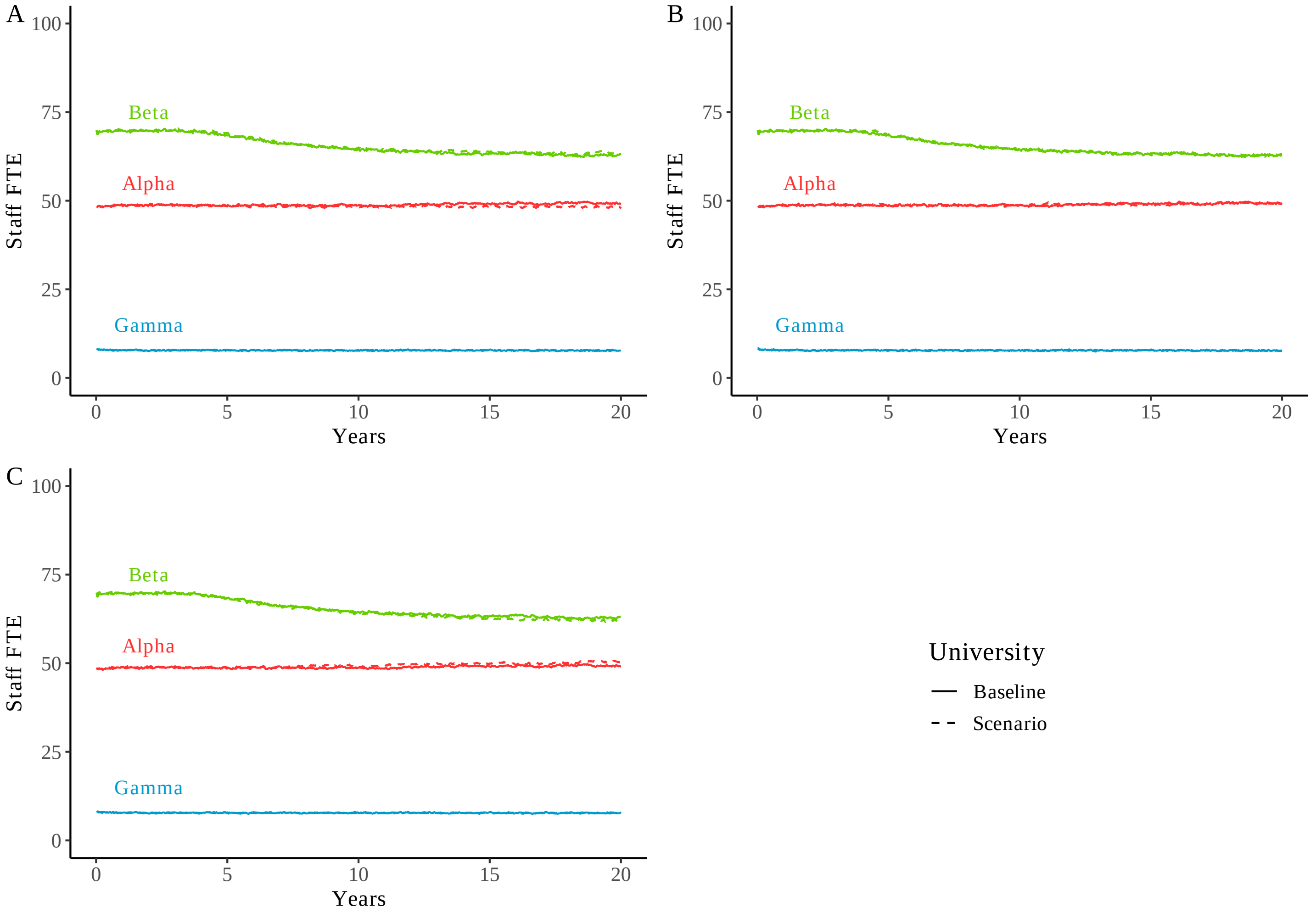

Figure E.15: Simulation output for agent learning sensitivity analysis showing the values for Academic Entrepreneurship ‘ae’ for the three scenarios with the no learning (A), all interactions being successful (B), and updating university preferences regardless of the success of the interaction (C).