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Exploring frameworks for mixing Discrete Event Simulation and System Dynamics methods in theory and in practice

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Declaration

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Abstract

Discrete Event Simulation (DES) and System Dynamics (SD) are popular modelling methods that have a broad range of applications. Both have been successfully applied to similar situations and are mixed with other Operational Research methods to provide insight into the behaviour of systems for organisations. Motivated by support from within the research communities, questions have been raised as to whether the two methods could or should be combined, and if so when and how they could be mixed.

Comparing the methods reveals points of dissimilarity but also of commonality. Consequently, this research considers how mixing these methods may contribute insights into real life problem systems. The multimethodology and simulation literatures clarify how methods could be theoretically mixed and what modellers are doing in practice. Mixed method designs developed from this literature are proposed. Their applicability to the real world was explored through mixed DES and SD example projects, leading to a proposed toolbox of guidelines to reflect upon when considering mixing methods.

Inspired by similarities and differences in the DES and SD model development processes, a model development framework was proposed. The toolbox of designs was placed at its heart to encourage reflection on mixing methods from project exploration and design to analysis and reporting. These frameworks were developed during an action research project within the Beatson Oncology Centre. This enabled their applicability throughout the cycles of model development to be explored in the context of a real, complex system.

The final outcome of this research is a framework to assist mixing methods, through a model development process and mixed method designs. This encourages reflection on how methods are used in a project and enables clear representation of work conducted to facilitate knowledge transfer. Lessons from the project and wider contributions of mixed DES and SD modelling are proposed.

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Figures & Tables

1 Introduction

This thesis is about mixing methods and exploring frameworks to inform mixing simulation methods. It is motivated by the desire to assist modellers in the development of useful, relevant models by developing mixed simulation method designs for consideration within a mixed model development framework designed to inform and describe the models created. A hammer is a useful tool, but is not suitable for all jobs. Sometimes more than one tool is needed for the job and how they are used together impacts on the outcome. This research is focused on System Dynamics (SD) and Discrete Event Simulation (DES), how they are widely applicable to inform on complex problems but individually are not always the only appropriate method. Rather than compromising by making a binary choice, this research explores how the methods might be used together, and what designs could be used to inform the modelling process.

The aim of this chapter is to introduce the thesis by providing the background to the research, highlight why it is relevant and of interest, and what the thesis aims to achieve. This chapter presents the relevance of undertaking this research within the healthcare setting, the value of using models in the health service, and the researcher's view on the role of modelling to inform understanding of a problem system.

1.1 Research Overview

In recent years, mixing Operational Research (OR) methods has gathered popularity. Specifically within both the SD and DES communities there is extensive interest in mixed methods, encouraging modellers to adopt a richer understanding of each method to *"grasp opportunities for making common cause in areas of similarity"* (Lane 2000, p.1). Morecroft and Robinson (2006) highlight the potential for the use of both methods to reveal complementary insights into a complex problem system. Simulation experts have sought to find the holy grail of mixing SD and DES: *"to develop both a conceptual philosophy and a practical methodology for combining SD and DES in a real context"* (Brailsford, Desai and Viana 2010, p.2294), and the practicalities and benefits of mixing the two methods need exploration in order to achieve this.

Debate exists around how to describe DES and SD: as tools, techniques, methodologies or all-encompassing philosophies with which to view the world. Such viewpoints are presented within the literature review (*Chapters 2* & *3*) but for the purposes of clarity and consistency throughout this thesis both SD and DES will be referred to as methods.

Several studies theoretically examine the benefits of DES and of SD within a particular context, and compare and contrast the methods (discussed in *Chapter 2*). Additionally numerous case studies exist which mix the two methods but contain limited discussion of the philosophical, mathematical or practical implications (discussed in *Chapter 5*). The aim of this thesis is to consider if and how the two methods might be used together by looking to the general mixing methods and multimethodology literature, as well as exploring these ideas in practice (*Chapter 6* to *8*).

1.2 Research Context

Both of the methods at the heart of this research are simulation modelling methods. This section defines simulation modelling within the bounds of the research by giving an overview of what a model is, how it is used by modellers and researchers, and the art of the modelling process. This is followed by a brief introduction to simulation modelling, specifically SD and DES, a discussion of modelling within healthcare and why healthcare provides a rich test bed for this research. The section finishes with an introduction to mixed methods, setting the scene for why we are interested in this approach to modelling.

1.2.1 Modelling as a process; an art

A model is seen as the basic tool in OR, providing ways of applying rational analysis to complex issues (Pidd 2003). A model is a device used to depict a system that is trying to be understood or controlled (Urry 1991). It is a statement of the beliefs held, which include assumptions relevant to the issue under study (used to describe the relationship between parts of the system), and the effects of changes to one part of the system on other parts of the whole system. Whether the system modelled is real or imaginary is not important; the focus is that a model should be a purposeful representation of something (Roberts 1978a).

Models may be described as being positioned along several dimensions (Mitchell 1993). One dimension often used to describe models is soft versus hard[1]. Models may be quantitative, qualitative or in the shades of grey in-between depending on the problem system modelled. The art of modelling is trying to find the smallest subset of features that sufficiently captures

1 A hard model is a mathematical representation of the problem, whereas a soft model assumes problem definition is in itself problematic; personal views of the nature of the problem are gradually made explicit and it is this process that takes us halfway to the solution.

the system to answer the question (Ackoff 1973, Shannon 1975). It is not necessary to represent the whole breadth of reality, but for it to be simplified to an appropriate degree: *"model simple, think complicated"* (Pidd 2003). It is the role of the modeller to clearly define the problem and this process can be more revealing and develop better understanding than outputs of the resulting model (Mitchell 1993).

1.2.2 Simulation modelling

The simulation methods of interest in this research, DES and SD, have some common overarching principles that drive them. One of these principles is that simulation is the process of designing a model of a real system in order to conduct experiments with the purpose of understanding the behaviour of the system and evaluating strategies (Pidd 2003). The other principle is that simulation is viewed as a multipurpose method, where knowledge is gained throughout its process (Mak 1992).

SD and DES have both been used to model a variety of systems, and each has played a role modelling healthcare (Eldabi, Paul and Young 2007). A detailed discussion of both methods is included in *Chapter 2*. The general applicability of OR modelling within healthcare, and the appropriateness of a healthcare setting for research is considered next.

1.2.3 Modelling in healthcare

OR has played an important role in healthcare since the mid-1960s, and has become an established form of decision analysis within the sector (Jacobson, Hall and Swisher 2006). Modelling and simulation have a vast range of applications in healthcare (Sachdeva, Williams and Quigley 2007). However, such projects also face key challenges. Projects can be complex and dynamic in nature, and diverse due to the number of potential stakeholders involved. This reflects upon the fact that healthcare modellers operate within a dynamic environment where political and social-economic factors give rise to constant reform within the sector. These issues and challenges, as discussed by Carter & Blake (2004), Gunal & Pidd (2005), Proctor et al. (2007), Harper & Pitt (2004) and Lane et al. (2000), can be broadly grouped into three categories: process complexity, data concerns, and stakeholder buy-in. Healthcare presents a complex environment for both an OR modeller, experiencing more than purely operational issues. This offers a rich setting for research which could expose practical considerations/constraints not revealed in a simple system.

The unique nature of healthcare projects means that each hospital system is different and experiences different issues. Healthcare modelling is often done on an isolated system, failing to account for the impact of processes outside the modeller's view. Systems can appear to be contained (Gunal and Pidd 2005), but in fact have numerous ties to and from other departments (Lane et al. 2000). This process complexity can mean that a single method is unable to capture the interconnectedness of the system. Healthcare systems offer a context in which simulation has been previously utilised but can still benefit from the methods in the same way as business and manufacturing (Kuljis, Paul and Stergioulas 2007); offering a potential environment in which to explore mixing DES and SD.

1.2.4 Mixed Methods Modelling

The terms multimethodology and mixed methods are used interchangeably throughout this thesis. Although multimethodology might be considered to represent a wider field than just OR/MS methods, OR/MS will be the boundary of this research.

Mixing methods is the combined use of two or more different OR/MS methods within a single project. Mixing methods holds the potential to provide better solutions, eliminating the compromise required when selecting a single method and reducing the limitations that are inherent within methods.

1.2.5 Summary

The model development process can be as or more important than the model outputs and so mixing methods should not only focus on the outputs but be considered for their contribution throughout the modelling process. This research will focus on how methods are mixed within the model development process rather than on the specific outputs of the models. It seeks to contribute to the overall art of the modelling process rather than appending the concepts of mixed methods to a single part of the model development process or proposing a single unique solution without reflecting on lessons.

1.3 Research Aims & Approach Adopted

This research seeks to explore what has been done in the field of mixed methods, and mixing DES and SD. It remains unknown how mixed methods fits within the DES and SD model development processes, and if frameworks can be used to inform this process. The main aim of this research is to explore frameworks to support mixed DES and SD modelling.

This research aim is explored first through the examination of the literature to develop a base theory which is then further developed and informed by the action research project. Learning points from the project will be reflected upon to adjust the designs and framework and the benefits of the mixed methods modelling will be examined. The philosophical stance of this researcher is ‘critical realist’ as according to this philosophy it is believed that multiple views of the real world can inform a clearer picture of the real world. There is a benefit to acquiring multiple views to a problem situation. The methodology for this research is discussed in full in *Chapter 4*.

1.4 Overview of Contributions

This research seeks to add to the selection of modelling methods which might be employed within a project by an OR practitioner. The methodology a modeller selects for a project is informed by their existing training, understanding and experience in practice of methods. By first examining the characteristics and relative strengths and weaknesses of DES and SD, as well as looking at mixed methods projects in the literature and multimethodology theory we incorporate mixing methods within a general model development process. This incorporates mixing methods throughout all stages of the model development process as at the heart of this process is a toolbox of mixed method designs to reflect upon when selecting appropriate project methods and modelling project design. This appreciation of mixing methods is proposed in the form of a decision tool of mixed method designs which form the key contribution of this thesis. This work provides structure to the mixed methods modelling process and the proposed designs are used to encourage the modeller’s consideration of mixing DES and SD, which is explored through a healthcare project. This research presents a common language for mixing DES and SD which may be applicable to the wider mixed methods community.

1.5 Structure of the Thesis

This thesis is presented as nine chapters which cover: an introduction to the research context and why it is interesting; a review of the DES, SD and mixed methods literature; the research methodology; the theoretical development of mixed methods frameworks; the action research project undertaken; and conclusions of the research. The structure of the thesis is illustrated in Figure 1.

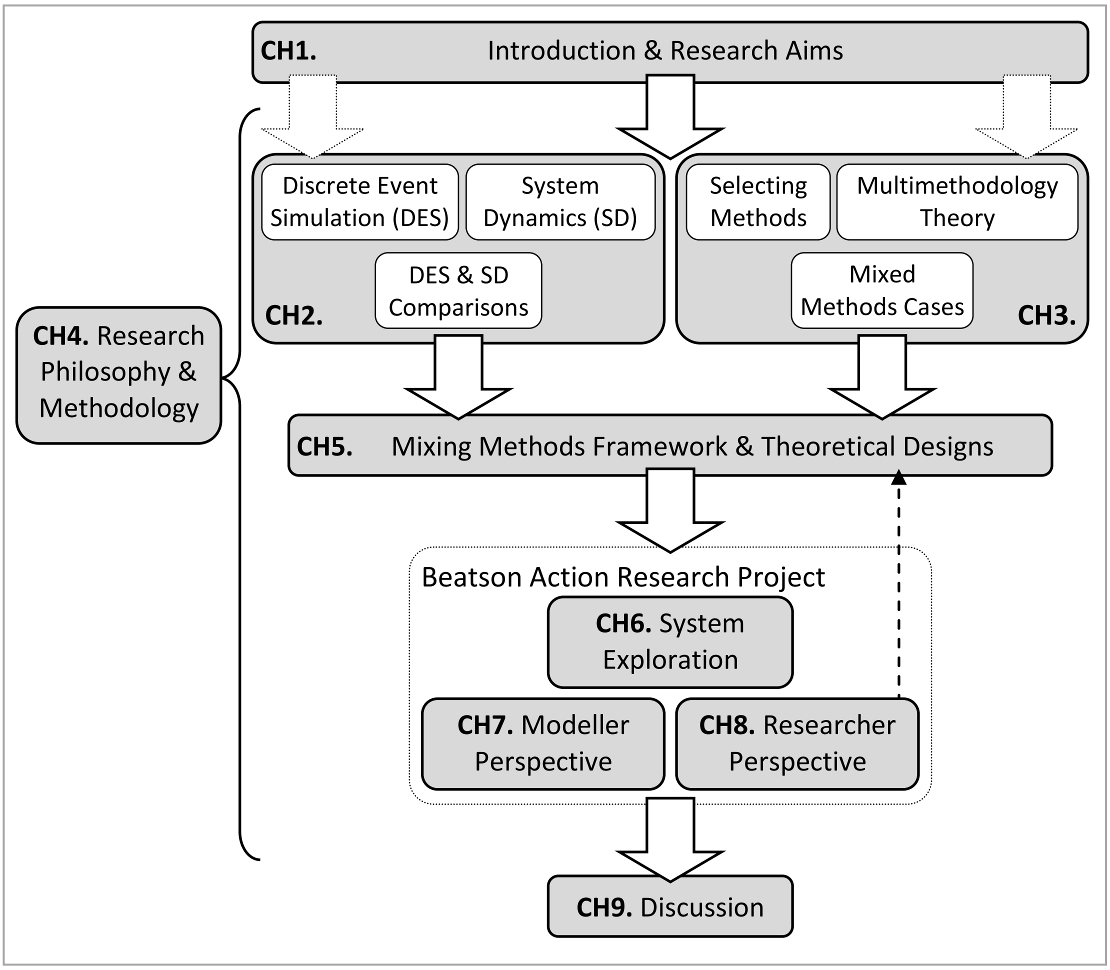


Figure 1: Structure of the thesis

The chapters of this thesis are presented as follows:

Chapter 1 provides an overview of the research context, discusses the relevance of healthcare modelling to explore the mixed use of SD and DES, and presents the research motivation.

Chapters 2 and 3 present the literature review undertaken to reveal the research gaps and the existing work in the field that underpins the research. *Chapter 2* discusses the components and characteristic of DES and SD and concludes with a comparison of the similar and differing philosophies, methodologies, tools and features of these methods. *Chapter 3* introduces the theoretical concepts of multimethodology, considers how these apply to this research and examines mixed methods cases which provide insight into how methods have been used together in the past and to what end.

Chapter 4 presents the methodology for this thesis following the research gaps highlighted in the two previous literature review chapters. It presents the philosophical standpoint of this thesis and the methodology undertaken to address the research gap. This chapter may be seen as an overarching chapter for the thesis, as illustrated in Figure 1.

Chapter 5 brings together *Chapter 2* and *Chapter 3* to reflect on how DES and SD could be mixed and presents elements that the researcher believes should be considered when undertaking a modelling project. A framework is introduced to incorporate these mixed method designs into the model development process.

Chapters 6 – 8 present the action research project undertaken to develop and reflect on the theoretical frameworks proposed in *Chapter 5*:

Chapter 6 takes the outcomes of *Chapter 5* into an action research setting and presents the background and context of the modelling project undertaken with the Beatson West of Scotland Cancer Centre. It shows that the system exploration and problem structuring work undertaken to ensure an issue pertinent to system stakeholders was selected and that a representative view of the system was obtained by the modeller. The chapter concludes with the selection of the theme of the project and the preliminary design of the modelling project.

Chapter 7 presents the modelling project from the perspective of the modeller. This chapter documents the modelling process and the model outputs with the client's needs as a priority. The focus of this chapter is the value of the models at each of the iterative stages of the modelling process and the final outcomes of the project for the client.

In contrast, *Chapter 8* reflects on the modelling project from the perspective of the researcher. It considers the balance to be struck between the needs of the client and of the research goals. The decisions of the researcher at each iterative stage of the modelling process are discussed and additional theoretical modifications to the models which might have been made, but were deemed unnecessary from the modeller perspective, are presented.

Chapter 9 concludes the thesis with an evaluation of the research versus the research agenda and discussion of the key contributions of the research. These are followed by reflection on the limitations of the research and consideration of further work in this field.

The next chapter will consider the following research questions through a review of the literature:

Q1. *How have DES and SD been used on their own and together to inform on issues important to key stakeholders in the past?*

Q2. *How do DES and SD compare, in terms of similarities and differences in their methodology, philosophy, application contexts and problems addressed; and, given these similarities and differences, what are key elements of complementarity?*

2 What are DES and SD?

2.1 Introduction

The previous chapter outlined the initial motivation of the research, gave an overview of the research context and aims, and presented the structure of this thesis. This chapter is the first of the two literature review chapters which expose the research gaps within the research aim. It presents a review of System Dynamics (SD), Discrete Event Simulation (DES), and the similarities and differences of the two methods to provide the same basis for comparison. This comparison of the methods enables exploration of points of commonality and consideration of how the two methods might complement one another, and therefore the potential of mixing the methods. The chapter concludes with the gaps in the existing literature regarding how SD and DES compare, how the classic[2] (or traditional) views of the methods might be adjusted and how this holds the potential for mixing methods.

2.1.1 Research boundary

Both SD and DES have been adopted within a range of fields but this research will centre on how they are used within the Operational Research (OR) / Management Science (MS) community. Insights are drawn from engineering and computer science where relevant case studies exist in the literature. Both the SD and DES communities show interest in the mixing of methods, specifically with each other and continue to seek to cross the divide between the two fields and reach the holy grail of mixing.

2.1.2 'Method' versus 'Methodology'

As will be discussed in the ensuing sections, there is debate around how both SD and DES should be defined: as OR tools or techniques, methods, methodologies or as wholly encompassing theoretical frameworks (paradigms). The terms paradigm, methodology, method and tool or technique, are subject to *"various interpretations"* (Mingers and Brocklesby 1997, p.490). Throughout this thesis, the following definitions will be adopted:

Tool / Technique – *"procedures which lead to an end point without need for reflective action"* (Mingers et al. 1997, p.2);

Method – a formal structure consisting of tools and techniques;

[2] *'Classic'* is a term used by Rawlings (2000) to refer to the original intentions and perceptions of a method. *'Traditional'* may be used interchangeably with *'classic'*, as is done by Johnson and Eberlein (2002) when discussing how their model could be adjusted to a more *"traditional system dynamics"* model (p.10).

Methodology – a structured set of methods within a larger process of judgement and interaction (Mingers et al. 1997): it is *"any kind of advice given to analysts about how they should proceed to intervene in the real world"* (Jackson and Keys 1984, p.477);

Paradigm – general set of philosophical assumptions that characterise the nature of the project.

As was discussed in *Chapter 1*, for consistency throughout this thesis both SD and DES will be referred to as methods. That is not to say that SD and DES will be viewed strictly and only as methods, as defined above. The term method is used by the researcher to reduce the chance of confusion when the term methodology is utilised to refer to the structured set of method(s) applied to a project.

2.1.3 Chapter structure

This chapter commences with definitions of SD and DES; their characteristics, the types of problems they are used to address, the systems that have been modelled and their applicability to healthcare systems. The methods are individually examined to capture their spirit and flavour in the OR field which provides the same basis for comparison, revealing points of similarity and difference, their complementarity, and their usefulness when used together. Figure 2 depicts the structure of this chapter within the overall literature review.

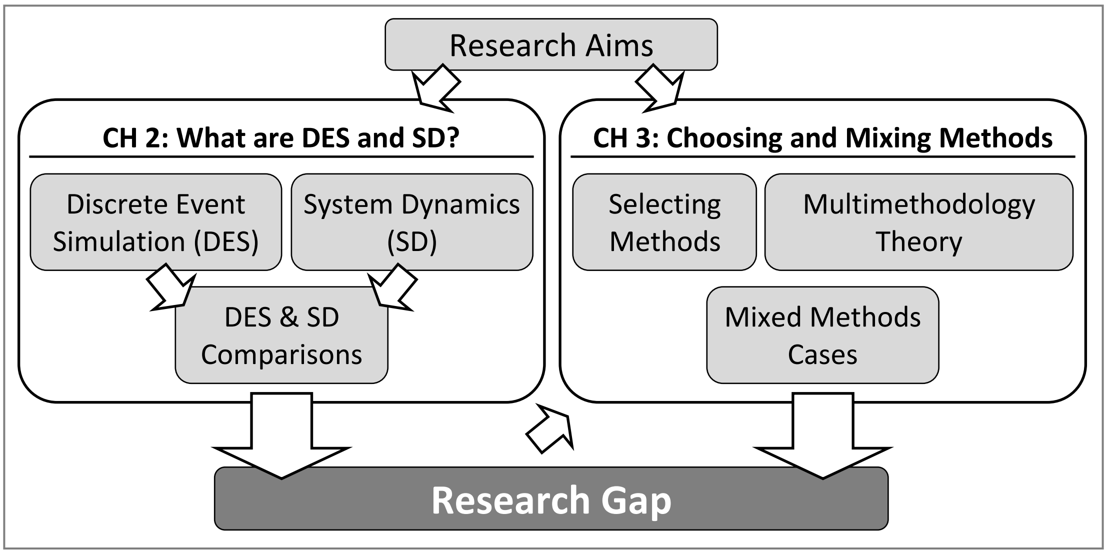


Figure 2: Structure of literature review chapters

The aim of this chapter is to present the motivation for this research, review SD and DES to highlight the potential of mixing, and present the research gaps which will be explored in the second part of the literature review (*Chapter 3*) and throughout this thesis. This chapter considers the following research questions through a review of the literature:

Q1 - *How have DES and SD been used to inform on issues important to key stakeholders in the past?*

Q2 - *How do DES and SD compare, in terms of similarities and differences in their methodology, philosophy, application contexts and problems addressed; and, given these similarities and differences, what are key elements of complementarity?*

2.2 System Dynamics

This section will outline the principles and characteristics of System Dynamics (SD), by considering key works in the field, the range of applications for the method, and its relative strengths and weaknesses. It will demonstrate the power of SD, the breadth of application and how this leads the researcher to conclude that it has the potential for combination with other methods.

2.2.1 Origins of SD

SD was developed through work at MIT in the 1950s, and was first broadly presented and put to theoretical use by Jay W. Forrester in the Harvard Business Review (1958) under the title ‘Industrial Dynamics’. Engineers have used control theory to model feedback systems via differential equations, and Tustin (1953) discussed applying this modelling approach to social-economic systems. Forrester was first to adapt the process to model industrial problems, and provided a systematic way of simulating such systems. The method is based on the philosophy of systems thinking: that a system should not be regarded as a sum of parts (Forrester 1961); *“it is an indivisible whole. It loses its essential properties when it is taken apart.”* (Ackoff 1973, p.664)

Forrester (1958) describes the method as a professional approach to management: to assist managers in understanding the dynamic within an organisation, leading to improved use of information and a focus on strategic issues. It is described as a unique approach, in contrast to other methods adopted in management research, social science and economics, as it was *“developed through intimate contact with the real worlds of practicing management and politics”* (Forrester 1992, p.8). The method was designed with the purpose to discover the underlying principles of system behaviour by bringing together the multiple views of management; a tool to aid conversion of experience into general theory (Forrester 1958). It is a method for analysing complex systems allowing for the inclusion of relevant cause-effect relationships, time delays and feedback which account for most of a systems (unexpected) behaviour.

2.2.2 Tools and distinctive characteristics of SD

A SD view of the world is such that the characteristic behaviour of a system is generated by the elements within the system interacting and their interaction with the environment (Pidd 2004). SD models are, in general, a macroscopic view of a system, with an interest in how the system structure impacts the system behaviour, recognising that the behaviour of individual components of a system is distinct from the behaviour of the system as a whole. The method is *"the design of harmonious combinations of policies and feedback structures which are appropriate to the behaviour required of the system"* (Coyle 1983, p. 369).

2.2.2.1 Model features

SD is recognised for its ability to represent feedback in systems and is a variation of continuous simulation modelling. Continuous simulation is a simulation in which the state variables change continuously with respect to time. The system may be graphically represented as a smooth, unbroken line as the relationship contains no sudden jumps, breaks or steps. SD may be characterised by its three key elements: levels and rates, and delays:

- **Levels** are used to represent the current state of the system, and are essential in SD models to understand the system and determine appropriate action. Levels[3] are defined as the accumulations within the system (Forrester 1961), influenced by the in and out flows.
- **Rates** represent the activity within a system, and it is these that determine the levels. They represent the present, instantaneous flows between the levels.
- A **delay** is *"a process whose output lags behind its input"* (Sterman 2000, p.411). Delays are an aspect of everyday life and occur for all manner of legitimate reasons which may describe the behaviour of a system. They are used in SD to represent the time it takes to measure and report information, make decisions or update stock. It may be possible to reduce some delays at a cost; conversely, some delays may be intentionally introduced as an appropriate lag may help produce a desired outcome.

[3] Levels do not have to be physical and may represent information levels, for example inventories and bank balances are levels, as are levels of satisfaction and desirability

2.2.2.2 Explicit representation of feedback

Feedback exists where *"an action-taker will later be influenced by the consequences of his actions"* (Roberts 1978b, p.7), and a feedback system is one which contains two or more interconnected loops. The two types of feedback are:

- **Positive:** Acts reinforce a change in a system level and increase the level further in the same direction as the initial change. This may lead to an ever increasing system.
- **Negative:** Goal seeking behaviour as the system attempts to move a level towards some desired target by creating action in the opposite direction.

Understanding the loops that exist in systems can help introduce appropriate policies and thus reduce the gap between the desired and realised values. This feedback is a key characteristic of SD modelling and SD can be useful for finding levels of stability, capturing the stability of feedback loops, and using this information to predict unanticipated side effects of altering a system variable (Martin and Raffo 2000).

2.2.2.3 Continuous variables, parameter estimation & aggregation

SD is able to represent continuously changing variables and the interaction between them (Martin and Raffo 2000). This means that it is effective at representing large (uniform) populations and simulating these systems quickly. However, this means that individual entities are not represented implying individual entity attributes cannot be utilised, observed and measured.

SD models are able to capture informational as well as material flows. This leads to an insightful view of the system but it is important for parameter estimation to be carried out subjectively, preferably assisted by expert opinion. SD models may also be described as comparatively insensitive to parameter fluctuations (Sharp and Price 1984). The models cannot easily represent variability, which is inherent in the estimated point values used, and the models fail to capture the variability in the data (Doebelin 1998). This means that data used within models and tipping points for changes in model behaviour should be carefully examined.

The term aggregation appears to be controversial within the discipline of SD. It may be said that detailed component descriptions are traded off against the potential to enable understanding of the behaviour of complex systems made from many components. *"The interactions between system components can be more important than the components* *themselves"* (Forrester 1961, p.14) and there is a need to distinguish between important factors in a system, and *"combine similar factors into a single aggregate"* (Forrester 1961, p.109). Aggregation does not imply unnecessary simplification; it is the inclusion of important factors at the necessary detail.

2.2.2.4 Summary of SD characteristics

The descriptions available of SD raise the question as to whether it is a tool, a method, a methodology or a paradigm. This appears to remain an unresolved issue with several authors using each of these terms to describe SD. Lane (1999) highlights the multiple views that may be held on SD depending on the paradigmatic view of the modeller. The system dynamics society (2009) refers to SD as a 'methodology'. Coyle (1983) discusses the 'paradigm' of SD, implying that it is closer to an encompassing philosophy; yet also describes it as a procedure of clearly defined iterative steps, supported by theory, planned to take an analyst from A to B, which is 'methodology'-like. Further to this, Lane (1999) asserts the belief that Forrester's ideas operate at the 'method' level and are not restricted to one paradigm, describing how SD may be redrafted. This demonstrates the range of views held on how SD could be defined, and that it may not be viable to use it within alternative paradigms or in conjunction with other methods. This viability alters depending on the perspective the modeller adopts.

Additionally, there is debate within the community about the qualitative and quantitative nature of SD. Wolstenholme (1999b) asserts that SD may be either and proposes mixing the two forms within projects. Different modellers may approach the method differently, and this flexibility on the quantitative-qualitative spectrum may allow modellers to stretch the boundaries of SD. The characteristics discussed above all contribute to the look and feel of SD models. The modelling process undertaken is what gathers, defines and populates these characteristics, and where along the quantitative-qualitative spectrum that a specific application of SD fall. The modelling process is discussed in the following section.

2.2.3 The SD modelling process

The process of developing SD models involves the stages embarked upon to build and experiment with models: the model development process. Tools which are employed within this process are also discussed. These are the dynamic hypothesis and reference mode, which are utilised to present the definition of the problem, and system archetypes, which are standard ways to represent system behaviour.

2.2.3.1 *Model development process*

Randers (1980) describes a four stage process of conceptualisation, formulation, testing and implementation (on the left hand side of Figure 3). Richardson and Pugh (1989) present a similar process with conceptualisation deconstructed into 3 stages: understanding the system, problem definition and system conceptualisation. Morecroft (2007) and Pidd (2004b) both present similar versions of the model building process in SD, consisting of problem articulation which can include mapping; formulation using stock and flow diagrams; model simulation; and finally transfer of insight. Sterman (2000) explicitly emphasise the cyclical nature of the steps for model building in SD (illustrated in Figure 4), whereby stages 1 and 2 are equivalent to the conceptualisation phase presented by Richardson and Pugh (1989).

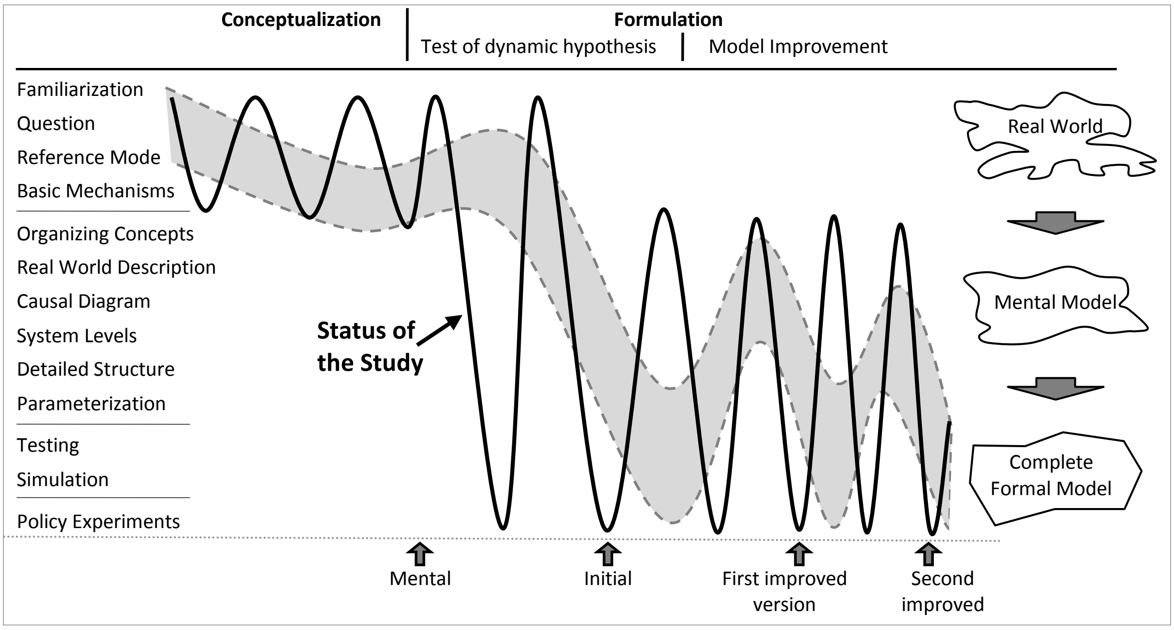


Figure 3: The recommended modelling procedure (Randers 1980, p.135)

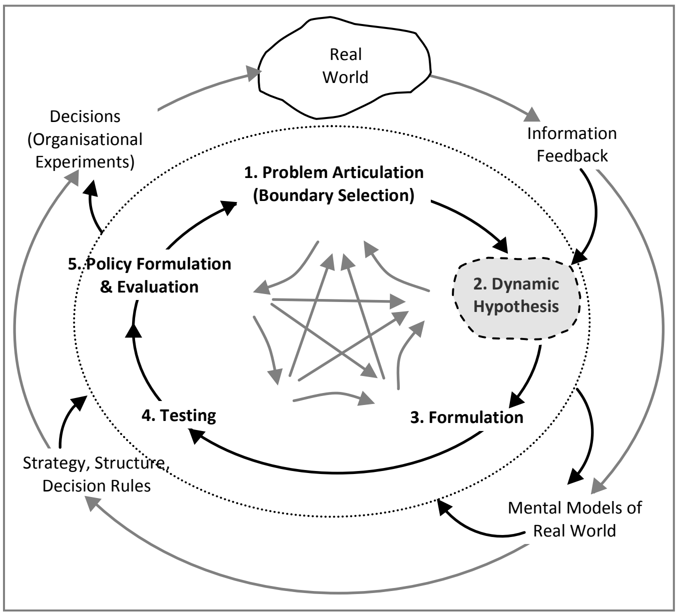


Figure 4: The Iterative Modelling Process of SD (Sterman 2000, p.87)

All of these forms of the SD modelling process put forward contain similar stages, cyclical in nature, with a clear view to reflect on and revisit the stages of the process. Each modelling process has a clear reference to the real world throughout and consists of key stages – conceptualisation, coding, and analysis – which are generally applicable to other general modelling processes. The process should fluctuate between mental models and the real world to create a formal model of the problem system (Randers 1980). These mental models may then alter the shape of this reality which in turn can change the nature and design of the model(s) produced.

The SD approach to building models is important because if we are interested in mixing SD and DES we need to consider the compatibility of the model development processes alongside the compatibility of the models they are able to produce. In light of the consistent view within the field regarding the overall process of model development we will now consider distinctive features often incorporated within this process.

2.2.3.2 Dynamic Hypothesis & Reference Mode

The reference mode helps to determine what to include and what to exclude (Randers 1980b) and takes the form of historical graphs over time[4]. It is the articulation of what will be examined or monitored over time (Meadows 1980). Causal maps (which are discussed further below) may be used to illustrate the causal relationship believed to generate the

[4] If available – graphs are hypothesised if historical data is not available.

reference mode of behaviour over time, and form an articulation of a dynamic hypothesis (Homer and Oliva 2001). This explicit representation of a hypothesis of how the system works, and the drivers of the problem, is characteristic to the SD method, forming a vital point for modellers to reference and reflect upon throughout a project.

2.2.3.3 Diagrammatic representations in SD

Information about the system, such as mental models, may be represented diagrammatically to organise information about the system under study. Principally this may be through a Stock and Flow Diagram (SFD) and Causal Loop Diagrams (CLD). Further structuring diagrams have been developed and other schemas include influence diagrams, causal maps and signed digraphs (Keys 1991, Morecroft 1982) but are not discussed here.

Causal Loop Diagrams (CLDs) are visual tools used to hypothesise how the underlying structure is causing and maintaining behaviour (Roberts 1978a). The diagrams are mental models to capture cause-and-effect relationships and are used to explicitly represent the feedback loops believed to generate the observed performance. CLDs are regarded by some as the basic tool for developing an SD model as relationships can be constructed from physical and informational flows (Coyle 1977, Wolstenholme 1982).

Stock and Flow Diagrams (SFD) are formal flow diagrams to openly document the model (Roberts 1978a). It is suggested that an SFD is developed simultaneously with the system equations (Forrester 1961). Most SD software's encourage this with the equations defined within the diagram, and some relationships defined automatically as elements are added to the model (such as in VenSim®, Vetana Systems Inc.). These diagrams may capture the physical qualities of the system, such as decisions, levels, rates and flows.

2.2.3.4 System archetypes

"Archetypes capture the essence of 'thinking' in systems thinking" (Wolstenholme 2004, p. 342). They allow the modeller to reduce a model down to its basic loops, and allow the modeller to locate opportunities for change within a system (Flood 1999). They are generic causal loop structures that form templates of system behaviour which *"can be used as free-standing solutions to complex issues"* (Wolstenholme 2004). One or several interconnected archetypes may capture the observed behaviour and provide an explanation for the puzzle (Flood 1999).

When modelling in SD the focus is first to conceptualise the system; constructing the causal structure and examining feedback (Morecroft 1982, Randers 1980). This form of causal modelling is a significant departure from others such as econometric modelling whereby the structure is more depending on the availability of data (Sharp and Price 1984). This is because the focus of the process is modelling the system rather than on whether the data can be captured to fill the variables included. The quality of the model is dependent on the quality of the definition of the internal structure and interactions (Wolstenholme 2003). During the modelling process, system archetypes can be used to help inform the model-builder of the simplicity underlying the dynamic complexity within the problem situation. Using standard definitions of the interactions within systems (such as archetypes or sample models) may then contribute to the quality of the model(s).

Originally associated with group model building, but also applicable to SD modelling in general, is recognition of two modes of practice in SD model building: developing models as micro-worlds of the system and using the model as a boundary-object to create shared understanding (Zagonel 2002). Group model building ideally strives to achieve both, and SD may also be used in this dichotomous way. Therefore SD models may be used in a spectrum of ways (Bayer, Brailsford and Bolt 2009), occupying a variety of roles according the degree to which they utilise these modes: from careful replicas of the real world (micro-worlds) to models as boundary-objects to build consensus.

2.2.4 Practical applications & issues addressed using SD

The first SD models addressed problems such as: inventory fluctuations, instability of labour force, falling market share (Coyle and Alexander 1997, Forrester 1968b, Richardson and Pugh 1981, Roberts et al. 1983, Wolstenholme 1990). It has been and continues to be applied to a broad range of applications such as business problems, corporate strategy, public policy, and improving project management (Sterman 2000), developing both organisational and strategic models (Roberts 2007).

As mentioned previously, SD is applicable to a broad range of problems. The driving force 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). Thus, SD is often used for strategic issues such as: policy analysis (Taylor and Lane 1998) and assessing the potential impact of altering services (Taylor and Dangerfield 2005#37). Taylor and Lane (1998) suggest that there was no reason why SD should not be as commonplace as DES when analysing policies in healthcare. Taylor and Dangerfield (2005) go on to write that SD can be of more benefit to healthcare issues than DES as it is able to appreciate the whole system and underlying feedback; and, supporting this, Lane and Husemann (2008) note that, when considering acute patient flows, working with maps helps participants to assess new proposals in a richer context.

2.2.5 SD summary

The above discussion highlights how SD has numerous strengths and offers a clear, considered approach to modelling systems. What may also be noted is that the discussed weaknesses of the method may in fact be offset more effectively using alternative OR/MS methods or indeed simulation methods. SD is effective because solely focusing on individual events, and remaining focused on short term goals and single measures of performance can lead to ineffective conclusions being drawn and ineffective policies being implemented (Taylor and Dangerfield 2005). However, for all its strengths, it *"is NOT the only pebble on the beach and it is not the most appropriate approach to all problems at all times"* (Coyle 1977, p.355). It is Coyle's own emphasis on the 'NOT' that forces the reader to acknowledge the strength of this statement. It would be easy to start to believe that SD is capable of tackling any system or indeed question thrown at it. Having a view of other pebbles, methods, may help to inform a modellers selection of the method(s) to be used in a project; to enable them to explore what or if other methods may be preferable and/or useful.

2.3 Discrete Event Simulation

This section will discuss the origins of DES, the distinctive characteristics of the method, and how DES models are developed. The section concludes with an overview of the problems and systems the method has been applied to, and thoughts from within the field on the future of the method.

2.3.1 Origins of DES

DES is a simulation where the dynamics of the system are triggered by events. It seeks to represent the movement of individual items through a system, and allows values such as the time spent in a system to be investigated (Harper, Phillips and Gallagher 2005). DES packages express the flow of work, one event at a time, often illustrating all the key interactions graphically.

The significant events in the development of DES were the technology growth and hence the portability of software, availability of micro-computers and then personal computers, introduction of graphics (providing a visual means to understand the model) and onto simulation optimisation, virtual reality and software integration. This research will not discuss the history of DES as two papers provide a comprehensive overview: Hollocks' (2006) paper provides detail of the history of DES over the period 1964-1992; while Robinson (2005) provides focus on 1950-1980, then post 1990.

2.3.2 Tools and distinctive characteristics of DES

This section discusses the tools that make up the method and the characteristics that help to distinguish DES from other simulation methods.

2.3.2.1 Queues & servers

The method may be characterised by its representation of queues and servers. Most DES packages consist of these components: entities, activities and events, and resources (Taylor and Robinson 2006). It is a simulation that pushes entities through blocks (Borshchev and Filippov 2004) and so most DES models contain considerable detail and present a microscopic (in depth) view of the system (Pidd 2004a). As a result, DES modellers represent the detail of the system, an operational view.

2.3.2.2 Randomness

The variability inherent in everyday life can be captured: randomness can be included easily within the models to allow for the natural variation observed in the system. Further to this, the multiplicative effect over time of stochastic elements can be observed. A particular area commonly investigated within DES is the impact of varying arrivals to a system on the queues. In this case, it is possible to directly observe the queues building within a system, interrogate the sources of the problems and experiment with ways to alleviate the issues. Additionally, although the models can be stochastic, they essentially include static numbers that vary according to distributions. A criticism of this is that over an extended period of time the model fails to acknowledge seasonal change and fluctuation (Taylor and Dangerfield 2005). Although such seasonal behaviour can be programmed into DES models, response to fluctuations and adaptation in response to the status of the system are not traditionally captured within DES models.

One distinct area of criticism of DES is its failure to model feedback. However, this may be modified to be that is does not explicitly represent feedback, as feedback within the system may be accounted for implicitly in the data used, the variability of parameters and in the decisions made.

2.3.2.3 Interactivity & model detail

DES software packages are often visually rich, with drag-and-drop led model building rather than only allowing models to be created by coding. These software packages provide the user with a visual aid that can enhance buy-in and acceptance of the model. For example, it is possible to directly observe queues building within a system, interrogate the sources of the problems and experiment with ways to alleviate the issues. Additionally, individual items or people are able to be easily represented in the model which allows attributes to be assigned, enabling individual behaviours to be modelled.

The method has widespread appeal as it allows a modeller to produce a simulation that may be a direct physical representation of the system under study. The models represent behaviours at an individual entity level; with complex behaviour emerging. It is possible to capture the physical movement throughout the system and study it at a level at which the system owner is able to compare the physical interactions of the model with the real-life system. The look and feel can provide an easily understandable version of the system, without a requirement to understand complex mathematical functions.

This interactivity and detailed visual appeal can, however, come at the price of model development and computation time as large simulations can be timely to build and run. DES models with a large number of elements require extensive testing but the interactive visual nature of the method can provide *"Operational Graphics … visually displayed as the simulation model runs through time to ensure they behave correctly"* (Sargent 2008, p.161) and assist with validation.

2.3.3 The DES modelling process

There are many *"flavors and paradigms in discrete-event simulation"* (Ingalls 2008). Unlike SD, a well-developed philosophy of practice does not exist in DES (Robinson 2005) as the methodology of building simulation models has evolved over time. There are recommended model development steps but as the method was developed by numerous people simultaneously[5], the method has flexibility (Robinson 2005). DES may be regarded as a methodology in its own right or as a tool that lies within an overarching simulation methodology toolkit[6]. This use of DES as a 'tool' within a wider methodology alongside other methods highlights how the method is adaptable and suitable for mixing with other methods.

2.3.3.1 Model development process

As a well-developed philosophy of practice does not exist for DES, work remains throughout the modelling process, and specifically to formalise the process of conceptual modelling (Robinson 2005). This is because published work focuses on the scientific approaches and the development of complex models rather than the initial (model development) stages of projects. Conceptual models are sometimes presented prior to explaining the full DES model but the process of development may not be discussed, as in Lara and Dickson (2008). Rather, the conceptual models are often developed to directly inform the simulation model build and do not explicitly consider the wider problem context or show what was excluded.

Although various model development processes are recommended in the literature, all include similar core stages and are similar to the general frameworks for developing models in the OR/MS literature. Two examples of recommended steps for DES modellers to follow are shown in Figure 5 and Figure 6. The first, provided by Banks et al (1996) illustrates the

[5] On both sides of the Atlantic (Hollocks, 2006)

[6] As discussed in section 2.1.2 DES will be referred to throughout as a method to reduce the chance of confusion throughout, but does not mean a restricted view of DES is adopted.

core steps in a mainly linear manner. An alternative representation of the process in Figure 6, from Brooks and Robinson (2000), further emphasises the recommended non-linearity of the process, in a framework that could be equally applicable to general OR modelling.

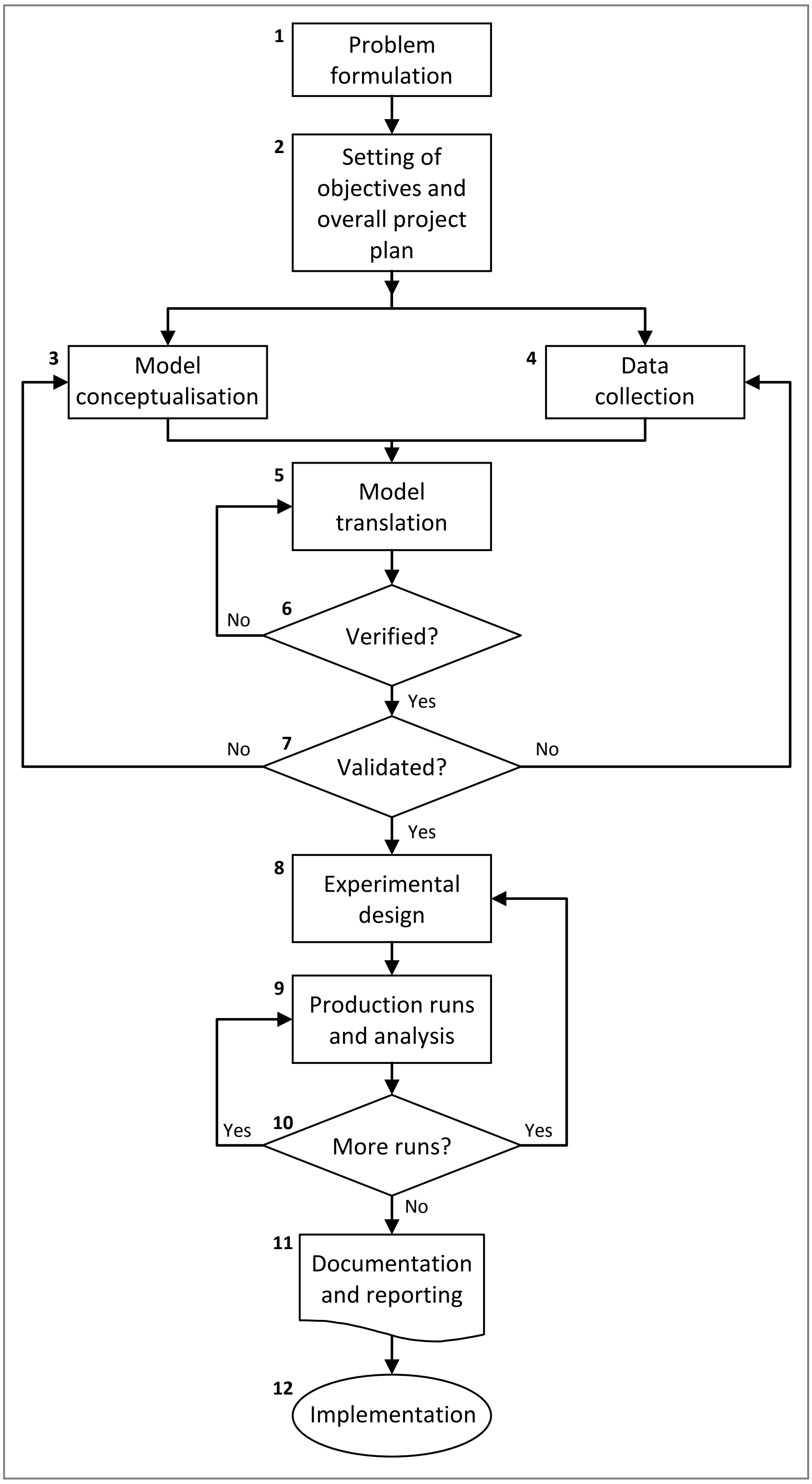


Figure 5: Steps to a thorough and sound simualtion study (Banks et al. 1996, Figure 1.3)

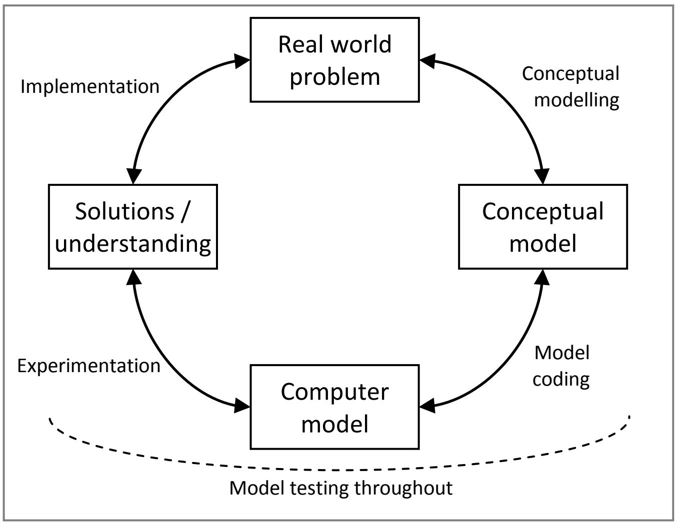


Figure 6: DES modelling process (Brooks, Robinson and Lewis 2001)

2.3.3.2 Conceptual modelling

Conceptual modelling is a key element to the model building process. It is *"the process of abstracting a model from a real or proposed system"* (Robinson 2008, p.278); it is the activity in which the model builder seeks to capture the essential features of the system under study (Pidd 2004a). However, a conceptual model does not contain information on how the computer simulation is or must be coded (unlike a SD stock and flow diagram). Advocates of DES view conceptual modelling as the intermediary phase whereby the modeller moves from a problem situation to a definition of what will be modelled.

Figure 7 demonstrates the conceptual modelling stage of a DES modelling project. It shows a clear two way relationship with the problem situation which is referenced when determining the model content and level of detail. This has clear parallels with the iterative relationship between problem articulation or conceptualisation and model formulation in SD.

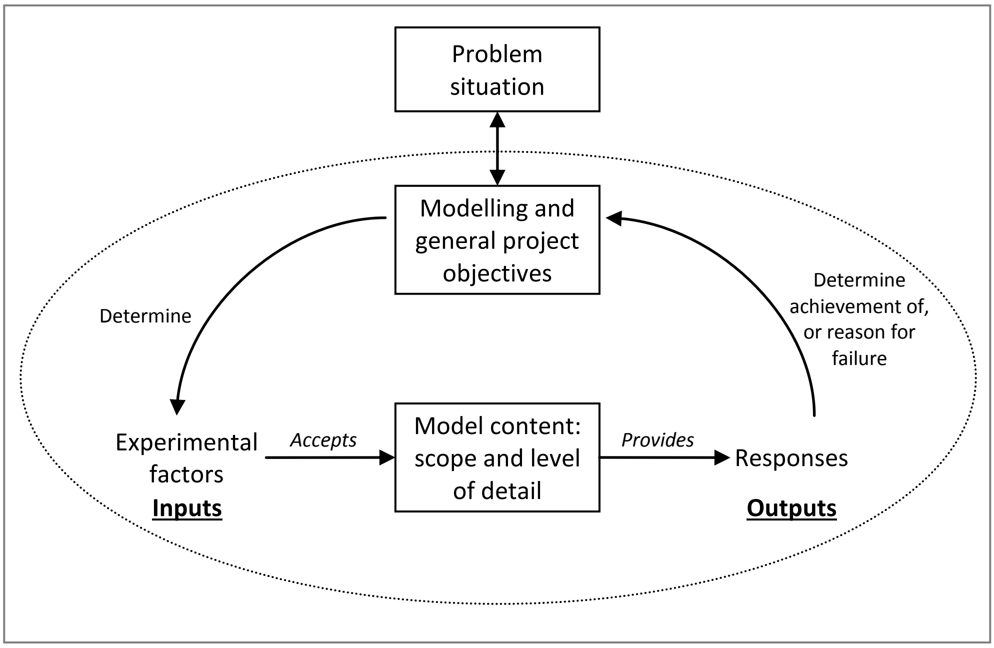


Figure 7: A Framework for designing the conceptual model (Robinson 2008)

There are four main methods for representing conceptual models (Robinson 2004, p.73-74):

- *Component list*: a simple list of all components to be included in the model with some description of the details needed
- *Process flow diagram* aka a process map: illustrates the sequence of the components
- *Logic flow diagram*: utilises standard flow diagram symbols to represent the logic requiring model coding (rather than the flow of entities)
- *Activity Cycle Diagram* (ACD): specifically used for DES (Hills 1971). The method lends itself to representation of queues and servers (Lehaney et al. 1998), illustrating the alignment of DES with queueing theory

Other conceptual modelling methods associated with DES include: petri nets, event graphs, digraphs, UML (unified modelling language), object models, simulation activity diagrams. Many methods are available to the modeller and so personal preference or previous experience is likely to drive selection.

2.3.3.3 Model validation

A criticism made of DES may be that it is hard to assess quality of the model as the situation is likely to have altered since the model was built: the model is only a snapshot of the here and now (Robinson 2002a). However, this is true for all simulation methods: they are only able to capture the system under study as it is at that moment in time. It may be argued that the time taken to develop a DES model, and its (often, but not always) strong dependency on the data within the model may mean it is out of date before a study is completed. This can be dealt with in part by the use of sensitivity analysis to assess the models dependency on the parameters used.

2.3.3.4 Model development summary

It may be said that DES has a characteristic style of entities, queues and servers. However it is proposed that DES may have different characteristics depending on the problem situation it is applied to. The application of the simulation method may be described as hard when seeking an accurate representation of a situation (simulation as software engineering) and soft when utilising it for problem understanding, as demonstrated in Figure 8. DES cannot be viewed as a single tool that is used identically across all projects, but there are common features of the model development process that are emphasised or not depending on the problem system. There is a spectrum of approaches to applying DES on the qualitative-quantitative spectrum. Examining key features of DES reveals perceived strengths and weaknesses of the method, but the weight of these may vary depending on how the method is applied, with strengths in certain instances but a weakness in others.

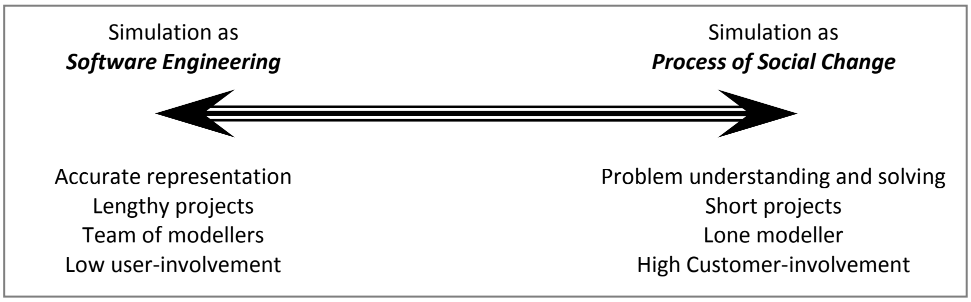


Figure 8: Approaches to simulation modelling: software engineering versus a process of social change (Robinson 2002b, 2005)

Quality of DES modelling projects has been viewed to be (as with other simulation techniques) made up of three factors which form an interdependent trilogy: the model content (model correctness and the efficacy of meeting client specifications); the process undertaken to develop the model (and if this met client expectations); and the outcome (such as the system owner's willingness to act upon findings[7]). The importance of and weight assigned to each of the factors is entirely dependent on the individual study and may alter during the course of the study as the situation evolves.

[7] Acting upon findings may include a developed understanding / a changed perception of a system rather than changes implemented within the system

2.3.4 Practical applications & issues addressed using DES

DES is one of the most widely used OR/MS methods when faced with uncertainty in system design (Bank and Carson 1984). It has been applied to a wide range of situations from manufacturing and engineering, to modelling of service such as healthcare systems. It has been used to understand complex systems and investigate the areas of concern within those systems.

As denoted in Figure 8, the way in which simulation may be approached spans a broad spectrum. An earlier project which illustrates this spectrum vividly is the twofold application of DES: using DES for facilitation, representing the softer problem structuring side, and to answer specific process questions, encapsulating the traditional hard operational side (Robinson 2001). This project may be viewed as the use of hard DES through a soft lens, and encapsulates the flexibility of the DES method. The stereotypical view that DES is only applied to operational issues is limited: it has a broad range of applications, serving a variety of purposes, and the continuing development of software continues to expand capabilities.

2.3.5 DES Summary

This section has discussed the key characteristics of DES, the breadth of its applicability, and how it is a method that may be adapted to the problem situation. DES represents systems as a series of queues and servers with activity dictated as a series of events. This enables the method to represent a broad range of systems but it is frequently utilised for operational issues.

Although DES is a very powerful method, it is not possible to effectively capture problems dominated by dynamic or organisational complexity (Taylor and Lane 1998). So, "*by failing to appreciate the underlying feedback mechanisms, these interventions [DES] only have a limited effect*" (Taylor and Dangerfield 2005, p.659).

The future of DES is noted by Robinson (2005) to include the integration of the method with other simulation techniques and communities. Nance and Sargent (2002) raise the point that as simulation is the union of art and science, collaboration between a mathematical and artistic view, and so is in itself a mixed methodology, but not in the way generally understood in OR/MS. Developments in computer graphics, virtual reality and virtual environments are creating new opportunities in the area of simulation but are also creating threats to overwhelm it (Nance and Sargent 2002). A fundamental concept of modelling is emphasised: the need to keep it simple, and so should new avenues be considered in order to produce the most insightful models with the smallest number of parts?

2.4 Comparing SD and DES

The previous two sections have discussed how the two methods each have many distinguishing characteristics, and the contribution they have to projects, leading to several commonalities and differences. Herein follows a discussion of the current work concerned with comparisons of the two methods and consideration of what factors modellers assess when selecting a modelling method. The first part discusses the two methods when contrasted, the work done within this area and the possibilities it opens. This is followed by a discussion of existing frameworks to inform methodology selection, including the role of modeller experience and preference.

2.4.1 Introduction

Comparing SD and DES reveals their comparability and the various views held on how each method may be applied more qualitatively or quantitatively depending on the problem system and modeller preference. Several studies exist that: consider the benefits of each method within a given context; compare and contrast the methods; or mix the two with limited discussion of the philosophical, mathematical or practical implications. Contrasting the methods encourages consideration of what factors might be under consideration where one method (SD or DES) is selected over the other. Such comparisons open the door for in-depth consideration of mixing methods, offering a first step towards mixing methods by enabling modellers to see enough of the other method (Morecroft and Robinson 2006), whilst revealing the overlap and gaps. This leads to the general question of how methods are chosen within a project, and the decision processes involved.

When the two methods are considered side by side, elements of similarity emerge. Examining and contrasting the distinguishing features of the methods sheds light on the facets used to select a method and reveal why one method may be most suited to certain situations over another. Lane (2000) advocates that a richer understanding of SD and DES allows both fields to have an informed and respectful understanding of the reasons why there are areas of difference and allows modellers to potentially cross the divide. Both SD and DES are popular modelling methods but existing comparisons are limited. Morecroft and Robinson (2006, 2008) discuss how, until recently, the majority of comparisons undertaken have been from the perspective of a specialist in one of the methods under study. They, and later Tako and Robinson (2009, 2010), sought to provide a more balanced, and in the latter case empirical, comparison of SD and DES, focus on comparing the two models, recognising representational and interpretation differences. Several comparisons are brought together with the aspects of SD and DES discussed in the previous sections to provide a broad comparison of the two methods. Such comparisons have been described as holding the potential to enable modellers to evaluate the methods, consider crossing the divide between the methods and generate complementary insights (Morecroft and Robinson 2008).

2.4.2 Elements of comparison

In order to compare the methods we will examine each from three perspectives: problem, system and methodology. These perspectives were originally proposed by Pidd (2004a) as criteria for general modelling and as an aid to the selection of methods. This basis for comparison was used by Chahal and Eldabi (2008a) who emphasised that a fit was needed between the three (illustrated in Figure 9) and using this framework the researcher will bring together the various comparisons. These three perspectives represent the core decision elements involved within projects: determining the system under study, exploring the problem and deciding the methodology to embark upon the problem (within the system) with. Therefore these three perspectives hold the potential to offer insight into method features which may be used to select appropriate modelling methods.

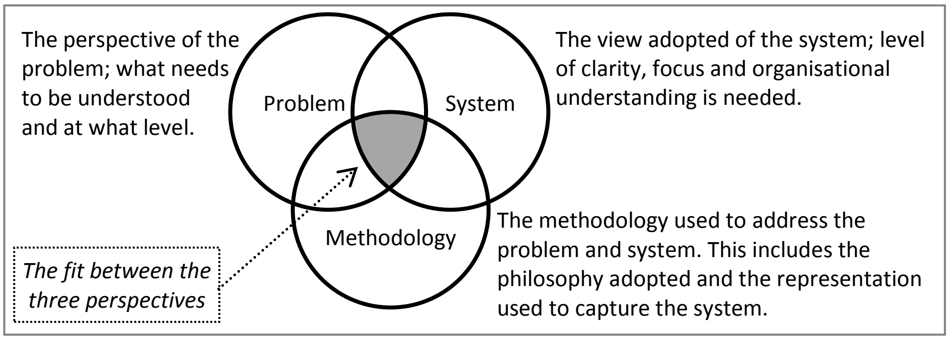


Figure 9: Perspectives used for comparison of SD and DES, and the fit between Problem, System and Methodology (Chahal and Eldabi 2008a, p.194)

This research utilises these perspectives as the basis for comparison of DES and SD throughout this section as the researcher aims to understand the various distinguishing and similar characteristics that inform the choice between DES and SD. The next sections will present a comparison of SD and DES from each of the three perspectives based on the descriptions of the methods collated from the literature, described in the previous sections.

2.4.3 Methodology perspective

The methodology perspective represents the tools, techniques, methods and philosophy selected to address the problem and to represent the system. The following sections consider characteristics of these elements of DES and SD.

2.4.3.1 Philosophy

As discussed earlier in section 2.1.2 philosophical assumptions and principals of methods are embedded within the methodology. One of the main concerns, for certain groups of modellers, when the concept of mixing methods is discussed is the issue of paradigm compatibility. Both SD and DES adopt quite separate modelling philosophies (Morecroft and Robinson 2008). The principle behind SD is that the structure provides the key to insight and generates the observed behaviour (Chahal and Eldabi 2008a). If the intent is to understand the impact of the system structure on behaviour then SD is appropriate (Owen, Love and Albores 2008). Conversely, DES is frequently used to model the randomness within a system and how this generates performance over time (Chahal and Eldabi 2008a). In contrast to SD, a well-developed philosophy of practice does not exist within DES (Robinson 2005). DES has moved away from being a methodology applied by OR specialists to a tool applied within a broad spectrum of fields with only the representation of events in the models being the common feature – it is a name synonymous with a broader field than just OR modelling.

2.4.3.2 Continuous vs. discrete model representation

The focus of DES is to model a system over time, where variables change state at discrete points in time. SD is acknowledged as being well suited to modelling continuous processes, using stocks and flows, where behaviour changes over time in a non-linear way, with feedback (Sweetser 1999). However, *"in practice most continuous systems can be modelled as discrete and vice versa at different levels of abstraction"* Greasley (2004, p.13) and so choosing between the methods depends on the level of system abstraction. Alternatively, Coyle (1985) discusses that it is in fact possible to model discrete events in a SD model. If the events in a DES model are equally spaced and sufficiently small then it is able to replicate the time slicing used within a SD simulation as all digital computing requires discrete time-steps to be calculated, an example of which is described by Martin and Raffo (2000). Although it is indeed possible and compatible, this approach is discouraged by Forrester as unnecessary cluttering of the system formulation with individual events may *"only obscure the momentum and continuity exhibited"* (1961, p.64).

2.4.3.3 *Stochastic vs. deterministic modelling*

SD models are most often deterministic whereas DES models are primarily stochastic (Rawlings 2000). In their comparison of SD and DES through the use of fisheries models, Morecroft and Robinson (2008) cite the stochastic ingredient of the DES model as a vital element of system performance, whereas feedback with the SD model is attributed such importance. The equations used within SD models remain approximations to a more complex reality and modellers may forget to include the noise that should be associated with a variable (Sharp and Price 1984). In general agreement, Mak (1992) deems SD to be deterministic in nature, with DES characteristically non-deterministic. The general, traditional view, is that the importance of stochastic elements in SD as low, whereas it is high in DES (Rawlings 2000). There can be crossover: it is possible for randomness to be introduced into a SD model through the use of appropriate delays (Morecroft and Robinson 2008), and DES models are not explicitly required to be stochastic. Therefore these are not strict conditions or required features of each method; modellers choose how much or how little (if at all) of each characteristic of the method they require. As such, the methods may be viewed along a spectrum which contains multiple dimensions.

The stochastic element of DES means that it must be run many times (as the results vary according the random number steams) and the output data be collected and examined. A SD model is only run once: the outputs are goal seeking, continuously feeding back in a closed system. These features may impact on how readily a model can be used interactively with the client of a project. Small and mainly deterministic models are fast to run, providing the ability to obtain fast client feedback on the dynamics of the model.

2.4.3.4 *Model look and feel*

Both SD and DES seek to model a system but the most striking difference (and most apparent distinguishing feature) is the visual representation of feedback in SD models (the use of stock and flows). In SD feedback is often depicted graphically (with curved arrows) and is included explicitly in the model equations. Conversely, a DES model may be defined as a collection of entities that interact together toward a goal through a flowchart experiencing queues (Borshchev and Filippov 2004). Feedback (if included) is captured in underlying coded decision rules, not obviously represented (like in SD). In DES lines of influence are hidden in favour of physical entity flow.

Much of this visual distinction is dependent on the software tool selected, but generally a DES modeller is able to visually represent on screen individual entities and servers, denoting the queues building and processes occurring during a simulation run. SD software simply depicts a static image of the system that contains explicit feedback loops, with graphs over time used to illustrate the dynamic behaviour being modelled.

2.4.3.5 Diagrammatic representation

Both SD and DES are concerned with material measurable flows but SD also models information flows whereas there is no explicit way to model this in Activity Cycle Diagrams and thus DES. Sweeter (1999) noted a difference between the two methods: the focus in SD is on developing a model representative of the system rather than being motivated by the data that can be located. This crude distinction is one which the researcher disputes: a DES model should not be data driven. Data collection is an area within DES that requires careful consideration, as should be done in SD and other simulation methods.

As discussed above, several diagramming tools are appropriate when developing SD models depending on the view of the modeller. Each may be used to explicitly represent the system structure and feedback, but the simulations have similar (equation based) structures. However, the methods used by a DES modeller are less standardised (Chahal and Eldabi 2008b): there is a tendency to produce a flow diagram of the system but little formalism exists in this area. Each simulation software tool can produce drastically different representations of systems.

2.4.3.6 Model development process

As noted by Tako and Robinson (2009), SD and DES both claim a wide range of applications but exist as two distinct streams, with little communication between them. There are notable differences between the model building processes of each: a DES modeller follows a more linear progression whereas SD modellers' cyclical and are *"more scattered between topics throughout the modelling task"* (Tako and Robinson 2008, p.13). DES modellers tend to create all elements of the model, fill it with data, try to validate the model and then go back and make alterations as needed. However, SD modellers begin with a basic model, then loop back to structure and conceptually model the problem to build on this basic frame, a more cyclical approach. During model development, DES has more focus on the model coding whereas SD modellers pay significantly more attention to the structuring of the problem and conceptual modelling.

In SD, the core difference appears to be the inclusion of a *dynamic hypothesis* whereby the reasons behind the problematic behaviour are deliberated and assumptions are explored. It is defined to be a theory *"to account for the problematic behaviour"* (Sterman 2000, p.95). It consists of a provisional view of how the problem arose and is there to guide the modelling efforts. The main purpose of the remainder of the modelling process is to test this hypothesis.

In contrast, the DES model building process often involves exploration of the problem and formulation of the model but it may be that only loose initial impressions are held of what the drivers of the model are at the outset of the project. Theories as to the drivers of the problems are then mainly developed once the model is built. In DES, if a dynamic hypothesis is made, it is done so implicitly with the DES process: it is an aspect of the formulation of objectives of the project and the conceptual modelling.

Although both modelling methods are distinct, they do contain several similar core elements and principles. Both modelling processes include a tie to the real world / problem situation, and require the modeller to bear in mind the cyclical nature of the process and the need to reflect and reassess. They encourage clear articulation of the problem situation and model conceptualisation, followed by model formulation, which may cycle back to further problem articulation. Both methods encourage testing and validation, followed by implementation of the model, with acknowledgement that this final stage may lead to further problem articulation and additional changes to be made to models.

The main difference between the model development processes of the methods relates to their characteristic features: entities and feedback. In DES, the focus is on the physical entities of a system and then determining the flow between them. Contrastingly, in SD a model should be formulated by first considering the loop structure and then add in the components of the loops (Forrester 1968a), as it is the loops which hold the most value. These differences may be responsible for the differing approaches to model development described by Tako and Robinson (2010).

2.4.3.7 Data dependency

DES models measure at individual entity level and seek to describe the variation in the variables through the use of statistical distributions. The models use physical, tangible data complemented by some informational data (Lane 2000). This utilisation of primarily numerical data results in DES models being highly data dependent (Chahal and Eldabi 2008b). Contrastingly, SD is described as a way of combining all available information, including written description and personal experience, with computer simulation to yield a better understanding of social systems (Forrester 1958). Like DES, SD models utilise physical, tangible data, but complement this with judgemental data and informational links. The result is that SD models are data dependent; but may also draw on subjective, judgmental data.

2.4.3.8 Model outputs

With regards to the outputs from the simulation, a DES model will most often have histograms of queuing times, and provide data on queue length or server utilisation. The output of a SD model, however, is typically the transient response to the inputs in graphical form, demonstrating the growth, decline or fluctuations in levels.

Another output from both methods is the physical diagrammatical representation of the system; the final conceptual model. This can form a vital part of the discussion and development of understanding for both methods and illustrates what has, and hasn't, been modelled (Robinson 2012).

2.4.3.9 Summary of DES and SD from the methodology perspective

This section has presented the distinctions and overlaps between the methodological characteristics of the two methods. Distinctions such as continuous versus discrete modelling of system behaviour and the explicit inclusion of feedback help to distinguish the methods. The progression of model development and analysis of model outputs required relate to the modelling method but also to the clarity of the modellers perception of the problem, and the model size and complexity included respectively. The diagrammatic representation of the problem system and the methods data dependency are dictated by the objectives of the modelling project and the client's desire to include auditable data rather than the method used. The extent to which these 'classic' characteristics of each method are included in models depends on the modeller and how they see fit to represent the problem system.

2.4.4 System perspective

This section will compare SD and DES from the system perspective. The system perspective encapsulates the view the modeller holds of the system, the detail observed and the nature of the processes occurring (what sort of dynamics).

2.4.4.1 Aggregation

Mak (1992) describes SD as a method that is concerned with linking and aggregating. Forrester (1961) himself has a chapter on the "*aggregation of variables*" noting that it is necessary to distinguish the important factors in a system from the unimportant, and combine similar factors into a single aggregate. A complex system requires variables to be modelled at an aggregated level to comply with the modelling principle: model simple, think complex. Sharp and Price (1984, p.2) state, in their invited appraisal of SD, that according to the SD paradigm it is *"necessary to model at a high level of aggregation"*. However, in response to this appraisal, Coyle (1986) emphasised that SD may be applied to a wide variety of problem situations, of various sizes and so a restricted view of the method should be avoided.

Despite this refutation, it appears that it is a common held belief that SD should only be used for large scale, aggregate problems, and although it is able to model at a more detailed level, the focus should be on selecting the most appropriate tool for the job: it is vital to select the right toolkit for the task at hand (Chick 2006). SD software has long been capable of representing intricate processes and is not limited to handling simplified variables. Owen, Love and Albores (2008) note that although SD is capable of modelling at entity level, it assumes homogeneous behaviour and must only be applied to situations where this holds true. A word of warning is that aggregation is desirable yet hazardous: it is vital to check parameters and that the policies of those parameters allow for aggregation.

2.4.4.2 View of the system: Macro vs. micro

In their review of SD, Sharp and Price (1984) argue that the method is applied to 'big' problems, their point being that when modelling a factory with SD the focus would be on the total demand, whereas in other simulation methods (e.g. DES) the modeller would seek to represent the individual product sales, allowing the tracking of entities. Although this representation of SD was deemed too simplistic and restrictive by the SD community, it represents one end of the spectrum of how SD is used. Lane (2000) describes this as SD adopting a holistic view and DES taking an analytic view of the system under study. The view being that SD models at the macroscopic level and DES models at the microscopic (Pidd 2004a). Tako and Robinson (2010) support this view, discussing how SD modellers tend to take a broader view of the problem situation than DES modellers. However, work by Pidd and Gunal (2011) developing a generic hospital simulation illustrates how DES may be used to capture the macro view of a system.

Each modellers view of a system, irrespective of the method employed, has a certain degree of subjectivity. It is a subjective process when assessing the level of detail (aggregation) to model at, and the area to be captured: the model boundary (An and Jeng 2005). A modeller's evaluation of method appropriateness and selection of method(s) is influenced by this view.

2.4.5 Problem Perspective

The previous two sections have highlighted similarities and difference in the methods. This research is interested in how these features impact the situations the methods can be used to model and the questions that may be posed of them. We continue to ask what is it that leads the modeller to conclude that a DES or SD is the simulation method most suited to answer the questions posed and produce the appropriate outputs.

2.4.5.1 Perspective of the issues

Both methods are understood to be of use in developing understanding of a system (Tako and Robinson 2008). Sweetser (1999) comments that SD is used to understand how a system alters over time and that DES is used to understand system behaviour now and if changes were to be made. There is no question that each method has its place, but the primary difference is that DES does not obviously allow the user to understand the underlying mechanics of informational flows and feedback; whereas in SD the links and flows are transparent (Tako and Robinson 2008). Speaking as a recent convert to SD, Brailsford (2002) cites the cross over in technique upon the nature of the problem at hand: the system was diverse and complex, with a long timescale, hundreds of thousands of entities. Overall, assessment of the queues and waits within the system was less important than the process flows.

2.4.5.2 Strategic vs. operational problems

Chahal and Eldabi (2008a, 2008b) propose that the distinction between the two methods with regards to the situations they are most suitable to address can be described as a strategic versus operational split. Several other authors – such as Rawlings (2000), Brailsford and Hilton (2001), Borshchev and Filippov (2004), and Lorenz and Jost (2006) – agree with this view when presenting a 'classic' view of each method during comparison. However, a review from Tako and Robinson (2010, p.810) into the use of DES and SD applied within the supply chain context found no evidence to support the operational versus strategic divide for DES and SD as *"no difference was found in the extent of DES/SD modelling on a* *strategic or operational/tactical level"* which contests this restricted view of the applicability of the methods.

Overall, the view presented in the literature is that SD is more appropriate for modelling systems where the problem is viewed as stemming from the structure, whereas DES is used to explore the randomness associated with interconnected events. This further highlights the overlap and clear distinctions depending on the situation: one system may be modelled in two ways for two different questions or to develop understanding of two differing aspects. Similarly, there are many situations where it may be difficult to determine under which category they fall, whereby the modeller is seeking to explore both how the structure impacts behaviour and the fluctuation of interconnected events.

As for the range of applications that each method is able to be of use within, there exists no comprehensive list. Taylor and Lane (1998) comment that overall SD projects cover a broader range of projects than DES. Although, little evidence has been found to substantiate this claim, overall it would appear that each method has their place but there exists distinct overlaps in many projects where either method would provide sufficient results and provide rich understanding of the system under study.

2.4.6 DES and SD in health

Many opportunities exist in healthcare for the application of both DES and SD. DES has been extensively used in a range of healthcare projects including hospital planning and evaluating design (Gibson 2007, Vos 2007); scheduling and analysis of overcrowding (Carter and Blake 2004); reduction of patient length of stay (Ceglowski, Churilov and Wasserthiel 2007); evaluating the impact of prioritisation of waiting lists (Comas et al. 2008); analysis of patient flow and allocation of assets (Jacobson et al. 2006); use of simulation to increase scrutiny on the systems (Kuljis et al. 2007).

Similarly, opportunities for SD to add value to healthcare have been discussed (Brailsford 2008, Homer and Hirsch 2006, Lane et al. 2000, Taylor and Lane 1998), demonstrating the support in the field for work in this area. Applications of SD in healthcare include the exploration of the impact of restricting demand or extending capacity: policy analysis (Taylor and Dangerfield 2005); and mapping acute patient flows (Lane and Husemann 2008). Many more opportunities for applying SD in healthcare exist and are discussed by a number of authors.

Overall, healthcare provides a rich environment of potential areas to explore through simulation studies, be it SD or DES. The wealth of opportunities outweighs the issues that may be encountered, and the unique and far reaching nature of the systems make it an interesting area to explore. Both SD and DES have been effectively, usefully and extensively applied to healthcare projects and thus it is deemed a suitable place to explore the possibility of combining the two modelling method. Some healthcare cases may need the complementary view gained from both SD and DES (Brailsford 2002). Further to this, it is an area that may benefit from taking a broader view of the elements of concern and considering their impact on the wider system.

2.4.7 Conclusions from comparing SD and DES

The above section has demonstrated the literature within the area of SD and DES comparison. This has revealed the classic or traditional views held of SD and DES (shown in Table 1) and interesting points for comparison have been made, along with the elements of similarity in the methods. But it is also important to reflect on the less traditional or classic implementations of SD and DES; such as how it is possible to code a lot more into a DES model to implement significant changes to the traditional simulation (such as altering values used in the simulation over time, and in response to the state of the system). Similarly, SD models can more accurately capture queueing behaviour and queue growth by modelling the age of items in a queue and breaking the population down into subsets. Focusing only on the differences would give the wrong impression of the methods – their similarities should also be included in comparison. Much like in Eden and Ackermann's 2006 comparison of PSMs, it may be more appropriate to focus on the similarities of the methods to draw meaningful insight.

The section has sought to demonstrate that each method has an element of overlap depending on the way in which it is used. Table 2 illustrates that the characteristic representations of SD and DES described in Table 1 can represent a spectrum: each method is not applied in an identical manner to every problem system. A method may be applied in different ways for different problems, even if the system under study is the same. Problem and system characteristics relate to the overall context of the project whereas a methodology is selected and imposed on the project. The chosen methodology must fit with the problem and system perspectives. When choosing between SD and DES the key deciding factors are the problem and the system perspectives, and the capability of each method to capture and provide insight into them.

The methodology behind the two methods can be very different but they can and have been used to address similar problems and applied to similar systems albeit in a variety of ways. This is confirmed by seeing examples of SD and DES in health, as both can add value to the assessment of patient flows, department strategy and ground level operations, but can provide different insights. What the methods model may be the same, but how they represent the system and problem(s) may be different.

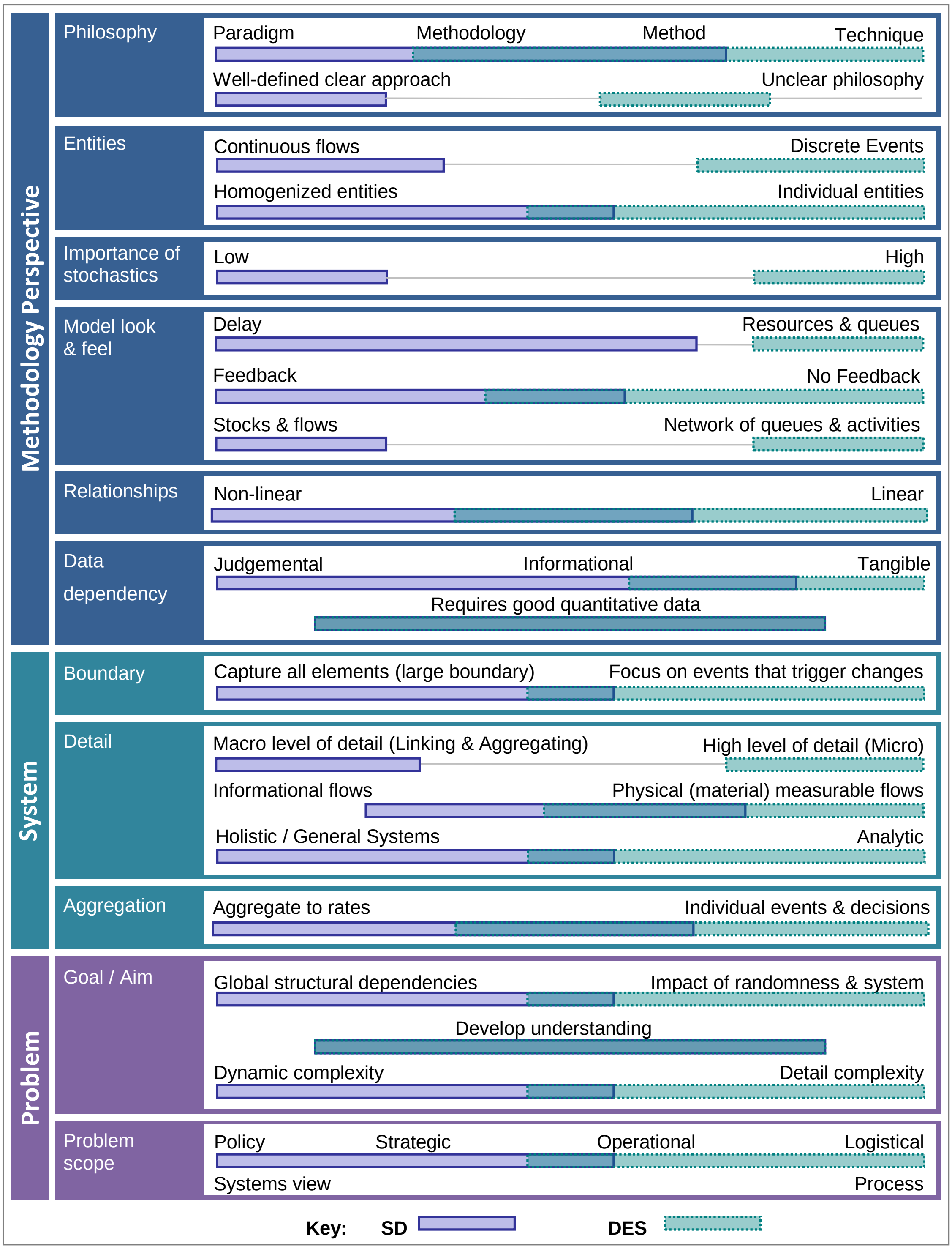
Sweetser (1999, p.8) hypothesised that *"many problems could be modelled by either approach and produce results that would look very similar"*. More recently Morecroft and Robinson (2008) illustrated that complementary insights could be garnered from creating two independent models from each method.

The chosen modelling method will influence what is included and excluded from the final model, which in turn affects the results (Davies, Roderick and Raftery 2003). When using simulation methods (specifically SD and DES) *"Different people have different experiences"* (Coyle 1986, p.406). When learning a method, a modeller learns to view a system in a certain way and this impacts their choice of method. DES proponents may naturally tend towards the method but it is necessary to take a *"step back and assess which toolkit should be used"* (Chick 2006, p.22).

Table 1: Comparison of classic perspectives of SD and DES

		SD	DES
Methodology	**Philosophy**	Method, a professional approach (Forrester 1958) Well defined methodology	Method, tool or technique No clear philosophy
	Entities	Continuous flows (Forrester 1961), homogenised entities(Lane 2000)	Individual Entities (Morecroft and Robinson 2006)
	Stochastic vs. deterministic (Rawlings 2000)	Low importance of stochastics	High importance of stochastics
	Model look & feel	Stocks, flows, delay structures (Sterman 2000) Explicit representation of feedback (Morecroft and Robinson 2006)	Network of queues and activities, resources (Pidd 2004a) Implicit representation of feedback (Morecroft and Robinson 2006)
	Relationships (Morecroft and Robinson 2006)	Mainly non-linear	Mainly linear
	Data dependency (Taylor and Lane 1998) (Tako and Robinson 2009)	Data broadly drawn: combining all information available (including judgemental and informational) Requires good quantitative data	Primarily tangible with some informational Requires good quantitative data
System	**Boundary** (Sweetser 1999)	Attempt to capture all elements (large boundary)	Focus on events that trigger changes to occur; narrower focus
	Detail (Pidd 2004a) (Mak 1992) (Taylor and Lane 1998)	More macro level detail Measurable and informational flows Holistic, general systems	High level of detail (Micro) Physical, tangible, material measurable flows Analytic focus
	Aggregation (Morecroft and Robinson 2006)	Aggregate events to rates, emergent behaviour	Event focus and individual decisions; state changes
Problem	**Goal / Aim**	Explore global structural dependencies (Morecroft and Sterman 1994),yield a better understanding of social systems (Forrester, Mass and Ryan 1976)	Explicitly explore the impact of randomness and how the system might behave (Tako and Robinson 2009)
		Examine dynamic complexity (as part of systems thinking) (Kim and Senge 1994)	Examine detail complexity (Brailsford 2008)
	Problem scope (Lane 2000)	Strategic & Policy, system view, conceptual level	Operational & Logistical, process view

Table 2: Comparison of the varied views which may be held on SD and DES



This section has illustrated how there exists tangible overlap between the two methods, as illustrated in Figure 10: the two methods are both similar and dissimilar depending on the way in which it is used. Attempts to draw clear delineations between the two methods only do so when a single form of application is considered; and the breadth of modes of applications along the soft / hard spectrum is ignored. Both methods are suitable for providing increased understanding and aid decision-making and therefore overlap. This raises the question of: can these two methods be mixed to provide a holistic view of the system, encapsulating the benefits of each method? If they can be combined, then what considerations need to be given to how they are combined? It is this author's belief that these two methods may provide complementary insights as suggested by Morecroft and Robinson (2006, 2008), and may indeed be linked. Comparisons between them have been made so is it now time to consider how the two methods may formally be used together, and to consider the possible frameworks for enrichment and integration.

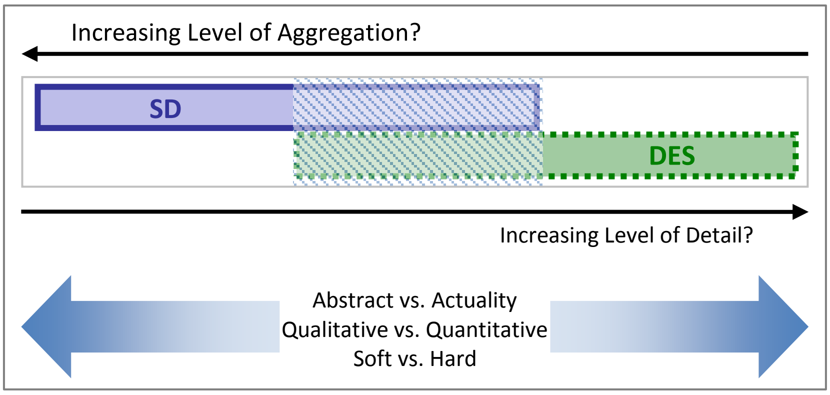


Figure 10: The possible continuum of SD and DES

It is necessary for modellers to side-line their beliefs with regard to how a system performs, to open their minds to the possibility of another approach and how it may provide complementary insights. Quoting Morecroft and Robinson (2006, p.11):

> *"Perhaps it is time that more SD and DES modellers crossed the divide … to adopt, or acknowledge a completely different modelling philosophy and to temporarily suspend deeply held beliefs… Probably each of us will remain anchored in our core disciplines, but we can now see enough of the 'other' discipline to sense where future collaboration might be beneficial."*

Considering the benefits, Brailsford (2002) is one of a wave of authors to pose the question as to whether it is necessary to choose between the SD and DES, suggesting an integrated approach may be beneficial. Both SD and DES consist of visual tool's portraying a view of the system to the problem owners. As SD is able to capture causal relationships and explicitly represent feedback within the system (Forrester 1958) through the scaled up structure with deterministic behaviour it is efficient in policy design projects. DES represents the system at individual entity level and the stochastic nature of the model informs understanding of the system (Rawlings 2000) and is efficient with policy implementation problems (Ceglowski et al. 2007). The question arises: '*can we have both?*' As simulation modelling can be time consuming (Pidd 2004a), could a combined approach help to reduce the time taken to produce useful, insightful models or increase the applicability and overall use of models?

2.5 Chapter Summary & Research Gap

This chapter has explored the literature to address research questions 1 and 2 by examining the characteristics of DES and SD. The characteristics of a method inform a modeller of its applicability and influence the decision to adopt the method. Considering these characteristics, alongside an appreciation of how models are developed within each method and the settings within which it is applied enables comparison to be made of SD to DES.

Having compared SD and DES we can now consider how to choose between the methods by considering existing frameworks for method selection and exploring how the two methods can be used together. Going forward with the view that mixing methods is feasible, practical and beneficial, it is necessary to explore how a method is selected as appropriate within a project, and how this decision process might then be adjusted to include mixed methods.

There exists support within each field (both SD and DES) to obtain the benefits of each method, but it is unclear how modellers could or should go about this. It has been necessary to explore how modellers choose between the two methods by examining the characteristics of each. However, this can be complemented by an understanding of overall method selection and examination of the theoretical concerns for mixing OR/MS methods and DES and SD specifically. It is necessary to gain an in-depth understanding of how DES and SD have been used together, theoretically and practically to inform on issues important to key stakeholders in the past; and what particular problem situations.

Both DES and SD have been given numerous labels and *"the existence of differing theoretical concerns can make relationships between the approaches difficult to pin down: it is not a matter of cataloguing agreements and disagreements on specific topics"* as there is the risk those concerned will talk through each other and so the research is aimed at *"establishing mutual comprehensibility"* (Crotty 1998, p.664).

The next chapter seeks to explore how DES and SD have been mixed, where they have been mixed and how and why OR methods are mixed. It will explore the following research questions:

Q3 - *What problem situations, including healthcare, have been shown to be amenable to mixed DES and SD and why?*

Q4 - *What value have mixed DES and SD projects been shown to have?*

a. Theoretically: what benefits have been stated and how are the methods mixed to obtain such benefits?

b. Practically: what cases exist where the mixed use of DES and SD is shown to be beneficial and how are the two methods used together?

3 Choosing and Mixing Methods

The previous chapter introduced SD and DES and presented the current state of thinking in the literature with regards to: characteristics of the methods which emphasise the similarities and differences; the various perceptions of what defines each method and the spectrum of ways which the methods have been used within projects; and the desire within the community to explore how to mix methods and obtain these benefits. If modellers were to choose a mixed method approach, how they could or should mix SD and DES remains unclear.

This chapter will explore the literature around how modellers select methods, how OR/MS methods have been mixed, where SD and DES have been mixed hence addressing the research gap highlighted in the previous chapter. This chapter highlights the gaps in the existing literature regarding the mixing of SD and DES and presents the need for coherent theoretical and practical frameworks. It concludes with discussion of the unresolved questions relating to mixing SD and DES and summarises the aim of this research.

3.1 Introduction

There is motivation from within the OR community to explore mixing methods. Specific to this research is the interest in how the decision to mix SD and DES is made, and what mixing is being done in practice. Taking a step back to consider how the two methods might be used together by looking to the general mixing methods and multimethodology literature allows us to formalise designs for mixing, and clearly and consistently depict what is being done in practice, and learn from case studies in the literature. Considering the project methodology[8] adopted when both SD and DES are used in projects will shed light on their compatibility and interoperability, leading to general lessons about the benefits of mixing the methods.

3.2 Selecting a Project Methodology

Problems can be considered to be subjective constructions: by structuring a problem it is possible to develop a shared reality. In a modelling project the modeller hopes to share and align mental models with a client (Vennix 1996), and the project methodology impacts the usefulness and outputs of the project.

[8] *Project methodology* is used to refer to the overall modelling approach to the project; the single or multiple methods that have been used within the project.

Sound models may be described as being characterised by a fit between the system[9], the problem[10] and the methodology. In addition it is important to fit the project methodology to the problem, and not the problem to the methodology selected (Linstone 1978). Ideally, modellers should not be tempted to "trim the problem to fit the technique" (Greenberger, Crenson and Crissey 1976, p.326). Also advocated by Lorenz and Jost (2006) who discuss that we must avoid using the modelling methodology as a starting point for an modelling project, and *"select the most suitable methodology for a given purpose and object"*, as illustrated in Figure 11.

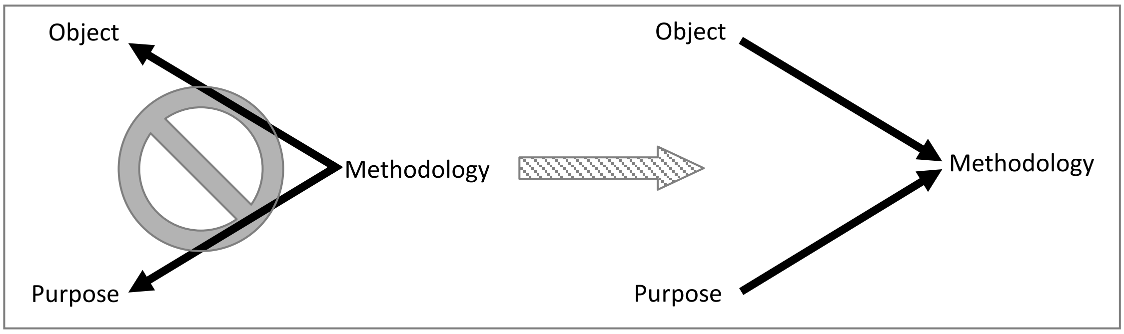


Figure 11: Order of methodology selection (Lorenz and Jost 2006)

In specific reference to health situations Carter and Blake (2004) highlight the importance of understanding the problem posed and how the system impacts upon it when selecting how to solve the problem. It is therefore necessary for modellers to ask key questions to select the most appropriate modelling methodology: which method would best represent the system under study, answer the questions addressed, and fulfil the model purpose? (Sweetser 1999). A sound problem and system definition process is needed to ensure that the project is answering the right questions and then build useful models (Curtis, Dortmans and Ciuk 2006).

3.2.1 Frameworks to inform method selection

Most OR textbooks contain sections providing overviews of SD and DES, and present characteristics which may contribute to this selection of methods, as discussed in the previous chapter. From these characteristics and case examples a modeller might infer why each method might be selected for modelling a particular situation. The uniqueness of real-life projects does not always make the choice simple, and a system may display behaviours

[9] *System* or object can be described as the area which the modelling project is seeking to describe; the context of the problem.

[10] The *problem* or purpose is the issue to be addressed in reference to the system and what is expected to be achieved.

and pose problems that could be modelled by both methods. Modellers may be supported in this choice with frameworks and tools. Brooks and Tobias (1996), propose looking at the level of detail, the complexity and model performance to choose between methods, and (Williams 2008) indicates a taxonomy of methods when separating them into four categories (soft methods, methods to calculate a system attribute, methods to replicate system behaviour and optimisation methods). However, limited further advice is available.

Specifically looking at method selection in healthcare, the 'Research Into Global Health Tools' (RIGHT) group conducted a large research project to develop a method selection aid (Naseer, Eldabi and Young 2010). Along with other OR/MS methods, the RIGHT group present definitions of SD, DES and their general category of 'hybrid' modelling methods using six categories: the time, money, data and knowledge available; and the levels of detail and insight needed for modelling. All three methods are cited as being suitable for system design at strategic level, with SD being more suited at policy level, and DES and 'hybrid' more applicable at operational level. The RIGHT group appear to describe the 'hybrid' method as equally expensive as DES, but with the ability to span all levels of detail and insight. This broad representation of hybrid modelling illustrates that it can span a broad range of problem system (from policy to operational) but that its application is dependent on the system it is used to model and the questions being posed.

It should be noted that the view proposed by the RIGHT group and the criteria for comparison of the methods represent one perspective and may not be reflected by others in the communities. As seen in the discussion of SD and DES in the previous chapter, there is a broad spectrum of views held as to the purpose; applicability and theoretical underpinnings of modelling methods. The tool presented by the RIGHT group adds quantification to the choice of methods along the broad OR method spectrum but provides limited distinction between DES, SD and 'hybrid'. It illustrates that it is difficult to choose mixed DES and SD modelling as 'hybrid' models are applicable to such a wide range of situations, but also that there is interest in the field for the development of frameworks to inform the modeller.

The potential for client participation can influence method selection when designing organisational interventions (Ormerod 1997). Modellers must consider the level of acceptance the modelling method will receive by the client and the ease and speed of development (Cooper, Brailsford and Davies 2007) alongside its overall appropriateness for the problem and the system. The following section discusses the role of personal preference in informing method selection.

3.2.2 Modelling preference

The characteristics of the system to be modelled, the intended use of the model and the properties of the modelling method should be carefully considered (Bider 2005), but practitioners each develop their specific modes of practice in response to the individual situations they are faced with (Corbett, Overmeer and Van Wassenhove 1995). The choice of method remains with the modeller, and each has their own *"deep implicit operating assumptions"* for methods (Meadows 1980, p.23). Method selection will depend on their experience (Brailsford and Hilton 2001, Morecroft and Robinson 2006) and how they perceive the problem system (Keys 1988). A modellers specific background, expertise and preference, the data and funding available, and the structure and complexity of the problem and system influence this choice (Davies et al. 2003). The problem alters depending on the observer; each modeller holds a unique view to them as each has acquired their own mental framework for interpreting the world (Eden and Sims 1979).

Adapting the problem and/or system to the available modelling methods can lead to a mismatch between the problem and the employed project methodology. It is necessary to be a problem solver not a technique peddler (Coyle 1977). However, this is often hard to put into practice as the modeller may be guided by familiarity with a particular method. It is wrong to propose that any single method is applicable to all cases encountered; clients are best served by modellers who offer flexibility, with an awareness of other methods and how they may be of use (Lane 1993).

Work by Tako and Robinson (2008, 2009) into the model building process of SD and DES empirically supports this common held view that modellers will embark on a study without first considering alternative modelling methods. The work backs the view that practitioners use the method with which they are more familiar and not necessarily the most appropriate for the task at hand. It is ultimately the role of the modeller to determine whether the problem and context are important enough and if the outcomes are to be sufficiently useful to warrant the use of SD (Coyle 1983), or indeed DES. DES experts may gravitate to DES packages just as an SD advocate may think in terms of ordinary differential equations and feedback.

Considering how modellers choose methods raises the question: *would a problem owner or modeller naturally gravitate to modelling through a specific tiered system?* Borshchev and Filippov (2004) propose a diagram comparing simulation methods, shown in Figure 12, which may be perceived as a hierarchy of methods for modellers to move from bottom-left to top-right. Methods that model systems at the micro, operational level may be adopted more readily than those whereby the system must be considered at a more macro, strategic level. The modeller plays an important role as any method may produce misleading results if *"incorrectly or unimaginatively used"* (Coyle 1986, p.405). Modellers, and their clients, may be more accepting of certain methods and be biased towards more operational methods as they perceive a system in a detailed manner, rather than appreciating the wider system.

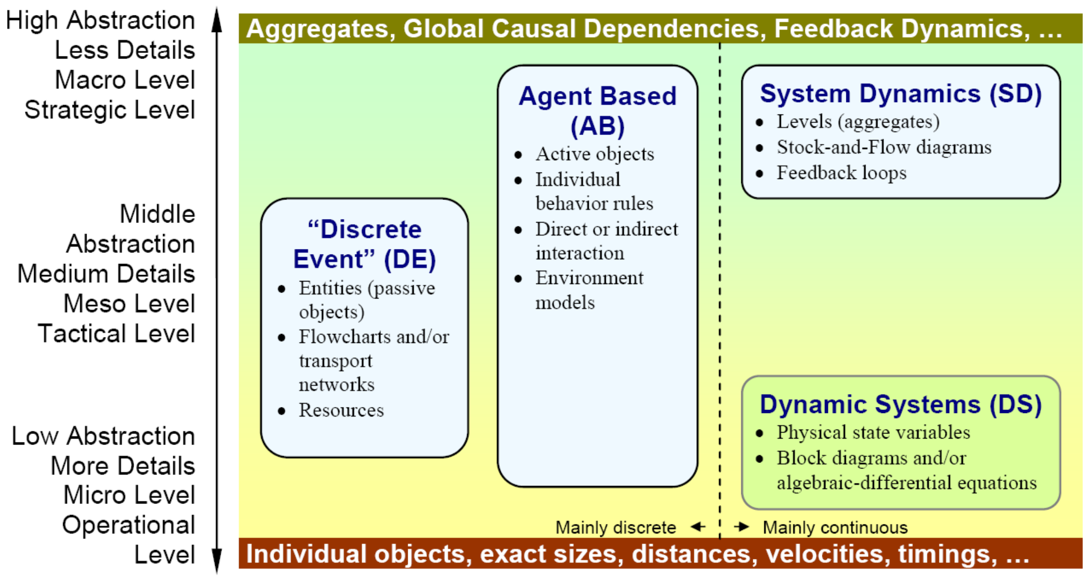


Figure 12: Paradigms in Simulation Modelling on Abstraction Scale (Borshchev and Filippov 2004)

3.2.3 Discussion: Choosing appropriate methods

This section has discussed what informs the selection of methods in a project. It is important to understand the problem and the system, but also to consider how method selection is a personal, subjective choice of the modeller informed by their perceived view of the problem and system, and their personal experiences, preferences and aims. SD and DES are not equally suitable for every situation; sometimes the choice is more apparent than others, and at times both hold the potential to add value. Considering all appropriate methods but selecting a single one may not address all facets of a problem and the system sufficiently; this choice may require a compromise. Mixing methods holds the potential to fill the gaps within a single method and enhance the overall robustness, integrity, acceptability or buy-in of projects.

3.3 Mixing methods: What, where, why and how?

The intention of this section is to provide the reader with information on the work conducted in the field of mixed methods, also referred to as multimethodology; the broad spectrum of work in the field; and the support and criticisms posed. A brief overview of the use of mixed methods is followed by a review of mixed methods projects which involve either of the two methods of interest, considering what, why, where and how methods were mixed. Following this, for mixed DES and SD projects, the way the methods were combined, the objective(s) of the project and the perceived benefits or limitations of using mixed methods are presented. Real projects in the literature will be focused on to demonstrate the feasibility of and support for mixing of DES and SD.

3.3.1 Definitions & background

As discussed in *Chapter 1*, the terms multimethodology and mixed methods are used interchangeably throughout this thesis. At this point it is necessary to refer back to the earlier discussion (in *Chapter 2*) of 'hard' and 'soft' OR/MS methods. Hard methods seek to generate a mathematical model to represent the real world whereas soft methods generate debate and insight into the real world (Pidd 2003). For the purpose of this research we will use the term 'hard' to refer to methods that are mainly quantitative, and 'soft' to refer to mainly qualitative methods. These terms are often used to delineate mixing methods into three groups: soft-soft, soft-hard, and hard-hard. Methods from two different groups might be thought to present modellers with more philosophical and conceptual challenges than methods from within the same group.

Mixing methods is the combined use of two or more different OR/MS methods within a single project. The main concern of mixed methods remains "*the extent to which paradigms are incommensurable, that is, mutually exclusive, unable to be combined or linked*" (Mingers and Brocklesby 1997, p.490). This means that careful consideration must be given to the compatibility of the methods when undertaking a mixed project. Comparing SD and DES helps to establish the theoretical perspectives of the methods and establish if points of commonality exist, identifying whether the boundaries between them are permeable, and *"to 'construct bridges' across paradigm boundaries"* (Mingers and Brocklesby 1997, p.497) to overcome paradigm incommensurability. When considering mixing methods it is necessary for the modeller to carefully consider if the methodology is consistent with the methods theoretical assumptions and their use (Eden 1990). Methods may be viewed as independent and incompatible when they are based on differing assumptions (Mingers & Brocklesby

1997) as for some it is not conceivable to separate an individual method from its theoretical backdrop. However, these concerns appear to have been overcome in practice when mixing with simulation methods (Pidd 2012). Modelling frameworks and comparisons of methods can form useful tools in deciding the appropriateness of mixing methods in each situation.

How methods are used and the emphasis of their characteristics alters depending on the modeller and the problem system. This means that careful consideration must be given to the compatibility of the methods when undertaking a mixed project. Mingers & Brocklesby (1997) discuss arguments for multimethodology in OR, demonstrating the call for new approaches to be considered. There is support within the community to formalise how methods are used together and inform modellers of the various multimethodology options available to them. A single, one size fits all mixed method design is not applicable to every problem system. Different designs of mixes are needed to account for different modeller views of methods and different problem systems.

The following section will discuss work undertaken in the field to mix SD and DES specifically, exploring how useful, useable and beneficial mixed methods can be.

3.3.2 What OR/MS methods are mixed?

Jackson and Keys (1984, p.485) summarise that the desire in the OR/MS community to mix methods is because *"a diversity of approaches may herald… increased competence and effectiveness"*. New methodologies can help to cope with new and complex problems and systems. Methods each have their benefits and their limitations and mixed methods offer the potential to begin to overcome some of these shortfalls, offering modellers an additional route through the maze of wicked problem solving. Mingers and Brocklesby (1997), Jackson (1999), Mingers (2000, 2004, 2006), and Kotiadis and Mingers (2006) provide a more comprehensive discussion of the benefits and potential problems with mixing OR/MS methods which are only touched upon due to SD and DES being the focus of this research.

Deciding if the methods under consideration are complementary is an issue sought to be addressed by Mingers and Brocklesby (1997) and they propose a framework for mapping methods (illustrated in Table 3). This framework enables a modeller to contrast the methods proposed to be mixed, providing a coherent view of what the project methodology will be able to provide. Through this framework it is possible to examine and compare the main philosophical assumptions underpinning a wide range of 'hard' and 'soft' methods for OR modelling. The dimensions of the framework represent the key factors to be considered to undertake a comprehensive project, and the framework enables easy comparison of the capability of each method along each dimension to assess suitability.

	Appreciation of	Analysis of	Assessment of	Action to
Social	Social practices, power relations	Distortions, conflicts, interests	Ways of altering existing structures	Generate empowerment and enlightenment
Personal	Individual beliefs, meanings, emotions	Differing perceptions and personal rationality	Alternative conceptualisations and constructions	Generate accommodation and consensus
Material	Physical circumstances	Underlying causal structure	Alternative physical and structural arrangements	Select and implement best alternatives

Table 3: A framework for mapping methods (Mingers and Brocklesby 1997)

Considering SD and DES in light of this framework (illustrated in Table 4 and Table 5) it is possible to examine the general potential the two methods have to complement one another. Table 4 represents Stotz and Grobler's perception of SD given the problem system the method was used on, and matches the classic view of SD presented in *Chapter 2*. The researcher's view of DES represented in Table 5 is informed by the literature review in *Chapter 2*. How each method maps to this framework may alter depending on the problem and system but these tables represent the classic view to hypothesise the complementarity of the methods.

Although each method has specific distinctive characteristics which lend themselves to particular aspects of a problem and the system being modelled, and which may map differently onto the framework depending on the problem and the system, this framework provides a useful summary of what each method is capable of within a project, and where gaps lie. Using this framework highlights the potential value for mixing DES and SD: for SD to contribute where DES is weak, and vice versa.

	Appreciation of	Analysis of	Assessment of	Action to
Social	Social practices, power relations	Distortions, conflicts, interests	Ways of altering existing structures	Generate empowerment and enlightenment
Personal	Individual beliefs, meanings, emotions	Differing perceptions and personal rationality	Alternative conceptualisations and constructions	Generate accommodation and consensus
Material	Physical circumstances	Underlying causal structure	Alternative physical and structural arrangements	Select and implement best alternatives

Table 4: Mapping SD using Mingers and Brocklesby (1997) framework (Stotz and Grobler 2006)

	Appreciation of	Analysis of	Assessment of	Action to
Social	Social practices, power relations	Distortions, conflicts, interests	Ways of altering existing structures	Generate empowerment and enlightenment
Personal	Individual beliefs, meanings, emotions	Differing perceptions and personal rationality	Alternative conceptualisations and constructions	Generate accommodation and consensus
Material	Physical circumstances	Underlying causal structure	Alternative physical and structural arrangements	Select and implement best alternatives

Table 5: Mapping DES using Mingers and Brocklesby (1997) framework – a personal view

3.3.3 Where and why mix methods?

Mixed methods projects occur in a broad range of situations with a variety of clients. One advocate of mixed methods is Richard Ormerod who has conducted numerous mixed method projects adopting a pragmatic approach to the studies (1995, 1998, 1999). The methods employed are based on what is seen to work, making no discussion of the philosophical implications. That does not mean that careful thought was not given to the projects: a project design that was produced in advance and adapted to each case.

As discussed in section 3.2, methods may be selected for many reasons. The preference of the modeller and the client must be considered when mixing methods as it is necessary to consider the cognitive ability of the actors within the system under study, with methods selected to be attractive, relevant and *"likely to be within the capacity of the participants"* (Ormerod 1999, p.7). Additional conceptual challenges for the modeller, and client, are presented when using mixed methods which must be considered when conceiving a mixed methods project design.

When mixing *research*[11] methods, the reasons are cited as: triangulation to confirm results, to compare results, or to tap into new insight, and these reasons are likely equally applicable to mixing OR methods. Howick and Ackermann (2011) discuss that OR methods are mixed in order to: deal with a complex system, support the stages of a project, obtain specific benefits or overcome weaknesses of the methods and complement one another. Overall modellers describe how the methods were 'required' and therefore mixing was necessary (Howick and Ackermann 2011, Munro and Mingers 2002). Additionally, modellers may seek to mix methods generally in order to gain client involvement and confidence or to try something different (Howick and Ackermann 2011).

[11] Note the distinction between research methods (such as surveys, trials, case study, etc) and OR/MS methods. Multimethodology in research methods is another field that this research draws inspiration from but will not be discussed in detail.

3.3.4 Examples of mixing methods

There are numerous examples of mixed methods in the literature but the focus of this work will be literature that discusses mixed methods projects involving SD and / or DES in order to obtain lessons from the variety of combinations, how the methods are mixed, and the problems they are used to address and systems studied.

3.3.4.1 SD + … what, when and why

The general pattern within the SD cases identified is that the method is primarily used in conjunction with soft Problem Structuring Methods (PSMs). SSM is popular in mixed methods projects, as discussed in 3.3.2, and has been mixed with SD in numerous ways: with one following the other, both used together in parallel and with interactive looping between the methods. SD and SSM were used in a sequential manner by Vos and Akkermans (1996) as the two methods are cited as complementary. Howick and Ackermann (2006) describe their work with SD and scenario mapping as first eliciting event maps and influence diagrams separately "*more or less in parallel*" (p.120), and then the boundary-objects are combined in a systematic way consisting of three phases of work which moved forward, suggesting this is a form of parallel linking on the cusp with interaction. Finally, a more interactive approach, developed in an action research study combining SD with cognitive mapping, is described by graphical illustration of the cyclical processes (Ackermann, Eden and Williams 1997, Ackermann, Eden and Williams 2003). This illustrates that no single solution for two methods is found in the literature, rather there are various right ways of mixing of methods.

Mixing SD with PSMs is justified by the view that they are essentially from the same paradigm (Paucar-Caceres and Rodriguez-Ulloa 2007). Alternately, when Stotz and Grobler (2006) first contemplated mixing SD with soft OR/MS methods; they did so by firstly mapping the methods using the framework proposed by Mingers and Brocklesby (1997), shown in Table 4. This was undertake to uncover the potential for the methods to complement or support each other, and to determine the degree with which the methods fulfil a role within the study, and provides a useful perspective on how SD was employed within the project.

In addition to PSMs, SD has been mixed with other OR/MS methods for various purposes:

- *Performance Measurement and MCDA*: SD is used to contribute to closing the performance measurement loop by providing a platform to explore (Santos, Belton and Howick 2002, Santos, Belton and Howick 2008).
- *Conjoint Analysis* is used to help progress thinking and increase confidence in the SD model (Schmidt and Gary 2002).
- *Interactive Planning*: using the two methods to support each other to address the cause of issues, being careful to be clear about the methodology (Magidson 1992).
- *DES*: discussed in section 3.3.4.3.

In all of these cases, the core motivation behind many of the mix described is that it creates something that is more likely to achieve 'successful' outcomes than either method taken on its own it (Andersen et al. 2006). As with SD and PSMs, the mixing of these methods is possible as the authors believe that they do not contradict one another.

The literature suggests SD may be used in conjunction with other methods if due consideration is given to why mixing methods is appropriate and how the method will be used in the project. Mixing methods with SD is deemed possible as it is believed that the SDs concepts *"operate at the level of method not social theory"* implying it is not implicitly tied to a single paradigm and may be *"re-crafted for use within different paradigms"* (Lane 1999, p.501). The degree of complementarity of methods, which may be assessed using the framework proposed by Mingers and Brocklesby (1997), is likely to alter depending on the problem and system, and how the method is intended to be used.

3.3.4.2 DES + … what, when and why

DES has been used with a small selection of quantitative methods. Bennett and Worthington (1998) use DES, sequentially following data analysis, to reveal stresses on the system and propose improvements. Cycling between data mining and DES has enabled modellers to construct models from data patterns, resulting in enhanced findings and outcomes (Ceglowski et al. 2007). Artificial intelligence has been used to represent decision-making within a DES in order to understand the performance of a system under different strategies (Robinson et al. 2005). Mixing DES with statistical methods is common due to the high data. In general, DES has a history of use with statistical methods because of the methods high data dependence and statistical analysis may now be described as part of the overall DES methodology.

PSMs are frequently used in mixed methods projects with SD (discussed in section 3.3.4.1) and have been successfully used with DES. PSMs have been used with DES to: aid the identification of activities in the system through the sequential application of SSM then DES (Lehaney and Paul 1994); overcome cognitive and cultural barriers by concurrently using SSM and DES to feed and inform each other during the project (Kotiadis and Mingers 2006); identify new issues and enhance results as the methods complement the strengths and weaknesses of each other (Sachdeva et al. 2007); and utilise the PSM as a soft overarching framework (Robinson 2001). The method may be enhanced by softening it to create an overarching method, which describes success similar as the application of SSM and cognitive mapping. In this instance Robinson (2001) discusses that DES is a 'technique' and not a 'methodology' and therefore it is possible to use it within the context of a softer study. Therefore the hard DES method might be softened to become more aligned with soft OR/MS methods, or be supported in its current form mixing with PSMs.

Frequently DES is supported by an overarching, typically soft, OR method. This trend is seen overall with both SD and DES, and represents the popularity of quant-qual mixes as discussed by Howick and Ackermann (2011). As with mixed method SD projects, no two cases are identical, nor provide explicit rules for mixing; it is important to select the most appropriate method for the situation. The *"true spirit of OR, where the analyst makes use of every available tool"* has been embraced within projects mixing DES with other OR/MS methods (Ceglowski et al. 2007, p.67).

Although a range of systems are discussed, mixed DES projects are generally systems traditionally modelled using DES, and the additional method is used to enhance the DES modelling process or representation of a part of the system. In the majority of projects the DES is the primary method, but this may not remain the case when exploring mixed DES and SD.

3.3.4.3 SD + DES: a spectrum of mixes and uses

Comparison of the two methods has highlighted their similarities and their potential for mixing. Both methods have been used with other OR/MS methods in mixed projects successfully. This section considers examples in the literature describing mixed SD and DES projects, highlighting how the methods were used together and why. The technical and practical considerations to be made when mixing SD and DES, and the project contexts will be reflected upon.

A limited selection of work exists on the subject of combining DES and SD and is from a range of disciplines: Management Science, Mathematics, Computer Science and Engineering. The literature can be split into two groups: work describing a hypothetical or sample project selected by the modellers to illustrate a specific approach to mixing the methods, real life projects that have used mixed SD and DES to contribute to a problematic system. The literature also splits into four groups according to how the methods are used together. These four groups are:

Methods in sequence: Following undertaking a mix of DES and SD the acknowledgement was made that SD may be *"a useful addition to the toolkit of DES practitioners"* (Greasley 2005, p.545). The use of SD independently from DES has been cited as enabling modellers to loop back to assess what may be missing from the DES model (An and Jeng 2005) to explain system behaviour. Conversely, Mak (1992) uses SD to aid the development of an ACD to then create a DES model, illustrating that the methods may be used in either order.

Several authors discuss the specific roles SD and/or DES played within their projects: to assist the understanding of simulation results (Chatha and Weston 2006), to analyse the physical design of the system versus the financial (Kljajić, Bernik and Škraba 2000). DES has provided valuable input into new facility design decisions within a health centre and demonstrated efficacy of pooling resources, whilst the SD models are used to predict implementation issues (Su and Jin 2008). This mix of SD and DES occurred in an ad-hoc manner as stresses within the system became apparent and it was felt that SD could provide insight on performance issues, and side effects of changes to the system.

Methods focus on different aspects of the system: Greasley (2005) utilised SD in a DES project to investigate the human aspect of the system. DES was used to address operational issues, and, although not part of the original plan for the project, SD was used to address issues in the wider environment around the DES. In this example, it appears that SD was used to close the open DES system: the DES assumed certain variables were static and the SD was able to quickly explore how the system behaves if these variables alter in response to changes made at the operational level. Numerous cases use DES to model a process consisting of a queueing network with SD used to represent the wider strategy of the system.

Alternatively, Donzelli and Iazeolla (2001) present a hypothetical case where SD is used at a lower abstraction level than the DES model, and models the implementation details.

The above projects either describe methods used in sequence or to capture different aspects of the same system. These are examples of mixing the methods by transferring insight but keeping the resulting models separate. Each of these mixed methods projects describes both methods as having significant value in the development of either model and on the conclusions drawn by modellers.

Comparison of methods: Morecroft and Robinson (2006, 2008), whilst modelling fisheries, also maintain a separation between the two methods by using two separate modellers to provide insight into system. The reason to mix is to provide complementary insight into a confusing situation, and enables each modeller to consider crossing the divide and appreciate the value held in their alternative method.

Hybrid modelling: The view of the system adopted by Barton (2000) may be seen as similar to Su and Jin (2008), such that the DES models a subsystem whilst the SD model captures the overall system. However, the two methods are used together to create an interacting model because the system exhibits both continuous and discrete behaviour. This results in a single hybrid model that is sensitive to the timing of events. Other 'hybrid' models take this form of mixing SD and DES further to ensure that discrete events are triggered to occur at every time step to represent the continuous behaviour (Naturo et al. 2007), creating a DES model with feedback within the system. In this case, it was deemed necessary for the 'correctness' of the system, to better represent reality. This form of mixing DES and SD may be described as the most integrated design of mix.

3.3.4.4 Concerns for mixing SD and DES

Philosophical concerns of paradigm incommensurability have been overcome in the above projects, but remain a debated issue. Each project situation is described as unique, and the viability of mixing methods and the potential for philosophical issues should be considered on a case by case basis; just as a project's methodology should be informed by the problem and the system (Lorenz and Jost 2006). However, mixing DES and SD system behaviours is not new. As early as 1970, Fahrland (p.61) asks *"Why limit the modelling to either discrete event or continuous when situations are evolving that require more interdisciplinary solutions?"* The technicalities of mixing continuous and discrete event simulations have been the subject of discussion since then. The number of mixed DES and SD projects in the literature illustrate that this is no longer a barrier to mixing the methods, and that mixing simulation methods is actually viewed as *"no big deal"* (Pidd 2012).

3.3.4.5 Summary

The majority of case study articles encountered discuss a successful project using mixed methods and infer that the overall methods employed would be used again within the setting of the project, or on new projects. In general, as discussed by Howick and Ackermann (2011), the area of mixing methods has developed significantly but more in-depth understanding is needed of projects.

SD and DES have been successfully mixed in other fields but this work does not *"capture the spirit and flavor of SD and DES"* as seen in OR: the Holy Grail, *"a conceptual philosophy and practical methodology for combining SD and DES in a real context"*, has not yet been achieved (Brailsford et al. 2010, p.2294). Existing cases offer interesting insights but are difficult to compare due to the range of designs of mix and the varying problems and systems they are applied to, resulting in a range of different methodologies. It is not yet possible to take forward general lessons for the mixing of SD and DES as a structured framework that captures all aspects for comparison between projects does not exist and is needed to characterise and group cases.

3.4 The Unresolved of Mixing SD and DES

Mixing DES and SD is not new; however, practically mixing the two methods within projects is not yet accessible and transparent.

3.4.1 What methods to mix?

What should be mixed in practice? Following the literature review it seems that modellers (both in practice and in academia) continue to be interested in mixing DES and SD, but are seeking information about *how* to mix in practice. Some modellers support and others disagree with mixing these methods; if modellers mix then careful consideration and explanation is required. If a pragmatic approach is taken and theoretical boundaries are treated as flexible and permeable then clear discussion of the design of mix adopted would help convey the message and allow others to adopt the methodology. If the theoretical boundaries of the two approaches are to be left intact, then modellers need to be clear that this is being done, and how this impacts the model(s) produced.

3.4.2 Why mix?

Morecroft and Robinson (2006) conclude that modellers need to consider crossing the divide and consider how using SD and DES *"may yield complementary insights"* (p.11), whilst Barton states that situations exist that exhibit discrete and continuous behaviour that would benefit from the mixing of SD and DES.

A key question is: what is sought to be achieved from mixing the methods? In the literature, it is discussed that numerous modellers have found benefit from mixing the two methods. But, is this just a positive outlook following a project. Clearly describing projects would allow others to evaluate the methodology and weigh up the cost benefit given the workload potentially required versus a singular methodology.

This raises the question as to when mixing SD and DES is, or may be, pertinent. All cases cite a clear need to include both SD and DES, and so potentially provide case examples for others to adopt, but the lessons and transferable methodology are ill-defined and not standardised. All of the literature in this area is positive and successful which implies that this is a desirable combination but how it can and should be done, what lessons others can take from those who have undertaken a mixed model, and how to mix the two methods in practice remains unclear.

3.4.3 How could or should we mix methods?

If OR/MS is concerned with messy problems, embedded within complex systems then a single method may not offer the best insights to the situation. Jackson and Keys (1984, p.475) provides the following definition of a complex system:

- *"Not all of the attributes of the parts of the system will be directly observable*
- *Even if laws can be established relating the actions of different parts of the system, they will invariably be only probabilistic in nature*
- *The systems evolve over time*
- *Inevitably involve more 'behavioural' problems. Decisions made in the system will be affected by political, cultural, ethical and similar factors. It can be hard to understand the rationale behind decisions."*

Therefore, seeking to simulate a complex system may require characteristics and benefits from more than one method. SD may be more suited to model some of these four features of a complex system; as would DES. This research seeks to reduce this binary choice between the two, and encourage the adoption of mixed method modelling to provide insight into these messy situations.

Although the RIGHT framework (discussed in 3.2.1) suggests a 'hybrid' method option, there is little information about how this is undertaken in practice. How do we actually embark upon a 'hybrid' or mixed methods project?

This leads to the question of how the methods *can* and *should* be combined, and how this insight can be passed on to other modellers to provide archetypes or templates of mixed methods. There is a need to place the idea of mixing methods at the heart of method selection: if it is personal choice that is one of the key drivers in method selection then there is a need to include the various options of mixing methods to allow people to move from the theoretical 'would like to' to the useable undertakings. Groups that mix softer versions of SD and DES, or do not completely merge the methods to produce a single model, remain isolated to those who mix for technical/computational reasons and thus create models that may be deemed inaccessible to a beginner in the mixed methods field. Until off-the-shelf products that enable easy, coherent, transparent and varied mixing of methods are available further thought should be given as to how to describe and inform the mixing of SD and DES, and whether templates of mixes can be gathered. The emphasis here is that mixing DES and SD does not have to be complex, but it should be transparent, coherent and justifiable. If it to be these things then clear characteristics to describe the methodology undertaken are necessary. The comparison of SD and DES reveal several of these characteristics to illustrate why each of the methods has been chosen, but the design of the methodology should also be coherently described.
Much like system archetypes, which *"can assist model conceptualisation by virtue of their isomorphic properties to transfer thinking from one domain to another"* (Wolstenholme 2004, p.342), can a framework of designs for mixing SD and DES be developed along with key features of projects to inform and classify mixing in theory and in practice?

Similarly, Robinson (2005) discusses the idea of cut and paste models: referring to the 'reuse' of models so can this idea be adopted within the mixing of SD and DES. It may not be the models that can be directly reused, but the designs in which the methods are combined can form a sample set to inform other projects.

Conceptually, modellers and clients may struggle to mix concepts and transfer between the two methods. Modellers may need to become experts in a range of methods, or the number of modellers required within a project may need to increase. Additionally, the relative infancy of mixing means that limited guidelines or frameworks exist which may impact on the propensity for modellers to adopt the approach, and clients to buy-in to the methodology. Following this review of the literature it is apparent this is a strongly debated topic. Both methods may be viewed from various perspectives, as tools, techniques, methods or all-encompassing methodologies, and it is necessary for the modeller to define how they view SD and DES when considering mixing methods as this restricts the options available.

Bringing together the SD and DES literature, the identification of a range of SD and DES mixes, and lessons from the multimethodology community to provide the basis for the development of a theoretical framework for mixing methods, informs the design of the practical application of a mixed SD and DES and provide key points for discussion in the research conclusions. The compatibility of the two methods is assessed through comparison and collation of the various views held on the methods. By considering the project methodologies undertaken when employing the two methods it is possible to infer their compatibility and interoperability.

3.5 Research Gap

These literature review chapters explored the following research questions:

Q1. *How have DES and SD been used to inform on issues important to key stakeholders in the past?*

Q2. *How do DES and SD compare, in terms of similarities and differences in their methodology, philosophy, application contexts and problems addressed; and, given these similarities and differences, what are key elements of complementarity?*

Q3. *What problem situations, including healthcare, have been shown to be amenable to mixed DES and SD and why?*

Q4. *What value have mixed DES and SD projects been shown to have?*

- *a. Theoretically: what benefits have been stated and how are the methods mixed to obtain such benefits?*
- *b. Practically: what cases exist where the mixed use of DES and SD is shown to be beneficial and how are the two methods used together?*

It has revealed the gaps in the literature surrounding mixing DES and SD which has led to the following research questions which will be explored throughout the rest of this thesis:

Q5. *How can we take lessons from the past and transfer them to current practice? How could or should DES and SD be used together in the future to inform on issues important to key stakeholders?*

Q6. *How can frameworks be utilised to support mixed method modelling with DES and SD?*

- *a. How can mixing methods fit within the modelling selection, design and development process?*
- *b. How can mixed methods thinking be built into existing DES and SD model development processes?*

Q7. *How can theoretical designs of mixed methods be utilised in practice and provide meaningful descriptors of how the methods are mixed?*

- *a. What theoretical designs exist to describe and inform mixed methods modelling?*
- *b. Do these designs have a demonstrable application to DES and SD mixed methods projects?*

Q8. *What challenges are faced when embarking upon a mixed DES and SD modelling project within a healthcare organisation and how can insights from a healthcare project be transferred to other organisations?*

The next chapter discusses the research design given the research aim, and presents four research objectives in summary of the above research questions identified through the literature review chapters.

4 Research Design

4.1 Introduction

Research is a *"systematic investigation or enquiry aimed at contributing to knowledge of a theory, topic, etc., by careful consideration, observation, or study of a subject"* (OED 2013). It has a clear purpose with systematic data collection and interpretation designed to increase knowledge (Saunders, Lewis and Thornhill 2003). The way in which people view the world varies from person to person (the notion of multiple realities) and impacts how a researcher views their research. When we contemplate conducting research we bring assumptions to our choice method. To help make these assumptions explicit we establish a research philosophy (Crotty 1998), and undertake a research design that fits with it.

This chapter presents the design of the research undertaken with the aim to: consider the strategies of inquiry, understand the researcher's philosophy in the context of a research question which informs this choice and display the assumptions these choices present. First, the research topic and aims of the study are outlined, followed by identification and justification of the chosen philosophy. This discussion of philosophy leads to a consideration of the proposed methodology for the research topic; considering the appropriateness of several research methods and comparing the strengths and weaknesses of each. There follows a discussion of two primary methods, with a consideration of the factors affecting the choice, and the methods interoperability (potential for combination). The chapter then discusses the auxiliary methods used in the research and the research project plan. It concludes with a discussion of issues related to the validity, reliability, triangulation and generalisation of the results.

4.2 Research Direction

As discussed in the previous chapters, this research is concerned with two simulation methods: Discrete Event Simulation (DES) and System Dynamics (SD), with the aim to *explore* how two methods can be mixed. It has been identified that future priorities for simulation include: managing the complexity of models, improving clarity of models; and mixing with other modelling methods and a need to solve the links between them (Taylor and Robinson 2006). Although the choice of modelling method is determined by the characteristics of the intervention (Cooper et al. 2007), it is more complex than simply matching the method to the nature of the circumstance as researchers gravitate to the method they are proponents of. The goal of this research is to contribute to the area of mixing methods, specifically DES and SD. There is uncertainty around *how* the methods could and should be used together and this thesis aims to contribute to this discussion. This research seeks to contribute to the process of undertaking mixed DES and SD modelling, investigate how to mix methods by considering the links between them, and developing frameworks for consideration during the modelling process and when presenting the model(s) to the client, project stakeholders and other OR modellers.

4.3 Philosophy

4.3.1 Introduction

There is no one best method for conducting all research (Saunders et al. 2003). Any researcher brings assumptions with their choice of research method, and it is unwise to conduct research without a clear understanding of these assumptions and the implications they will have on the research, as it defines what is important to the researcher. A paradigm[12] is a device employed to describe a researcher's philosophical stance which indicates the assumptions of the research. It may be viewed as a set of beliefs and practices that provide a lens through which the work is viewed (Weaver and Olson 2006), a framework for thinking. It determines how the research may be conducted: what methods and tools fit within the frame, the types of problems that may be addressed and the questions that may be posed. The paradigm determines how theory is developed and the legitimacy of results, as these are required to be applicable within the same frame (Bird 2008). Further to this, once the research has been framed within a paradigm, it is possible for a reader[13] to view the work with an appreciation of the underlying beliefs, allowing the researcher to discuss the problem at hand without having to over justify their belief system (regulates inquiry within the discipline). Each researcher may have a view as to what their philosophical stance is, but this may be separate from the philosophy with which they approach and conduct their research within. The types of questions a researcher seeks to answer are informed by their view of reality, which in turn informs the questions.

Two main elements discussed in this section are ontology and epistemology, which inform the theoretical perspective of the researcher:

- Ontology is the study of the nature of being (Crotty 1998). It may be viewed as the assumptions the researcher holds with regards to the nature of reality. Ontologically, it is

[12] The term was first introduced by Kuhn (Bird, 2008)

[13] Some outside party, possibly from a different subject area

the researcher's view that an objective, mind-independent reality exists, but perception and cognition help to construct this reality.

- Epistemology is concerned with what is determined to be acceptable/valid knowledge within the chosen field of study (Saunders, Lewis and Thornhill 2007), finding the criteria of this validity. For this study, the researcher believes that no single framework can be adopted for all instances of problem situation and that frameworks developed will be valid for each situation.

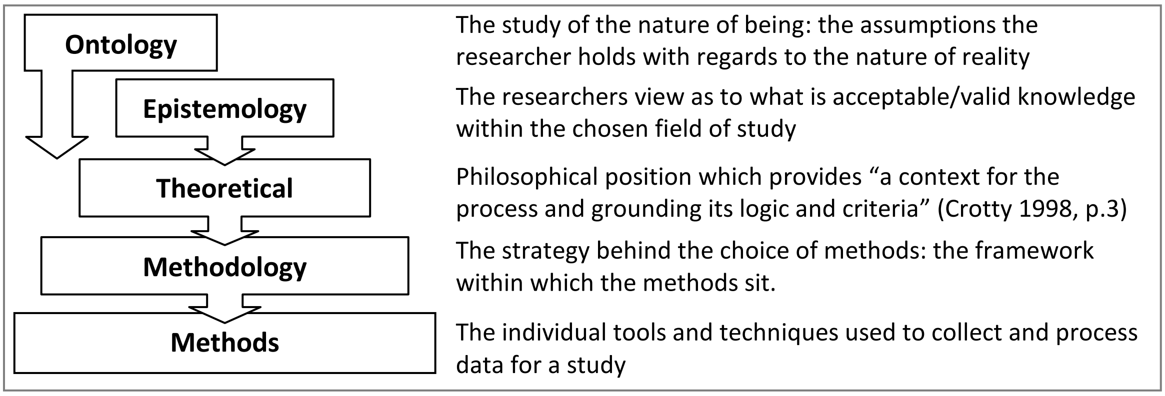


Figure 13: Layers – Adapted from Crotty (1998)

During any research study there are four basic questions which define the research process: what *methods are suitable for addressing the research questions*, what *methodology* governs the choice of methods, what *theoretical perspective* lies behind the methodology and what *epistemology* informs this theoretical perspective? (Crotty 1998) These elements are often illustrated in the form of a hierarchy (shown in Figure 13), with the researchers epistemology informing the theoretical perspective, which informs the research methodology, within which research methods sit. This would imply that the only way to conduct research is to first establish an ontological and epistemological view then work down. However, Crotty (1998) encourages the researcher to view this from the bottom up; the researcher will have some views as to how the research should be conducted, and they need to strip these away to find the theoretical views lying behind. It is this researchers view that these elements need to fit together but their selection is two-way; the researchers epistemology will inform the area which they choose to research which will inform the suitable methods, which fit within a methodology and theoretical perspective.

Subsequently, after considering these beliefs and that the motivation of the research is to explore, the researcher adopts the critical realist or radical structuralist epistemological position. If the diagram of research paradigms, proposed by Burrell & Morgan (1979), were considered it is this researcher's belief that they would sit[14] within the quadrant associated with radical change and an objective ontology in order to explore situations that lend themselves to the combined use of SD and DES (illustrated in Figure 14).

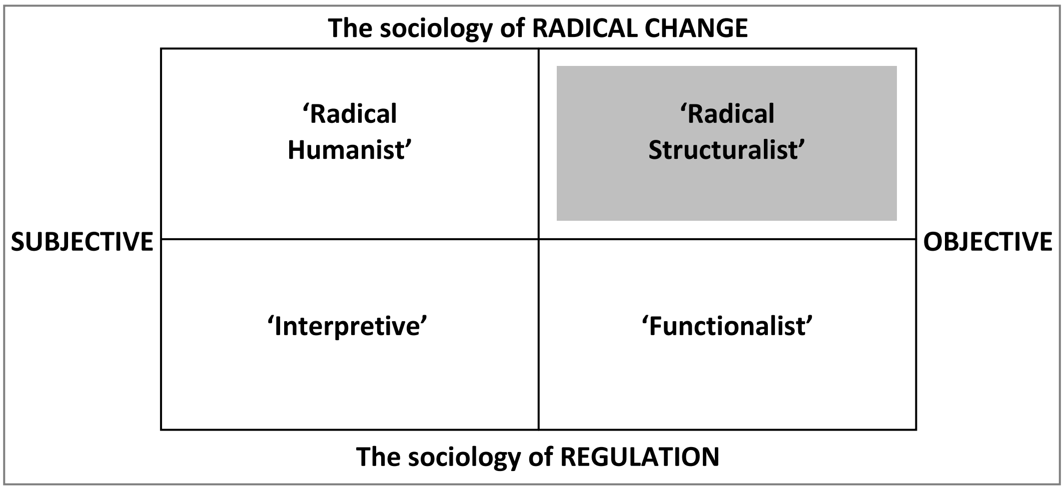


Figure 14: Four paradigms for the analysis of social theory from Burrell and Morgan (1979)

4.3.2 Critical Realist approach to research

So, what is critical realism? This researcher would deduce that critical realism is a paradigm which takes the view that reality is socially situated but not socially determined: a world exists out there that we seek to understand. It maintains, and it is this researcher's view, that it is possible to see parts of a solid, fixed, external reality and also parts of a perceived, subjective reality[15]. In building simulation models the researcher aims to produce a version of this reality that is based on observable facts and intangible, subjective views held of a system.

Critical realism maintains the possibility for objective critique to motivate social change. It differs from an interpretivist approach through the intention to appreciate the power dynamics, making it amenable to the intention of this study. To explore and build an appreciation of potential frameworks for the combined use of SD and DES, the researcher must unpack and examine common held views on selecting simulation methods, proposing that it should not be a purely binary choice between the two. The research hopes to free modellers from the binds of existing frameworks by working together, liberating and proposing change.

[14] Any researcher is hard pushed to fit neatly and exactly within such a box, but the researcher feels their work is more strongly associated with this paradigm for certain aspects than others.

[15] An objectively knowable, mind-independent reality exists, but perception and cognition help to construct it.

Within critical realism the researcher is embedded in the research, becoming one of the group; unlike a positivist approach where the researcher is taken to be an independent objective observer. It is implied that science should be viewed as an on-going process whereby the researcher continues to improve the models and concepts they employ to understand the subject of study. As there exists little literature on the subject of study, it is felt that the most appropriate way forward is for the researcher to work closely within an organisation that lends itself to both SD and DES, and work to develop in conjunction proposed frameworks and insight to the subject: to revisit and improve models. Critical realism is particularly suitable within Management Science as it allows for a distinctive approach to be taken; and, according to Mingers (2004 & 2006), supports the use of multimethodology.

4.3.3 Research implications

The ontological and epistemological views discussed provide a framework within which the research should be conducted, imposing restrictions and requirements. Adopting the critical realist position implies that the researcher has a similar ontological view to a positivist: a belief in a real world to model. However, it differs at the epistemological level as the researcher believes that knowledge can only be created with a full appreciation of the world, including the social world. This is aligned with the research as it is necessary to understand and incorporate the social structure when developing frameworks.

Critical realism tends towards an inductive approach to research which will be adopted. The researcher proposes to work on projects in collaboration with organisations to develop theories and allowing for exploration. Overall, the impact this theoretical position/perspective has on the research question is that the research seeks to explore, to propose a framework, or frameworks, for the mixing of SD and DES. Due to the limited work conducted in this field, adopting a critical realist position enables the framework(s) to be developed in conjunction with organisations and the research design to be dynamic. The focus will be on developing frameworks to assist understanding, not to measure the value of such frameworks.

If a positivist stance is taken, instead of a critical realist one, then the aim of the research should no longer be to explore. It would focus on the development of one definitive formal framework for the mixing of SD and DES, most likely based on previous theories currently untested within the specific context of the research (a healthcare environment). The design of the research should be static, and context free so experiments would be conducted to assess the potential utilisation and benefits incurred from the use of such a framework.

This researcher believes that the theoretical position and research methodology adopted need to be sensitive enough to recognise and utilise human attributes of the researcher, such as reflection, and the results of these attributes such as reasoning and learning. The positivist epistemology adopts an objective view of social science (Burrell and Morgan 1979), with the view to adhere to *"rigid rules of logic and measurement"* (Weaver and Olson 2006, p.460) and observer independence (Mingers et al. 1997). Similarly, an interpretivist research approach would be incompatible with the aims of the research as the focus would be on understanding the social and psychological implications of mixing methods (Welman et al. 2005), which does not fit with the research objectives.

It is the researchers' belief that when developing simulation, measures can be assigned to objects, but these measures also contain subjective information. There exists a real world but it is constructed of tangible and intangible elements. Adopting a critical realist epistemology enables the researcher to adopt an involved, action research approach, working with an organisation to develop frameworks for mixing methods. This is discussed further in the following section.

4.4 Selecting a Research Methodology

4.4.1 Introduction

Research is conducted to provide knowledge and understanding to make a difference in lives (Stringer and Genat 2004). Research methodology is concerned with the nature of the approach taken to research; a framework for use prior to determining the techniques to use and practices to follow when conducting research. The research questions and research propositions guide decisions about the research design. In research, activities are usually taking place simultaneously, each influencing one another; it does not commence from a fixed point nor proceed through a defined series of steps (Maxwell 2005). Although there may be no one elite method for conducting research (as discussed in the previous section); there is a need to make the research design explicit, to understand its strengths, limitations and implications (Maxwell 2005). The quality of findings is determined by the quality of logic employed in the study which allows others to evaluate the work undertaken (Ghauri and Gronhaug 2005).

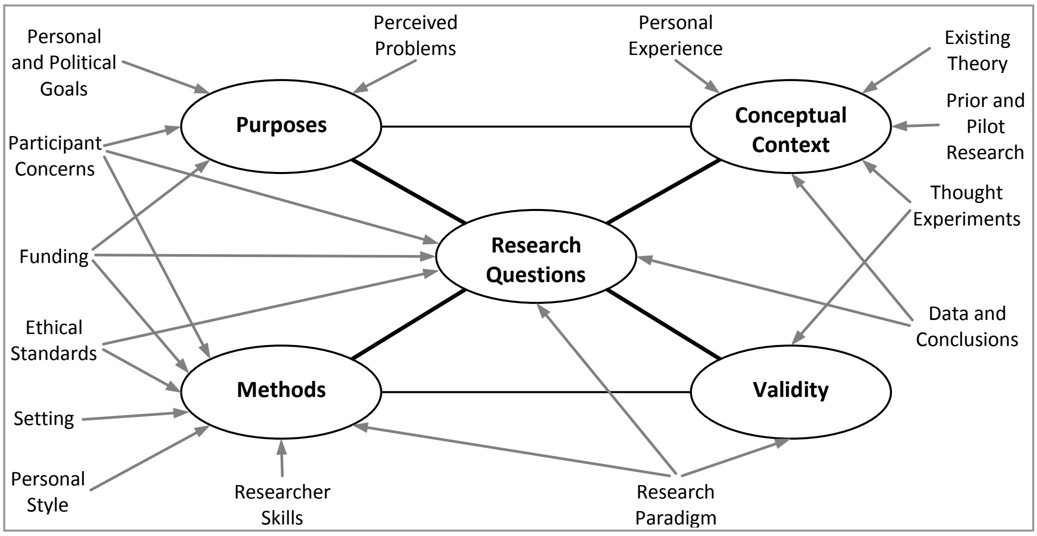


Figure 15: Contextual Factors Influencing a Research Design (Maxwell 2005, p.7)

Figure 15 illustrates components of research design, key issues requiring decisions and emphasises the interactive nature of decisions in design; highlighting the unseen external factors facilitating good design which promotes efficient and successful functioning. However, it must also be noted that good design does not imply rigidity, but a need to explicitly understand the strengths, weaknesses, limitations and implications of the research methods. The definition of good research is viewed differently within different fields of study. Of high importance in all, however, is the need for rigour and clarity. The following sections discuss two research methodologies under consideration.

4.4.2 Case study research

Research within the mixed DES and SD field involving real life project are often described as case study methodology[16]. These are presented as a singular case where no comparison is drawn, and a unique undertaking of mixing DES and SD is presented. These projects often look to contribute to the understanding of the context within which they are based. The simulation methods employed are a means to obtain this insight and the generalizability of the mixing process is not considered. The aims of the research are generally to examine the applicability of the mixed methods within the specific context, rather than contribute to informing discussion around the development process undertaken in a mixed methods project.

[16] Case study research has historically been used when looking at the benefit to be had in the application of SD and DES within a specific project: Brailsford et al. (2004); Ashton et al. (2005); Vasilakis et al. (2007); Sachdeva, Williams and Quigley (2007); Santos, Belton and Howick (2008) and Lane, Monefeldt and Rosenhead (2000). Further to this, more recently by Morecroft and Robinson (2008) to examine the differing conclusions to be drawn from the two modelling methods applied to the same case.

A case study is, according to Yin (2003), an empirical enquiry that *"benefits from the prior development of theoretical propositions"* (p.13). Case study research is the preferred research approach when how and why questions are to be addressed within the real world. It is a suitable methodology for this research as it allows for exploratory analysis of real-life phenomena. The methodology benefits from the prior development of theoretical propositions to guide data collection and analysis. However, there are several ways to employ case study research methodology depending on the epistemology of the researcher, described in Table 6. The alternative undertaking of case study research, denoted by Stake, may lend itself to objectives of this research.

Table 6: Key features of case method informed by different (Easterby-Smith, Thorpe and Lowe 1991)

	Positivist (Yin)	**Positivist and Constructionist (Eisenhardt)**	**Constructionist (Stake)**
Design	Prior	Flexible	Emergent
Sample	Up to 30	4 – 10	1 or more
Analysis	Cross case	Both	Within case
Theory	Testing	Generation	Action

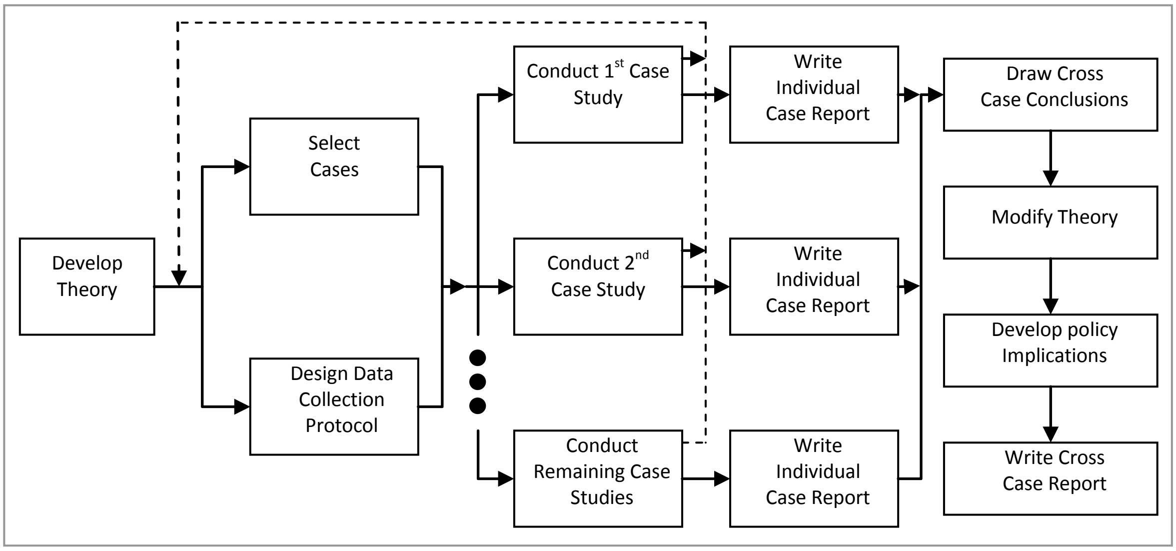


Figure 16: The Case Study Method (Yin 2003, p. 50)

Case study research can be described as taking the form as illustrated by Yin in Figure 16. In this research the use of a single case but with several projects within the case would allow cross case conclusions to be drawn (shown in Figure 16). Of importance for this research is the feedback loop (represented by the dotted line), illustrating that this process can indeed be re-evaluated. It is this loop that allows the case study to be adaptable in the event of an important occurrence, allowing for redesign.

In case study research it is deemed important to go in with a clear focus to collect data systematically; this adds to the replicability of the research. Strengths of case studies are that the researcher is likely to generate novel theory (Eisenhardt 1989); and in addition, the emergent theory is likely to be testable and verifiable as they have already been measured during the research process.

Eisenhardt (1989) also discusses how the constant comparison between what is seen and what was expected (preconceived ideas) assists theory building, and in fact can be less biased than other incremental studies. Additionally, case study research is tightly tied with evidence meaning that it is highly probable the resulting theory will be consistent with empirical observation, and the close contact assists in the development of a theory which "closely mirrors reality". It is likely to provide insight that is not necessarily obtainable through objective, non-interactive methods; tying theory closely with practice. However, this closeness can mean that the resulting theory is overly complex with the quantity of rich data leading the researcher away from simple, parsimonious theory. Although a case study aims to investigate real-life phenomena, even if more than a single case is used, the results may be narrow, with the researcher unable to raise the level of generalizability.

A concern for using a case study methodology for this research is the focus on the study setting. Case study is *"a research strategy which focuses on understanding the dynamics present within single settings"* (Eisenhardt 1989, p.534), but this research is interested in the process of mixing methods rather than the uniqueness of a situation using mixed methods. Examples of mixing methods in the literature (see Chapter 3) often describe themselves as case study research. Some of these projects focus on the appropriateness of mixed methods within the setting and the novelty of the mix, as would be expected in a case study design. However, a selection of cases in the literature includes an element of reflection on the process which is more aligned with an action research study. Within this research the aim is to develop a transferable framework therefore the researcher needs to reflect upon the modelling process throughout. No specific situation has been predetermined for modelling therefore the potential for mixing methods can be examined within the entire model development process. The focus of this research is on the process of mixing methods rather than how methods are mixed in a particular setting. It aims to take a step back and explore how to incorporate mixed methods into an overall modelling process and so a research methodology is required to enable adaptability to the situation and generate useful practical insights, which leads to the question: is an action research approach needed?

4.4.3 Action research

It is generally acknowledged that the term action research was first employed by Kurt Lewin when discussing the research needed for social practice. Action research is a form of comparative research that leads to social action (Smith 2001); and it is the purpose of action research to generate living theories (McNiff and Whitehead 2006). The methodology has many proponents, but what constitutes action research and how to undertake the methodology are not generally accepted by all practitioners (Greenwood and Levin 1998). One recognized feature is that the process is cyclical and reflexive, as illustrated in Figure 17.

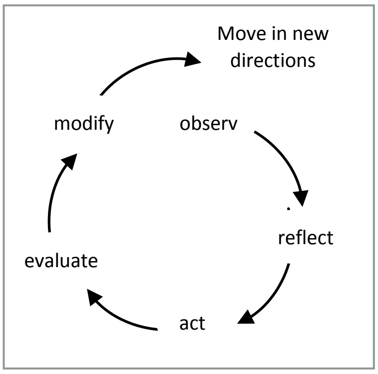


Figure 17: Action Research Cycle (Huxham and Vangen 2001)

It has been said, by Rapoport (1970), that action research has a dual agenda: practical and scientific; it is tailored and innovative: systematic processes of enquiry to enhance the outcome for clients, providing methods to improve intervention effectiveness (Stringer and Genat 2004). It is these characteristics which make action research suitable for this research topic, as the desired outcome needs to be practical and implementable; whilst the approach also acknowledges the existence and importance of the client. Rather than asserting to be an impartial spectator in a case study, observing and collecting data; intervention is at the heart of action research. The researcher becomes a participant in the research which helps to reduce boundaries with the organisation, increasing the chance of obtaining rich data. It is emergent, grounded in data and action, with a strong practical relevance (Huxham and Vangen 2001).

Action research is *"almost always emergent because the researcher cannot know in advance what intervention opportunities will arise"* (Huxham 2003, p.241), and it is this emergent process which is taken in this research. It would enable the researcher to extend the problem understanding and to formulate action directed towards problem resolution. Through this method the researcher would look to gain specific understanding through collaboration of the context of study (Stringer and Genat 2004). It is through this collaborative approach that action research illustrates its applicability to this research area, as it is the researchers desire to work in collaboration with a cancer unit to generate useful tools and techniques, and hence develop new theory.

This form of research differs primarily from other applied research by the existence of a client and an actual problem/concern to be addressed (Rapoport 1970). But this is not giving a true picture of action research, failing to illustrate the whole depth of value possible. As there has been little research conducted in mixing DES and SD, an exploratory and adaptive methodology, able to respond to organisational change and developments, would be preferable.

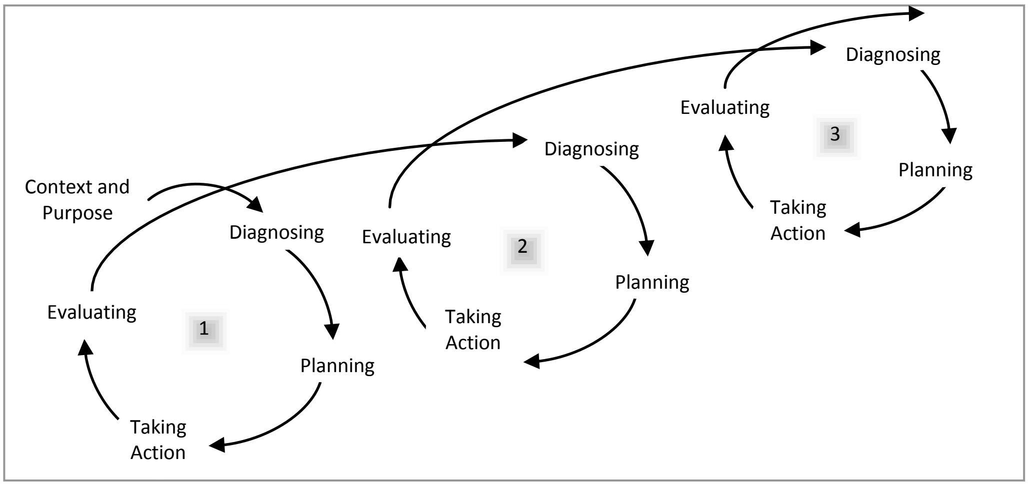


Figure 18: Spiral of Action Research Cycles (Coghlan and Brannick 2010 , p.24)

Action research has its similarities with case study research but an important distinction is the resulting action, and its responsiveness to evidence; the reflexive approach (see Figure 18). The research derives theoretical insight from naturally occurring data and uses this insight to move the research forward. A threat to validity is questions over rigour, and it is suggested that quality can be improved through the use of multiple cycles (Dick, Passfield and Wildman 2000). An issue that may be encountered is the call for replicable research, but certain advocates of Action Research seek to address recoverability (Checkland and Holwell 1998) rather than replication as the belief held is that no two situations are able to be identical in every aspect; they are unique to that moment in time. It is noted that although a result of the research is intended to be change, there are some forms of action research which focus more on research than on the action: it is dependent on the emphasis of the research and how the action is defined (Stringer and Genat 2004).

Rapoport (1970), quoting Lewin, states *"there is nothing as practical as a good theory"* (p.505), supporting the view that action research adds another dimension to research; looking for practical application and not purely theory based (Stringer and Genat 2004). Action Research involves participation, providing rich data not necessarily obtainable through more neutral observation methods; however, a threat to the research is justifying it to a wider audience and the criticism it may come under.

Platts (1993, p.16) states that in action research *"the knowledge resulting from this research is not aimed at describing, explaining or representing manufacturing systems but rather providing a means of dealing with them in the real world"*. This can be transferred to this study as the research seeks to generate knowledge in relation to a process rather than a distinct unique phenomena or an individual organisation. The knowledge resulting from this research is not aimed as describing, explaining or representing a system that seeks to develop understanding through modelling, but to provide frameworks for developing mixed methods models. During the research, the output for the client will be models that inform their understanding of the system, that are created following the process depicted in the framework developed during the research.

4.4.4 Proposed research methodology

Choosing between the two feasible methodologies is based upon key characteristics of each methodology and the ability to cope with an underdeveloped/limited selection of research currently in the field. Modelling is a method which ties together well with the case study research methodology as a model can be used to illustrate the unique situation. As for the suitability of using modelling within an action research study, a model may be viewed as a potential basis for managerial interaction (Pidd 2003) which could be interpreted as (constitute) the action. Therefore both methodologies are suited to the use of models for theory development as needed in this research. Action research should not seek to draw comparisons, illustrate statistical correlation or express cause-and-effect relationships (McNiff and Whitehead 2006); none of which are required within this research. Case study research, however, is designed to put a theory to the test, implying that a convincing and robust theory is developed prior to embarking on the project. Both the action research and case study research methodologies provide a level of client interaction not seen in alternative methodologies, which raises the potential for capturing rich data and encourages buy-in. Further to this, both case study and action research require a strong level of rigour to be employed, with a clear design. Given the nature of the research, it is seen to be advantageous to select a research approach which is adaptive and responsive to change; supporting the need for a collaborative and reflexive strategy and a method which supports the participatory role of the researcher, and action research supports this.

Considering both methodologies, case study is designed to understand the uniqueness of the situation; whereas action research is a form of enquiry allowing practitioners to assess their work, allowing the researcher to *"evaluate whether what you are doing is influencing your own or other peoples learning… you may want to: improve understanding, develop learning and influence others' learning"* (McNiff and Whitehead 2006, p.15). It embraces the emergent nature of theory through an iterative process that converges towards a better understanding of what happens (Dick et al. 2000). This means that action research stands up academically whilst being of use to practitioners.

An action research methodology is adopted for this research project as it enables the researcher to develop an understanding of situations amenable to mixed methods and develop the theory collaboratively with the project stakeholders on how to physically integrate the two methods in a practical way. The output of action research is *"not intended to be context bound"* (Huxham 2003, p.2) meaning that the theoretical frameworks developed as not intended to be situation specific. Action research places the individual at the centre of enquiry (McNiff and Whitehead 2006), whereas case study research is focused on the system. It was planned that an initial project would lead a theoretical framework to inform the mixing of the methods, which could then be assessed in different contexts. However, this was not able to be completed in practice due to the complexity of the initial project undertaken. Rather than several projects and reflection taking place after each, this research ended up being a single project completed in phases, following the cycles of action research to ensure that reflection took place throughout.

The setting for this proposed methodology was the Beatson West of Scotland Cancer Centre. The appropriateness of the healthcare centre as the setting of the action research project and for mixed methods modelling to be undertaken is considered in the following section.

4.4.5 Modelling in Healthcare

Operational research (OR) has played an important role in healthcare since the mid-1960s, and has become an established form of decision analysis within the sector. Projects range from scenario analysis to examine the spread of disease (Davies et al. 2003), stakeholder analysis whereby key players are identified and their impact quantified to bring forth many views, and optimisation to get the most out of a department whilst also considering the constraints such as cost and the limited resources. Stemming from that, the investigation of systems and processes within healthcare has been extensively populated by two OR methods: SD and DES. Healthcare offers a complex interconnected system with questions to be addressed at both strategic and operational levels. As there is a long established role of simulation in health it is relevant to use a healthcare setting as the context for this research.

The university and the researcher already have an established relationship with the Beatson West of Scotland Cancer Centre, Glasgow. The Beatson is Scotland's largest cancer treatment centre, serving a population of 2.6 million, and the second largest in the UK. The centre focuses on non-surgical care with treatments, and each year handles over 8,000 new patients, over 15,000 courses of chemotherapy and 6,500 courses of radiotherapy whilst maintaining some of the lowest waiting times for radical patients in the UK. Stakeholders from the centre have previously shown themselves to be willing to spend time working with representatives of the department to produce models, and are keen to be involved in research to assess their system, and have previously been involved in projects utilising both DES and SD.

4.4.6 The researcher as the modeller

As part of the action research methodology the researcher will perform the role of modeller and facilitator throughout this research project. This means that the researcher must wear multiple hats throughout the project but enables the theory being devised to be reflected upon and adapted throughout the project. Although there are disadvantages (such as the lack of an independent objective observer) there are also benefits: the integrated goals of the two roles are complementary, the modeller/researcher develops an in-depth appreciation of the research requirements in hand with the client's needs which is likely to reduce the need to negotiate and compromise and alleviates communication issues. In terms of ability, the researcher has training in both DES and SD, and experience creating DES models within a healthcare. The researcher has worked as a tutor with the university (which involved facilitating small student groups) and as a consultant, providing experience of working with a range of individuals and groups to elicit information and facilitate discussion to define and inform the objectives of a project. The ramifications of these multiple roles will be considered prior to embarking upon and reflected upon during and following the project, which is discussed in *Chapter 8*.

4.5 Research methods

A research method may be defined as *"a technique for collecting data"* (Bryman and Bell 2007, p.40). An integral element of research design is the identification of the techniques for use in the study. Research methods can impact the type of data obtained, how data can be analysed and hence the resulting conclusions. This section will discuss the methods for data collection used within the action research project.

4.5.1 Literature review

The purpose of a literature review is to acquire an understanding of your topic; appreciate what has been done before, how it was researched and what the key issues are (Hart 1998). As was discussed in the introduction of this thesis, the first stage of this research was to undertake an analysis of the literature. In that review we sought to consider the direction of the research and decide the research questions, as illustrated in Figure 19.

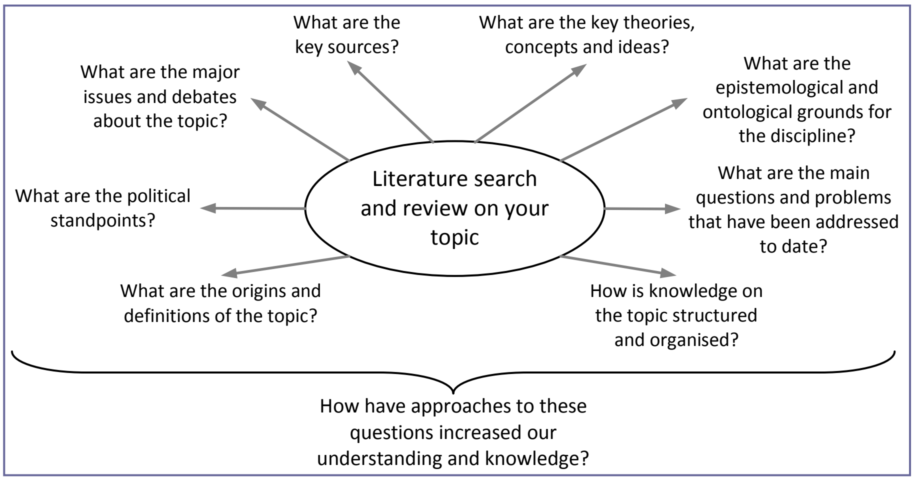


Figure 19: Some of the questions a review of the literature can answer (Hart 1998, p.14)

In the second stage of literature analysis (*Chapter 5*) we consider how the study might address how to mix modelling methods which has yet to be examined, and extend the discussion by collating and incorporating new elements. A literature review is an analysis of ideas, an illustration of relationships between ideas, and a demonstration of the researcher's understanding of the nature and use of argument in the research (Hart 1998). This is achieved by looking at the DES and SD literature, comparing the methods, exploring how modellers choose between them and determining what lessons and ideas can be taken from the wider multimethodology literature. The intention of the second stage of literature review is to develop theory to re-specify the puzzle of how mixed DES and SD methods have been used.

4.5.2 Building theory from models

During and following the literature review model building will also be used in order to understand the modelling processes of published studies in the field of mixing DES and SD, and to develop theories on how to mix the methods. Model building is compatible with many forms of research methods provided they are used within the researcher's philosophical framework. A model is a tool for thought; according to Pidd (2003, p.12) it is *"an external and explicit representation of part of reality as seen by the people who wish to use that model to understand … that part of reality"*. This illustrates that model building fits with the researcher's subjective ontology, that reality is not believed to be definitive.

4.5.3 Interviews & group model building

As discussed by Huxham (2003, p.242): *"the ideal situation is when an intervention tool can double as a means of recording data"*. DES and SD model(s) will be created within the action research project which requires the modeller/researcher to undertake a coherent problem exploration and model development process. Therefore the use of unstructured interviews is proposed throughout the development of the mixed DES and SD model(s) to provide the modeller with the opportunity to gain valuable insight from those within the system (stakeholders) in an informal setting whilst enabling the researcher to collect data on the stakeholder views/impressions/thoughts on the model(s) being developed. This enables, from the modeller perspective, a sound model development process to be undertaken and useful model(s) to be produced; and from the researcher perspective, data collected throughout to generate *"descriptive theory that captures the experienced world"* (Huxham 2003, p.246).

Model building in simulation benefits from being viewed as a collaborative process, therefore it is felt the use of group model building and focus groups would provide a forum for all participants to express their views and add to the research. However, the availability and work pressures of staff within the centre limited the feasibility of gathering stakeholders for multiple group modelling sessions. Therefore individual semi-structured interviews are undertaken, mapped and the merged map was discussed with stakeholders as part of the initial system exploration (discussed in detail in chapter 6); unstructured interviews took place with the client throughout the model development iterations to obtain feedback on the models developed.

4.5.4 Stakeholder selection

The research is informed by Friend and Hickling's (1997) view that it is preferable to work into a problem initially to be distinct from working towards decisions later. For this reason, and to ensure the data is available for analysis, the researcher has chosen to undertake an explicit, well documented problem structuring process to first explore the system, and then select an issue relevant to the stakeholders to explore using mixed methods.

Stakeholders will both inform the model(s) being developed and provide data for the research. As part of action research the researcher must consider the stakeholders values, objectives and needs (Bargal 2006). Stakeholders involved in the project will provide invaluable insight into the system. Participation has a mutual benefit by enabling people to have a say over how the project will impact their working life, to generate a sense of ownership, to provide an opportunity for learning (both for the modeller/researcher and the stakeholders). The selection of stakeholders and the interview process are presented in *Chapter 6*.

4.5.5 Summary

The research methods employed are selected to provide rich data about the project for research and for the modelling project. They reflect the demands of both the research and of the modelling project. Having defined the philosophy, methodology and methods of this research the research questions which were developed through the literature reviews in *Chapters 2* and *3* are discussed next.

4.6 Research Objectives

The purpose of the research is to contribute to how mixed DES and SD modelling is undertaken; process knowledge. The proposed action for this project is the impact on the real system, which will be to improve stakeholder(s) understanding of their system. This section presents the research objectives based on the questions resulting from the literature review.

The research gap presented in Section 3.5 was described in the form of eight research questions. Throughout the research process the questions were reflected upon and summarised to develop the research objectives. Chapter 2 explored the first two research questions proposed, which sought to highlight the characteristics of DES and SD, how the methods have been used and the potential to mix methods. These two questions were used to derive the first research objective:

> ***Obj 1.*** *Obtain a broad understanding of: how DES and SD compare; how modellers choose between them; and the theoretical concerns for mixing OR methods and DES and SD specifically.*

Chapter 3 examined the third and fourth research questions which had the theme to explore why and how DES and SD are mixed. This led to the second objective:

> ***Obj 2.*** *Gain an in-depth understanding of why and how DES and SD have been mixed, theoretically and practically to inform on issues important to key stakeholders in the past; and what problem situations, particularly healthcare, have been shown to be amenable to mixed DES and SD.*

Following the literature review (Chapters 2 and 3), four further research questions were presented. Questions 5, 6 and 7 focus on taking lessons on mixing DES and SD from the literature to propose frameworks for mixing. These questions are summarised as the third objective:

> ***Obj 3.*** *Explore the development of frameworks to support mixed method modelling with DES and SD, and how these fit within the modelling selection, design and development process.*

Research question 8 is reworded in light of the other research objectives to become the fourth objective:

> ***Obj 4.*** *Reflect upon the value of and challenges faced when embarking upon a mixed DES and SD modelling project within a healthcare organisation, and how insights from a healthcare project could be transferred to other organisations.*

The main aim of this research is to explore the use of a model development framework and develop mixed method designs to support the concise description, adoption and implementation of mixed DES and SD modelling. This aim is explored through both the literature and engagement with a healthcare action research project. The research questions which resulted from the literature review may be summarised into the following objectives which are referred to throughout the thesis.

The literature review (Chapters 2 and 3) has presented the research conducted into objectives 1 and 2. The following chapters explore objectives 3 and 4 whilst continuing to reflect on objectives 1 and 2. Chapter 5 presents the theoretical developments made throughout this research: to examine frameworks for mixing methods and how they are embedded within a robust OR/MS modelling process (objective 3). The remainder of this thesis discusses the action research project and its application to contribute to objectives 3 and 4.

4.7 Research Plan

The research project is conducted solely with the Beatson. Due to the complexity of the system under study and the length of time required to gain access and develop adequate basic understanding of the system further healthcare cases are not feasible in the time period available. Also, due to the large and complex nature of the system it provides a rich environment to explore the possibility and applicability of mixed SD and DES modelling.

The steps of the research are depicted in Figure 20. The research plan consists of four sequential reflective cycles with the theory being reflected upon and adjusted as seen fit throughout all four.

1. **Theoretical Framework(s) version 1** – Consider DES and SD at tool, method, methodology and paradigm level. Explore the multimethodology literature and case studies of mixed DES and SD to inform theoretical framework(s) that consider how (to mix methods), what (which methods) and why (the paradigm assumptions). Undertake the initial system exploration and problem selection stages of model development using and considering the theoretical framework(s) developed from the literature. After this stage discuss the problem structuring model(s) with stakeholders to obtain feedback to inform the next stage of model development and aid the researcher's reflection on the framework(s).
2. **First modelling cycle** – Embark upon conceptual modelling and model construction informed by the theoretical framework(s). This is completed through semi-structured

interviews with key stakeholders at the Beatson and frequent discussions with the client. As the modeller, reflect on how and why the methods are mixed, and if further modelling is needed. As the researcher, reflect on the framework(s) by considering what was appropriate or necessary, what wasn't applicable and what changes should be made.

3. **Second modelling cycle** – As with the first modelling cycle.
4. **Third modelling cycle** – As with the first and second modelling cycle, followed by presentation of the final changes to the framework.

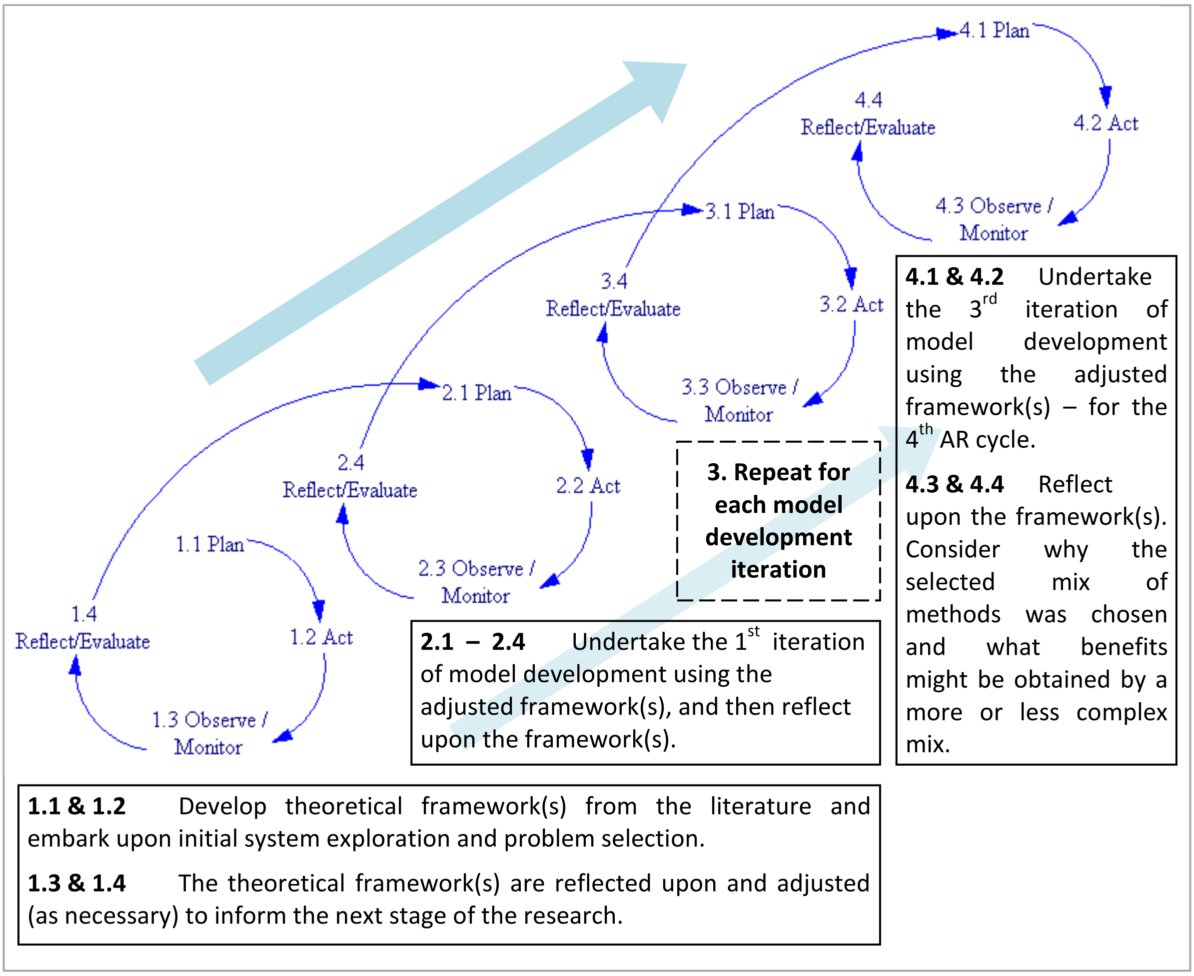


Figure 20: Research plan consisting of 4 cycles of reflection

4.8 Research Ethics

This research was approved by the University Ethics Committee and all activities of this research complied with the Code of Practice[17] as prescribed by the Ethics Committee. Advice was sought from the West of Scotland Research Ethics Service (WoSRES) who confirmed that NHS ethical review was not required for this study (see Appendix 10.5 for details). Consent for involvement in the research project, including: the conduct of face-to-face interviews, conduct of face-to-face interviews, the audio recording of the interviews, the safe-keeping of interview transcripts, and the use of anonymized quotes in all publishable materials in connection with this research.

4.9 Chapter Summary

This research is informed by a critical realist research philosophy. That is, it is the researcher's belief that a fixed reality exists and that individuals are able to contribute their personal perspectives of that reality to build a picture of that reality. The key characteristic of interest with a critical realist philosophical view to research is the involvement of the researcher, the decision to start with data and the use of fieldwork. This chapter has shown that the critical realist paradigm adequately encapsulates the researcher beliefs and the research characteristics. That the integrated and realist nature of the research design reflects the researchers views.

The methodology undertaken is an action research project. Although only a single project is undertaken, the iterative nature of the model building process lends itself to the action research reflective cycles enabling the modelling to reflect on the theory being developed at several points of the project. The methodology and philosophy fit with the aims of the research: to contribute to how mixed DES and SD could be undertaken (process knowledge). The researcher is able to collate existing views of mixed methods and add their own perspective based on experiences garnered throughout an action research project to provide an updated/refined/newer version of reality.

The auxiliary methods used within this research are: literature review, modelling for theory development, and semi-structured interviews. Modelling is a consistent theme of this thesis and is used to provide structure to the results from the literature review. Interviews provide opportunity for data collection as well as their use throughout the model development

[17] The Ethics Committee, University of Strathclyde. http://www.strath.ac.uk/media/committees/ethics

process to ensure an appropriate problem area is selected for modelling, and to obtain data for and feedback on the models(s).

In terms of ensuring research saturation and triangulation action research presents the biggest risks but provides the opportunity for deep insights into the model development process when mixing DES and SD. Existing research presents a variety of mixed DES and SD models as a single novel application. This research seeks to inform the selection and undertaking of mixed methods modelling by considering various ways to mix the methods. The proposed framework(s) are used to examine published case studies and thus demonstrate the applicability of the framework(s). Four reflective iterations of action research are undertaken within a single research context which has implications on the framework(s) generalizability and transferability. The healthcare setting of the project has been previously shown to be a complex system which is frequently explored using DES or SD. The learning acquired from within this setting is transferable to inform the modelling of other complex systems

Finally, this discussion acknowledges that an ideal research method does not exist. Although it is possible to combine methods in order to address challenges and limitations, it is unavoidable that they will be encountered. It is predicted that time will be a constraint on the research, for either method, due to the availability and work pressures of staff within the centre and so it is proposed that the researcher takes this into account as this impacts the quantity and quality of data.

5 Frameworks for Mixing Methods

5.1 Introduction

The previous chapter presented the design of this research, with the view to contribute to the mixed methods field through the exploration of frameworks to help with the description and undertaking of mixing methods. The first stage is to explore and reflect on mixing methods and mixed DES and SD literature to establish the gaps in the literature and potential theories to contribute to the field. This chapter collates frameworks from the literature to provide a refined set of designs. Their applicability is examined using them to review mixed DES and SD projects in the literature. The chapter concludes by proposing a model development framework that incorporates the model development process of DES and SD and mixed methods frameworks, whilst encouraging the use of mixed methods throughout.

5.2 The Terminology of Mixed SD and DES projects

Examining the literature for mixed SD and DES examples reveals a range of descriptors to classify project methodologies by. The term hybrid is used within a range of contexts with a variety of meanings – it is not a term restricted to the mixing of SD and DES. It is also a term that fails to convey the degree to which the methods are mixed and the intricacies of how the methods interact. Table 7 illustrates the range of terms used by authors to describe work that uses, or intends to use, both SD and DES. At one end of the spectrum authors may not acknowledge/recognise/state that the work uses both SD and DES within the same project. Alternatively, others may inadvertently be over emphasising the relationships created between the two methods by following the trend to call simulations hybrid. The computer science and engineering definitions of the term may not align, with the tendency to use it to describe mixed methods that are simulation based. This supports the research objective to collate a set of useful, practical and applicable descriptors to prevent confusion and provide a clearer basis for comparison between mixed SD and DES projects.

The aim of this review was to reveal the variety of methodologies undertaken within mixed method projects and establish what can be learnt from these projects. Examining the literature for theoretical discussions of multimethodology and mixed method projects reveals the use of numerous terms to describe a mixed methods project[18]. The term hybrid modelling in MS/OR was first proposed by Shanthikumar (1981, 1983) to broadly describe the mix of

[18] These papers were identified throughout the literature review discussed in *Chapters 2* and *3*.

simulation and analytic models, the design of which could take several forms. Shanthikumar (1981, 1983) presents these various forms of hybrid modelling diagrammatically which illustrates the clarification necessary between the various mixing methods. Hybrid continues to be a widely used term but clarification of the form of the hybrid modelling is rarely given. Hybrid is a useful term for mixed simulation modelling but adds little insight into the design of the mix, providing few methodological lessons.

Table 7: Papers discussing a mixed DES and SD modelling project

Description of mix	Paper
Both	Dierks, Dulac & Leveson[19] (2008), Martin & Raffo (2000)
Combined	Chatha & Weston (2006), Lee, Cho & Kim (2002)
Comparing or versus	Morecroft & Robinson (2006, 2008), Ozgun (2009)
Hierarchical	Kouskouras & Georgiou (2007)
Hybrid	Alvanchi, Lee & AbouRizk (2011), Barton (2000), Borshchev, Karpov & Kharitonov (2002), Donzelli & Iazeolla (2001), Han et al. (2006), Jacob, Suchan & Ferstl (2010), Lee, Han & Pena-Mora (2007), Mazaeda et al. (2012), Pena-Mora et al. (2008), Rabelo et al. (2007)
Hybrid & Integrated	Venkateswaran, Son & Jones (2004)
Integrate & Synchronise	Helal et al. (2007)
Integrated	Brailsford, Churilov & Liew (2003), Reiner (2005)
Inclusion / addition	Phelps, Parsons & Siprelle (2002) – referred to by brand name: *Simulation Dynamics*
Discrete events in SD	Wolstenholme (1980), Howick & Eden (2004)
Unclear – DES then SD	Brailsford et al. (2004)
Unclear – SD for DES	An & Jeng (2005)
Unclear – SD in DES	Fioroni et al. (2007)
Unclear – only states both used	Su & Jin (2008)

Within these examples there lies no clear terminology or methodology design for the projects. The justification for mixing SD and DES conversely reveal a limited range of reasons: from when neither method is sufficient on its own to capturing the benefits of both. Further investigation is needed into how the two methods are used together and for what reason this design of mix is selected. The terms currently used to describe how SD and DES are mixed in a project are unclear, ambiguous and can lead to confusion due to the same term being adopted for a broad range of mix designs. So, this research seeks to add clarity to this by examining: what is done and what terms might be appropriate to describe the mix of the methods.

The following section looks to the multimethodology literature to examine what research is being done within this wider field and how it can inform the mixing of SD and DES

[19] Not described as mixed methods.

specifically. The issues associated with mixing methods are outlined and a hierarchy with which to view the theoretical considerations. Designs for mixing methods from the literature are discussed and refined based on characteristics which emerged during the refinement process and are summarised at the end of the chapter (in Table 9).

5.3 How to Mix Methods

5.3.1 Introduction

This section outlines the broad philosophical issues of mixing methods, demonstrating the challenges faced and how careful consideration of the design of the mix can address these issues. Designs from the multimethodology literature are summarised to inform the form a mixed project takes. These designs are evaluated and reflected upon in light of existing SD and DES projects. Characteristics of the design of the mix in each project are examined to propose a refined set of designs.

As discussed in Chapter 3, real-world problems are highly complex and multidimensional and it is possible for different research paradigms[20] to focus on different aspects of a situation. Mixing methods has posed some philosophical issues centring on the ability (or lack of) to separate the method from its underlying theory, and the possible incompatibility of methods from differing philosophies. Mingers & Brocklesby (1997) discuss arguments for a multi-paradigm project methodology and multimethodology in OR whilst considering the philosophical aspects of mixing methods, and incommensurability there remains a lurking undercurrent in mixed methods (as illustrated in recent viewpoints: Harwood 2011, Jackson 2011, Mingers 2011). Formally presenting the design of the mix may help the modeller openly explore the issue of paradigm compatibility by presenting a toolbox of designs proven to work in practice, as seen by (Swinerd and McNaught 2012). This is inspired by Flood and Jackson (1991): to develop a set of methodologies and to ask what method when?

The following sections examine the terms used within the wider multimethodology field to describe the mixing of methods. On inspection these designs for mixing can be refined to produce a coherent set which seek to capture the range of multimethodology options available to a modeller and highlight the implicit paradigm considerations that should be made. Factors pertinent to consider when selecting a mixed method design emerged whilst

[20] Paradigms, or indeed techniques and methods

reducing the number of designs to a coherent set. These factors for design selection are proposed and their applicability reflected upon.

Figure 21 illustrates a hierarchy with which to consider OR methods which is used to help collate and represent the mixed method designs from the literature. The hierarchy from techniques to paradigms is inspired by Crotty (1998) which was used previously in this thesis to discuss the research design. It illustrates that tools and techniques lie within methods, and methods may be clustered into methodologies. Methodologies may be associated with paradigms which guide the functioning of methods and tools/techniques that are lower in the hierarchy, influencing how they may be used. As methodologies sit within their respective paradigms, the mixing of methods may need to be considered at the paradigm level and the mix of individual methods must be considered within their own context. This hierarchy is used as a key to mixed method designs in the literature. It is used to aid consideration of paradigm issues that might apply to the designs by making the applicability of the designs at various levels of the hierarchy explicit.

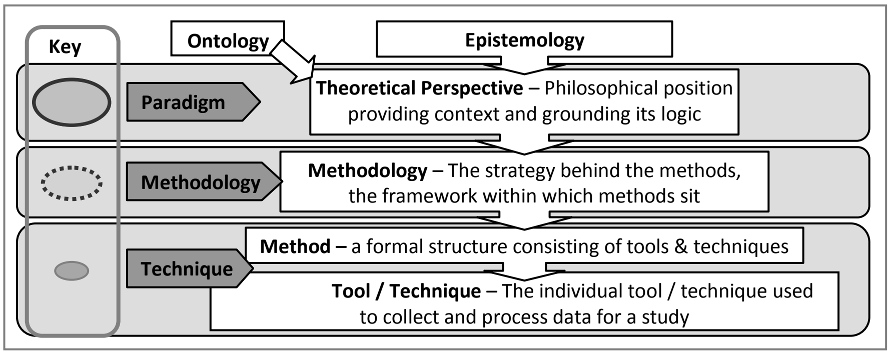


Figure 21: Key to presented mixed method designs (based on Crotty 1998, p.7)

Three key bodies of work which specifically discuss designs to mix methods are considered. These papers were selected as they are regularly referred to, or expanded on, by those undertaking mixed methods in practice and those seeking to add to multimethodology theory. The terms proposed in these papers for describing mixing designs are discussed and diagrammatically represented using the key from Figure 21.

5.3.2 Comparison, Enrichment and Integration

Bennett (1985) presents an early discussion of multimethodology, he discusses the view that tools and/or methods may focus on, emphasise or encapsulate differing aspects of a particular issue (illustrated in Table 8). This in turns motivates bringing two methods together: as it holds the promise of an overall better methodology. Individually, each method has its strengths, and areas that are captured less sufficiently. If the methods are not mutually exclusive then the question arises as to whether they are complementary.

Table 8: Discussion of Designs as proposed by Bennett (1985)

Linkage	Description / Questions	Outcome(s)
Comparison	In what ways are the methods similar (theoretically or practically) and where are they incompatible or complementary?	A precursor to more ambitious forms of linkage allowing clarification of the applicability and usability of the tools and does not imply alteration of any methods.
Enrichment	One method may be enriched by adopting elements (theoretical or practical) of another. The process need not be one-sided, and may consist of mutual enrichment.	Overall, no *new* content is created: nothing emerges that was not previously contained in any of the methods. This design allows for the transfer of ideas between methods.
Integration	Integrative theory may be provided by some more general formal framework used for existing models.	Consists of elements of existing methods but seeks to provide something that is distinct from either method.

The three designs proposed by Bennett (1985) have been interpreted by the researcher and diagrammatically represented in Figure 22 to aid visualisation and demonstrate that they may operate at paradigm, methodology or technique level. Each design progressively provides deeper integration with the first merely suggesting a lens with which to view two methods (by exploring compatibility and complementarity) whilst maintaining paradigm integrity, the second seeking to add value to a dominant method using the tools of another and the final separating methods and tools from their paradigm to mix. Each design specifically considers the outcome of mixing methods: from no alteration of methods to the creation of a new method.

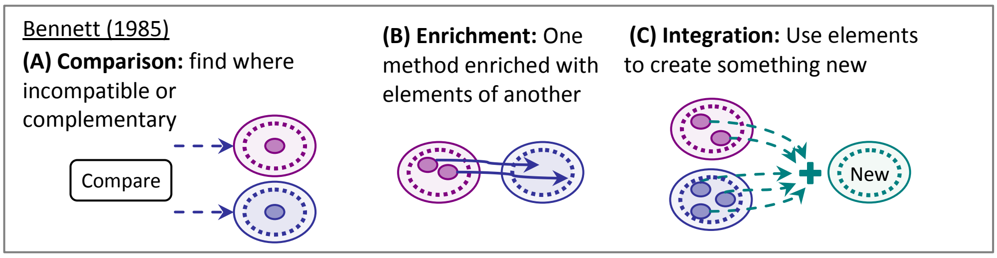


Figure 22: Mixed method designs based on the concepts presented by Bennett (1985) – refer to Figure 21 for key.

5.3.3 Sequential, Parallel and Interaction

A second set of designs of interest are those proposed by Schultz and Hatch (1996), illustrated by this researcher in Figure 23. The first two options refer to the order in which different methods are applied, maintaining the integrity of the paradigm boundaries. For example, within the *sequential* design, paradigms are viewed as *"mutually complementary"* (p.533) by revealing sequential levels of understanding, with the relationship between paradigms as linear and unidirectional. *Sequential* and *Parallel* designs could be viewed as precursors to deeper mixing of methods described as Interaction. However, *Interaction* does not specify an order, but encourages connections to be made between the methods. Schulz and Hatch pay careful attention to describing the paradigms and their boundaries, highlighting the need to consider the permeability of these boundaries to allow connections to be made between methods for an interaction design.

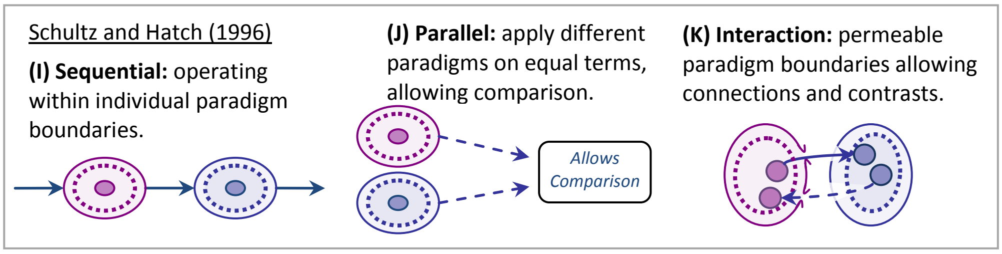


Figure 23: Mixed method designs based on the concepts presented by Schultz & Hatch (1996) – refer to Figure 21 for key.

5.3.4 From Isolationism to Multimethodology

Finally, Mingers and Brocklesby (1997) discuss the overall spectrum of methodology selection, from a single method to fully combining two methods (illustrated in Figure 24). *Isolationism* highlights the basic single technique, methodology or paradigm selection and how it is often a choice: an 'or' rather than 'and'. *Selection* illustrates the assessment of methodologies that often forms an internal process of the modeller but does not inform the design of a mixed project specifically. *Combination* simply implies the use of more than one method within a study. The term provides no insight into how this mix might occur so as a design it is not regarded as directly useful or insightful within the context of this work. *Enhancement* is a design used to adjust a primary technique or methodology with aspects of another allowing deeper insight, whereas *Multimethodology* involves partitioning methodologies in order to mix and may be perceived as the deepest, most complex mixed method design. These designs illustrate a broad range of mixing options with the authors focusing on methodologies and considering their compatibility.

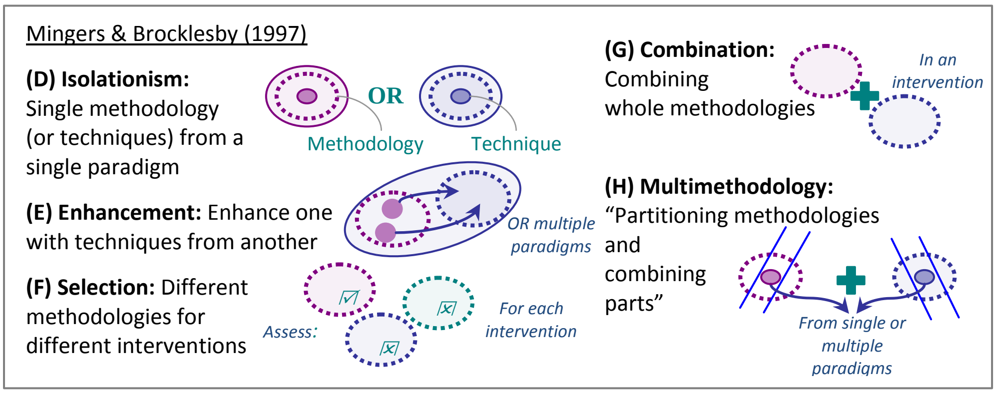


Figure 24: Mixed method designs based on the concepts presented by Mingers & Brocklesby (1997) – refer to Figure 21 for key.

5.4 Proposed Mixed Method Designs

This section will consider what characteristics distinguish the mixed method designs, how these characteristics can be used to refine the designs into a coherent set of options for modellers, and what additional factors may be used to define the design of a mixed methods project.

5.4.1 Toolbox of mixed method designs

The mixed method designs illustrated in Figure 22 – Figure 24 demonstrate the variety of ways in which a modeller might want to select or mix methods. In order to compare the designs and remove repetition they are compared using the key characteristics that emerged from the three sources and from describing the designs diagrammatically.

The designs are compared in Table 9 but it should be noted that the research acknowledges that not all designs from the literature were presented at the same level of detail so are not directly comparable, but there are clear points of commonality. The purpose of the table is to demonstrate the broad groupings of mixed method designs in existence, highlighting their similarities and differences.

The columns of Table 9 are labelled using three broad categories: *what* is being put in (the number of methods and paradigms), *how* the methods are mixed (the level of interaction between methods, the level of overlap of the methods and the dominance of the methods within the overall methodology) and *what* the final output of the project is. Using these categories to analyse the designs reveals groups based on similar characteristics. *Isolationism* and *Selection* have identical characteristics meaning a single term (*Isolationism*) is applicable. The term comparison may be used to describe contrasts drawn throughout any project but as a mixed method design, *Comparison* has similar characteristics to *Parallel* therefore it is proposed that the term *Parallel* is used as the name of a mixed method design and comparison is not used as a mixed methods specific term. It is deemed reasonable to consider *Enhancement* and *Enrichment* to be describing similar situations as both produce a single method which contains elements of another. *Sequential* and *Interaction* are unique terms as they are not equivalent to any others in the table. The term *Combination* is dropped as it does not convey the nature of the mix of methods and could be used to describe several designs (such as *Sequential*, *Parallel* or *Interaction*). *Integration* could be viewed as a form of *multimethodology*. However, multimethodology is a term widely used to describe the whole research field of mixed methods and so it is proposed that *Integration* is used to avoid confusion. As a result, a refined toolbox of mixed method designs may be proposed (Figure 25), where all designs are applicable at the paradigm, methodology or technique level.

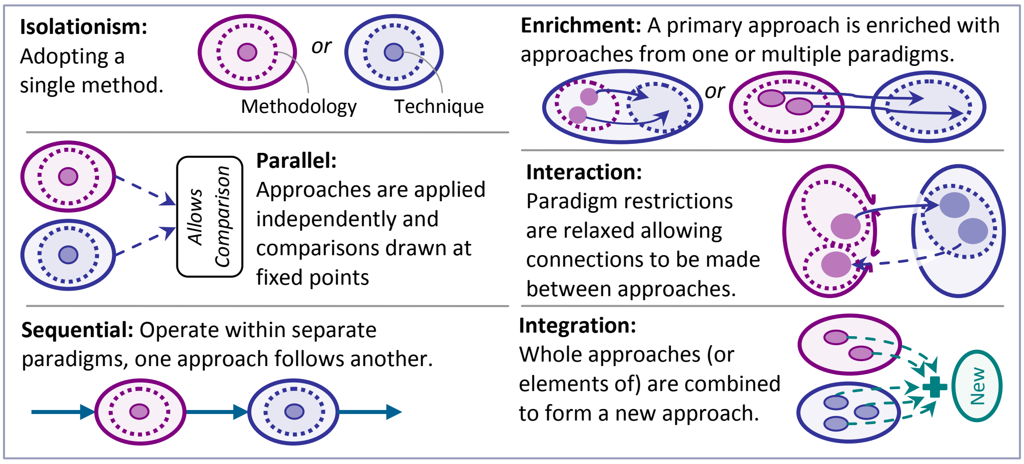


Figure 25: Refined set of mixed method designs developed in this research

This analysis of the designs highlighted factors to consider when discussing mixed projects. The ordering of the methods and the forms of interaction(s) between the methods are captured by the mixed method design, but the priority or dominance of the methods is not obvious, nor is the view of the system that each method within a mixed method design is responsible for capturing. These factors not captured in the mixed method designs are discussed in the following section.

Table 9: Matrix of mixed method designs

Label	Name of Design	Level of Interaction	Number of Methods	Number of Paradigms	Level of Overlap	Dominance of Methods	Method Output
(D)	***Isolationism***						
		Zero interaction	Only 1 method	Single paradigm	-	-	1 method
(F)	***Selection***						
		Zero interaction	Only 1 method	Single paradigm	-	-	1 method
(J)	***Parallel***						
		Zero/limited interaction	2-n method	from 1-n paradigms	Zero	Applied on equal terms	2-n methods per project
(A)	***Comparison***						
		Zero/limited interaction	2-n method	from 1-n paradigms	Zero	Not nec. on equal terms	2-n methods per project
(I)	***Sequential***						
		One feeds another	2-n method	from 1-n paradigms	Zero	Not nec. on equal terms	1 method
(G)	***Combination***						
		Combining whole methods	2-n method	from 1-n paradigms	Significant	Applied on equal terms – combining whole methods	1 method
(B)	***Enrichment***						
		One method enriched with elements of another	1 method enriched with 1-n methods	from 1-n paradigms	Significant	One core method – Not nec. on equal terms	Produces 1 final method (based on one)
(E)	***Enhancement***						
		One method enriched with elements of another	1 method enriched with 1-n methods	from 1-n paradigms	Significant	Not nec. on equal terms	Produces 1 final method
(K)	***Interaction***						
		Connections and contrasts	2-n methods	from 1-n paradigms	Significant	Not nec. on equal terms	Produces 1 final method
(H)	***Multimethodology***						
		Partitioning and combining	2-n methods	from 1-n paradigms	May exist	Not nec. on equal terms	Produces 1 final method
(C)	***Integration***						
		Selecting elements to create new method	2-n methods	from 1-n paradigms	May exist	Not nec. on equal terms	Produces 1 final method

5.4.2 Factors of mixed method design selection

The mixed method designs do not give a complete descriptor of a mixed methods project methodology, as illustrated in Table 9. Within each mixed method design there is several options available to modellers. This section presents the researchers conclusion from comparing the designs that two factors in addition to the mixed method design are required to defining a project methodology when mixing methods.

Mixed methods projects using the same mixed method design may have very different methodologies due to the emphasis of the methods used in the design and so the dominance of methods should be explicitly considered. The dominance of methods can be viewed as how much of method A and B are used within the project and how they interact over the duration of the project. The consideration of dominance has been inspired by work by Brown, Cooper and Pidd (2006). Within a project it may be that one method is used to enrich another, and it is important to consider and clarify the dominance of each method applied to determine the function each method performs within the project. Overall, the dominance of method may alter through time during the project, with the focus moving from one method to another during the course of model building and/or analysis, resulting in an interweaving of methods (shown in Figure 26).

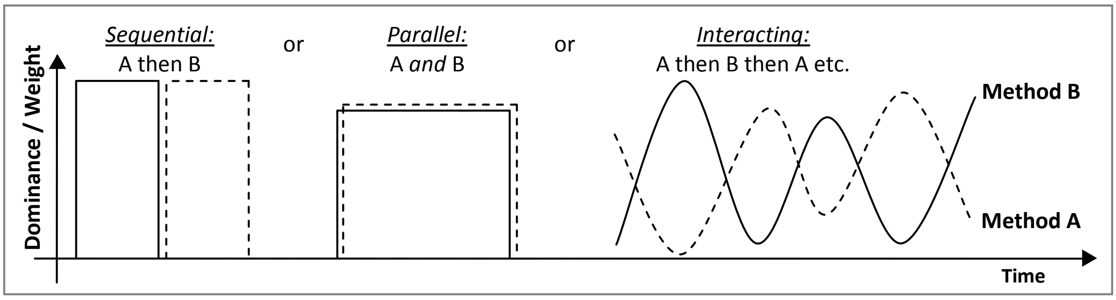


Figure 26: Dominance of method throughout a project – inspired by Brown, Cooper & Pidd (2006, p.66)

As discussed in Chapter 3, the project methodology should be informed by the problem and system, and for when selecting a mixed method design it is also necessary to consider the view of the system and the problem boundary. The system modelling view is a clarification of the problem, the system it lies within, and how the adopted methods seek to capture the system under study. Chapter 5 posited that a modeller selects a projects methodology informed by their personal experiences and preferences. A project methodology should be informed by the problem and system (Lorenz and Jost 2006), but how a modeller views the problem system is also dependent on their own personal world view (Corbett et al. 1995). Given a modellers view of a problem system (Figure 27a), a modeller may choose a method that best captures this problem system, or mixed methods may be used. A mixed method design could be utilised to: look at differing points providing insight into the whole space (Figure 27b), capture the same area but reveal complementary insights (Figure 27c), or create additional new insight (Figure 27d).

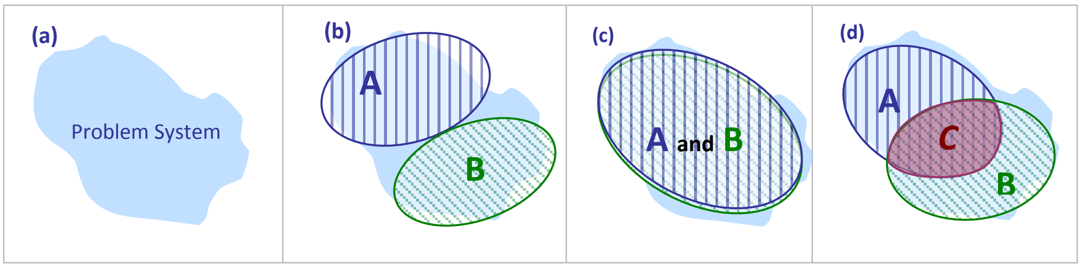


Figure 27: The problem space and the possible views captured by modelling methods A and B.

This section has proposed set of mixed method designs developed from the multimethodology literature that seek to represent the broad range of mixing methods a modeller can choose. These factors and the mixed method designs may form key determinants for selecting a mixed method design of the modelling project, along with the modeller's appreciation of the problem and system. Applying these designs to existing projects enables the researcher to determine if the toolbox of mixed method designs and factors for selection capture the essence of the methodology. This will be explored in the next section.

5.5 Applicability of the Mixed Method Designs

Having examined the literature for mixed method designs their relevance and usefulness are explored by applying them to real life projects from the literature. The following section examines the applicability of the mixed method designs applied to mixed DES and SD projects. The applicability of the designs and factors to convey how the methods are mixed within the project are reflected upon.

The brief descriptions of the projects in this chapter are intended to provide a complete overview of each projects aims and outcomes. It seeks to highlight the manner in which the methods are used in the project and if the proposed mixed method designs are suitable for distinguishing between these mixed methods projects.

5.5.1 Introduction

Five projects describing the mix of SD and DES were selected to represent a range of designs of mix in the literature and were deemed to contain sufficient detail for the purposes of this work. These projects illustrate the various mixed method designs being used in practice and provide insight into how the proposed designs and factors can be of value in describing work undertaken. This has led to the mixed method designs and additional factors being refined to remove overlap and improve clarification.

5.5.2 Project 1: Parallel SD and DES

Morecroft and Robinson (2006, 2008) present a project that applies both SD and DES to the same problem for comparison, providing insight into the applicability of the two methods to modelling a fishery. The work examines how SD and DES may be considered complementary when used in parallel, concluding that both have a role to play in developing understanding of the dynamics of fisheries and the associated graphs over time.

Design: Within this project the two methods are applied completely independently, by different modellers, to provide insight into the same problematic area and form hypotheses about reasons for the observed behaviour. Both are undertaken from a common starting point and applied independently according to the modelling philosophy of their method by experts in their respective modelling field in parallel. The mixed method design is summarised in Table 10.

Table 10: Mixed method design of Morecroft & Robinson (2006, 2008)

Mixed method design	*Parallel* – illustrated in Figure 28
Level of interaction	*Zero* – comparisons drawn but no interaction between the models
Number of methods	*Two* – adopting the full paradigm / modelling philosophy of each
Level of overlap	*Zero* – methods remain distinct
Result of the mix	*Two* – independent complete models

System View: Both methods take an identical view of the overall problem situation, defining the same problem boundary to the system, aiming to capture the same outputs by examining the level of fish stocks over time. The models are described as commencing from the same point and continue in parallel to ensure that the same boundary was captured for each model throughout the project as two separate modellers undertook the work. This view of the system boundary may be represented as Figure 28b.

Dominance: The methods were applied equally, with each receiving the full individual attention of a modeller specialising in each method. Both models were used to provide insight at three stages in the development process, revealing similarities and differences between the methods and their outputs. This is illustrated in Figure 28c where both methods (the two lines) have the same weight/dominance over the duration of the project. Additionally there are three distinct points in the modelling project whereby outputs (insight) from the model are provided to the client.

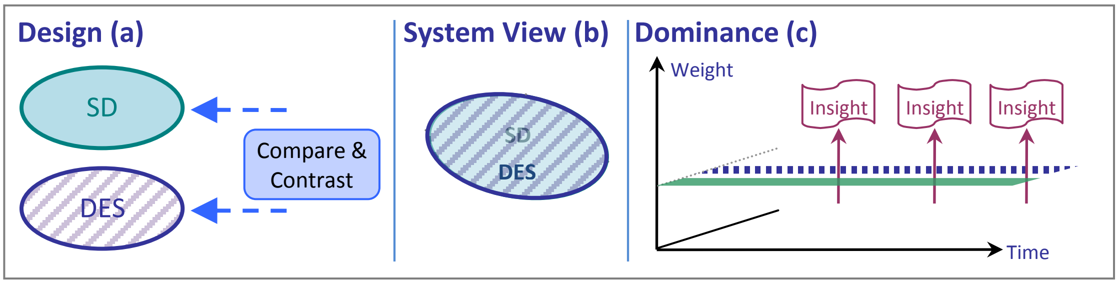


Figure 28: Application of distinct SD & DES models in Morecroft & Robinson (2006, 2008)

Summary: The value cited of adopting a *Parallel* mixed method design are to enable the modeller to *"compare and contrast hypotheses about how the system behaves"* (Morecroft and Robinson 2006) and to see what value each method can offer when modelling the same system. The project demonstrates how both models offer plausible explanations for behaviour, suggesting that each method can provide value and either may be useful within a specific context. The overall design of the project can be clearly described by the three aspects of the framework: the mixed method design, the system view and the dominance of methods. The term parallel succinctly captures the design of the project, and all key factors of the methodology are able to be summarised. This mixed method design utilises the characteristic elements of either method at their traditional, classic (opposite) ends of the SD and DES spectrum (see Figure 10 and Table 1).

5.5.3 Project 2: Sequential SD and DES

The project presented by Brailsford et al. (2004) describes mixing SD and DES whereby the decision to mix the methods emerges over the course of the project. The work was embarked upon under the belief that it would be a SD project, and it was only during the process a DES was deemed necessary alongside the SD model to answer the client's questions. Insight from the SD model helped to define the DES model. The two models are used in conjunction to answer the research questions posed in the project, with each model fulfilling a unique purpose.

Design: The mixed method design might be described as *Sequential* as each method is selected for specific purposes. Within this project, one method distinctly follows the other with each applied for a distinct purpose with each method answering specific research questions. The paper describes this as a linear process, with the most focus of the project on the SD model and this design is summarised in Table 11.

Table 11: Mixed method design of Brailsford et al (2004)

Mixed method design	*Sequential*
Level of interaction	*Zero* – insights taken from each model independently, but producing the first model revealed the need for the second
Number of methods	*Two* – adopting the full paradigm / modelling philosophy of each
Level of overlap	*Zero* – methods remain distinct
Result of the mix	*Two* – distinct standalone & independent models created

System View: The SD model was used to capture the whole problem system under study, whereas the DES model focused on a specific part of the system. SD is used to look at the majority of the system, and the DES is used to complement this insight: to explore the same system but an area not fully captured in the SD model (illustrated in Figure 29b).

Dominance: The project is presented such that the SD method was applied entirely, and then the DES was rapidly developed for the final insight required. This is illustrated in Figure 29c whereby the solid line represents SD, and is the only method used for the majority of the project. Then, DES (represented by the dashed line) is used at the end of the project, based on the understanding of the system developed from the SD model.

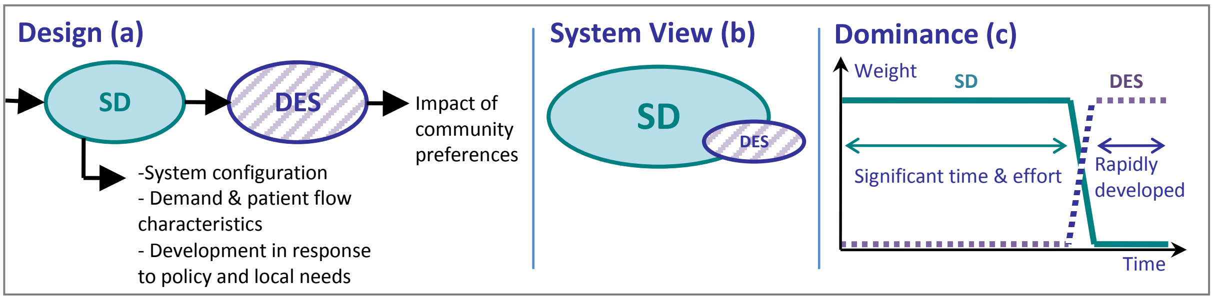


Figure 29: Application of distinct SD and DES models in Brailsford et al. (2004)

Summary: This project demonstrates how understanding of the problem and the system develop during a project and how the methodology initially selected may need to be adapted rapidly during the project. It demonstrates the importance of the time aspect within the dominance of the method as over time the paradigm in use shifts. In this case, each method fulfilled a specific purpose; each model looked at distinct areas with only a small element of overlap as the DES was deemed suitable to zoom into a detailed area. This illustrates the importance of the system modelling view when describing a project and providing clarity. Despite the fact that both methods had to be fully developed, it would appear that the DES was able to utilise understanding gained in the development of the SD due to the sequential design of the study.

Both Chatha and Weston (2006) and Su and Jin (2008) present similarly designed works utilising the sequential application of SD and DES but in reverse order. Both papers discuss a project whereby during the development of a DES it was deemed necessary to embark upon a SD model to provide complementary insights (Sequential DES then SD). In both projects each method had a specific role at different levels of the system with the DES revealing bottlenecks in the system and the SD assessing strategic changes. Although the DES models answered specific questions, they revealed the need to develop SD models to answer questions regarding system behaviour. Although benefits of the project methodology are discussed in this case, the integration was coincidental with the projects dictating the progression.

When adopting a sequential mixed method design all authors discuss the value of the different perspectives provided by the methods. Additionally it is noted that the design is chosen due to the system having two distinct sets of questions (two problem groups that are best answered by different methods) but lie within the same system, or that the concepts of each method are important at different levels (Chatha and Weston 2006) of the system or during different phases of the project (when the situation is emerging as in Su and Jin 2008). It is also recognised by Reiner (2005) that this design of mixing methods may form a precursor to deeper mixing as a feedback loop between the models became apparent.

5.5.4 <u>Project 3</u>: Enriched SD and DES

In 1980, Wolstenholme & Coyle first demonstrated how SD can be extended to include discrete events and further applications of this design have followed[21]. This can be viewed to be an example of *Enrichment*, whereby an aspect of DES is transferred into SD modelling. The core of the modelling project methodology remains to be SD and it is enriched by the inclusion of discrete events. This has also been applied with DES being enriched with an element of SD. Phelps, Parsons and Siprelle (2002) and Fioroni et al. (2007) both present projects whereby a DES is made to model continuous processes: a non-item based example.

Both of these demonstrate the idea of taking a particular element of a modelling method and moving it into another. The projects continue to take the shape and form of the original, enriched, method but have the added benefit of the additional elements. The justification for adopting this design is driven by the needs of the model: it was deemed important to capture discrete or continuous behaviour in SD or DES respectively.

Design: Within all of these projects, one method is selected as the base model which is enriched with elements of a second method and the project continues to take the form of the initial method. The model is developed as a single unit and the requirement to include the second method dictated by the problem context and the system. This design is summarised in Table 12 and illustrated in Figure 30.

Table 12: Mixed method design of Enriched Modelling

Mixed method design	*Enrichment*
Level of interaction	*Complex* – One model produced that interacts with no other model. However, the enriching elements fully interact with the main elements of modelling method.
Number of methods	*Two* – adopting the full paradigm/modelling philosophy of one method and enriching it with technical aspects of another method.
Level of overlap	*Full* – the methods are fully mixed into a single model.
Result of the mix	*One* – complete model (based on one method) containing features of second method.

System View: Both methods take an identical view of the overall problem system, defining the same boundary, as the main modelling method is used to define the system and the second (enhancing) method is used within the main models context.

[21] Howick & Eden (2004) also present a more recent example of including discrete, discontinuities to add value to a SD project to enable the accurate portrayal of systems behaviour.

Dominance: One modelling method is dominant throughout the project, with the enhancing method included throughout but embedded within the primary method. Figure 30 illustrates the two projects whereby SD and DES respectively are used as the dominant method that is enriched with elements of the other for the entire duration of the project and model time window.

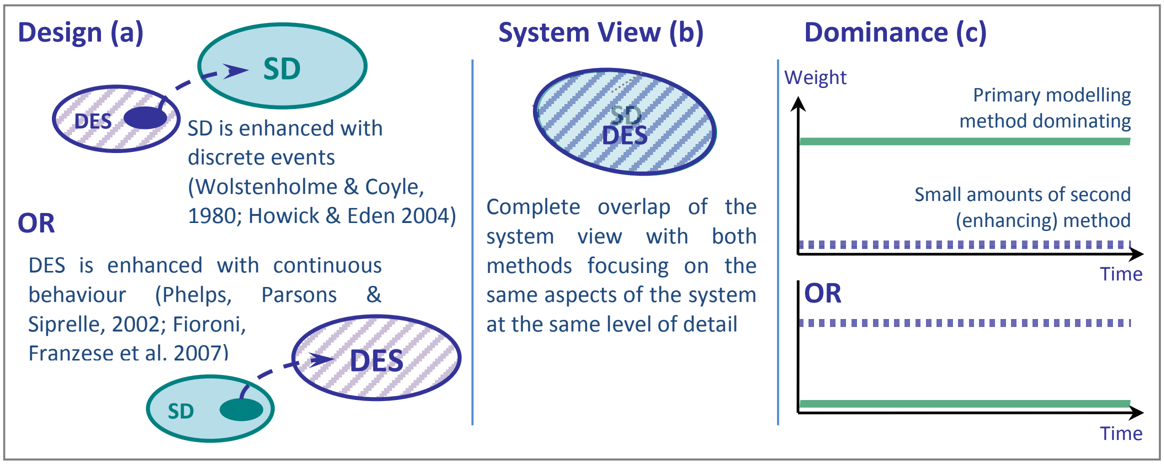


Figure 30: Application of enhancing SD with DES or DES with SD.

Summary: These projects demonstrate how SD and DES were extended, with the method modified to meet the specific needs of the project. This enrichment means that the projects benefited from the inclusion of another method without the need to undertake an additional project. However, caution must be exercised when bringing elements from one method across paradigm boundaries and modellers may need to clarify the relationships between model elements as there may be technical implications relating to how the model elements interact.

This project illustrates the relevance and features of an *enriched* project design. The framework used concisely summarises the key features of the project and captures how the level of enrichment (dominance of the methods) remains constant throughout. An enriched design for mixing SD and DES is likely to be particularly applicable when modelling projects that require both the continuous and discrete behaviour often observed in real life systems to be represented. Examples in the literature describing the enrichment of SD with discrete events or of DES with continuous behaviour, state how the inclusion of these behaviour was integral to the modelling process to suitably capture the system behaviour. This design is particularly applicable when modelling a single system problem that is not sufficiently captured by a single method, where system influences would remain unaccounted for otherwise.

5.5.5 Project 4: SD and DES Interaction

Venkateswaran et al. (2004) presents a project where an SD model interacts with a DES model over fixed timesteps, the design of which is summarised in Table 13. In this case, the models run for a set time period, data is exchanged and then the models run again for the set time period. The DES model captures a subsystem of the whole SD model and new optimal values from the DES model are then fed into the SD model. It would appear that the two models are independent and can function on their own but there is an exchange of information between the two.

Design: Two models are developed with the intention of creating a single final model with the two methods passing data back and forth at fixed points in time in the model.

Table 13: Mixed method design of Interacting Models

Mixed method design	*Interaction*
Level of interaction	*Complex* – Two models are joined together to form a new model. Interaction between the DES model and the SD model occurs at a fixed time step.
Number of methods	*Two* – both methods have been mixed to create a new method. The two models created are not used 'standalone'.
Level of overlap	*Moderate* – the methods remain distinct during development and are then fully mixed into a single model in the final phase.
Result of the mix	*One* – two models are created but interact to result in a mixed single model. The two models might be used independently or in a mixed way.

System view: Within this project the SD method was used to capture a broad view of the system and the DES represented a specific part of that system (illustrated in Figure 31b). This is a choice specific to this project and is not a prerequisite of the *interaction* mixed method design.

Dominance: When the two models are run, it is evident from the paper, that data is exchanged at fixed regular intervals. The order in which the DES and SD models were developed is unclear but the final mixed model requires information to be passed between the two and therefore the dominance illustrated in Figure 31c. This diagram represents the dominance of methods within the final model rather than the use of methods throughout the model development process, as was standard in the previous examples.

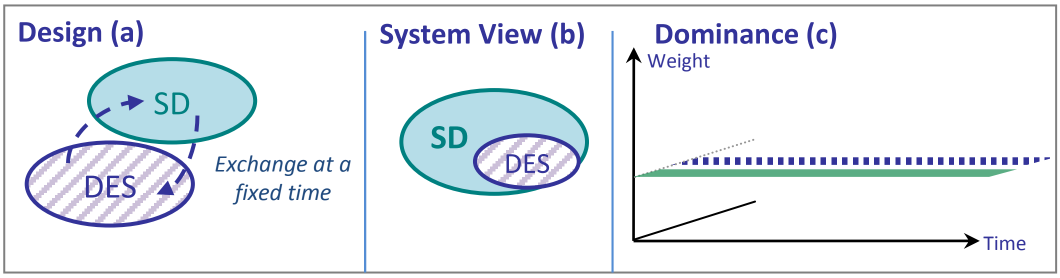


Figure 31: SD and DES model Interaction.

Summary: During the search of the literature three papers (Dierks et al. 2008, Donzelli and Iazeolla 2001, venkateswaran et al. 2004) were identified that appear to describe their model as constructed of SD and DES components interacting over time. These interacting models are described by the paper authors as valuable due to their ability to capture the operational processes and the interactive influences acting upon them, for example: allowing analysis of operational details within a *"strategic and holistic perspective*" (Dierks et al. 2008, p.2507). This design may be described to be of use when examining two problem sets, within the same system, that are believed to interact and influence one another.

5.5.6 Project 5: Integration of SD and DES

Helal et al. (2007) present a project which discusses full SD and DES integration which they refer to as *'SDDES'*. This particular project uses continuous time modelling in simulation with the inclusion of discrete events to simulate a manufacturing enterprise.

Design: The two modelling methods are applied in the same model to the same problem situation, producing a model with characteristics of both SD and DES. The mixed method design is such that a single model combining features of both methods is developed (summarised in Table 14).

Table 14: Mixed method design of Integrated Modelling

Mixed method design	*Integration*
Level of interaction	*Complete* – The two methods are no longer distinct; they form a single method described as SDDES set within the same timestep. Interaction between the discrete and continuous elements occurs at both the timestep (SD) and event triggers (DES) as required.
Number of methods	*Two* – both methods have been mixed to create a new method.
Level of overlap	*Full* – the methods are fully mixed into a single model.
Result of the mix	*One* – complete model (creating what the authors describe as a new method).

System View: Both methods take the same view of the system, defining the same boundary. Different aspects of the system may be captured in SD or DES type ways but all are presented in the same model.

Dominance: Within this case, clear description is provided regarding the interaction of the two methods over time. The dominance in Figure 32 summarises a diagram presented by Helal (2007) demonstrating the variable time gap between SD and DES: each method being dominant as this is dictated by the events (DES) and thresholds to levels (SD) occurring in the models

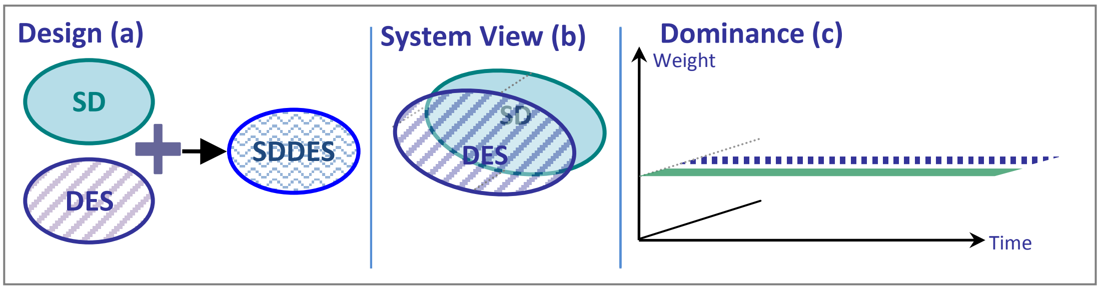


Figure 32: SD and DES full Integration.

Summary: This project has been viewed as a full interaction of the two methods, resulting in one final model and a single project methodology. The DES features are used to specifically represent elements of the system not captured to a sufficient level of granularity within an SD model, but this may be difficult to conceptualise and put into practice due to the differing views of the world that SD and DES take. It is necessary to clearly state the role elements of each method will play within the integrated model. An *integrated* mixed method design enables the modeller to work within one modelling environment which may help modellers overcome conceptual barriers to mixing methods. From a practical perspective the modeller is able to present one concise and coherent view to the 'client' of the project. From a technical perspective, it is important for the modeller to be clear as to how the two methods will interact within the single space, the timings within the model and validation.

Describing the project as the *integration* of SD and DES rather than simply a mixed or hybrid model provides clearer definition on how the two methods work together in the final resulting model. Illustrating the system view and dominance of methods provides further clarity to the design adopted and how it may be applicable to a reader.

Several other examples in the literature may also be described as *integrated* SD and DES models all seek to provide more operational detail to the system view (Alvanchi et al. 2011, Donzelli and Iazeolla 2001, Han et al. 2006, Jacob et al. 2010, Kouskouras and Georgiou 2007, Martin and Raffo 2000, Mazaeda et al. 2012, Rabelo et al. 2003). Within these examples the SD and DES components may be distinguishable sub models or may have been enriched to borrow concepts from DES or SD. However, the projects result in a single model that is intended to be analysed as a whole. Although this design is described as beneficial as it can reduce modelling efforts (Jacob et al. 2010), the time to develop such a model may only be offset by the inclusion of existing models, as suggested by Helal et al (2007).

5.5.7 Summary

This section has examined a selection of papers which represent a range of designs for mixing DES and SD within a real life project. Analysis of the papers reveals a lack of collective terms to describe the work undertaken and no standard terminology emerges from the papers but the proposed designs may help to fill this gap. From this analysis it appears that papers with the more complex mixes of SD and DES provide limited discussion of the design of the methods adopted and methodology employed, therefore providing little detail to inform other modellers how to undertake the same project methodology. Even in the more straightforward mixed method designs there is a lack of clear terms that might be used to describe a mixed project. This may be due to: the limited space available within a paper; the view that the methodology adopted is apparent and non-complex; that the project methodology does not warrant description (the focus is on the project results not on the process undertaken/methodology) or uncertainty as to what would be useful to discuss; or the lack of clear terms that might be used to describe the design adopted. This further supports the proposal that there is a need for a common language to provide a more detailed picture as to the practicalities of mixing, allowing others to adopt the practice.

Examples 4 and 5 illustrate two closely related mixed method designs: interaction and integration. Projects adopting these designs are often referred to as hybrid modelling (as discussed in section 5.2) which would indicate to the reader that an identical project methodology was employed. Projects adopting an *interaction* mixed method design develop two models with a view to passing information between them. However an *integration* mixed method design involves a larger number of interactions between the two methods, such that the methods are unable to function in isolation.

5.6 Modelling Framework

The previous sections have discussed a toolbox of mixed method designs and explored its applicability to published mixed DES and SD projects. The next stage is to consider how to incorporate this toolbox into the model development process to facilitate the undertaking of mixed methods.

The designs have been deliberately described and pictorially represented at a level of detail to provide a grouping of terms under the mixing methods umbrella, allowing for a degree of generalizability and comparability of mixed methods, but acknowledging that further designs may continue to emerge. Using this toolbox of designs, can we now see patterns of use or quickly adopt similar designs? We have clarified what has been discussed in the literature and been conducted in practice, so can we now take it forward to utilise the designs to inform the methodology selection stage?

Following evaluation of the designs through their applicability to published projects this section will consider how they could be applied prior to and during projects. A framework for methodology selection is proposed placing the mixed method designs, factors for consideration and illustrated examples at the core of this decision process for reflection upon throughout projects.

5.6.1 Framework for methodology selection

Chapter 3 explored the literature relating to how modellers select methods and frameworks in existence to support method selection. It was discussed that selection of a project methodology is dependent upon establishing the level of accuracy and detail required in the model: the nature of the system (system) and the nature of the study (problem) (Chahal and Eldabi 2008b, Lorenz and Jost 2006, Pidd 2004a); that merely examining the problem perspective can be misleading (Lane et al. 2000). Methodology selection is often a personal choice and in practice the modeller may be guided by familiarity with a particular method (Corbett et al. 1995). When learning a modelling method, a modeller is taught to view a system in a particular way and this impacts their choice of method, and their experience and preference to use a method continue to inform this view. Work exploring the model building process of SD and DES empirically supports this common held view that modellers will embark on a study without first considering alternative modelling methods (Tako and Robinson 2008).

If modellers already have methodology preference, how might we facilitate selection and find room for mixing methods in addition to singular OR methods? We propose that a *personal filter* and an appreciation of *mixed method designs* needs to sit at the heart of this selection process (see Figure 33). This framework represents the need to use the system and problem to define the project methodology, but allows for the fact that modellers have views that alter their perception of the system and problem. It is proposed that this filter contains bias and modellers should seek to add an appreciation of alternative options.

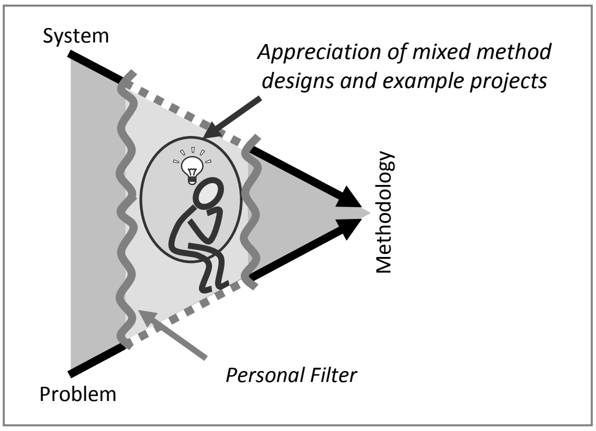


Figure 33: Framework to inform method selection and facilitate the use of mixed methods

5.6.2 Existing modelling frameworks

The previous section has considered where mixing methods could fit within the methodology selection process. This section considers how to incorporate mixing methods into the DES and SD model development process to provide a generic framework for modellers to follow which provides the scope and support for mixing DES and SD.

5.6.2.1 The SD and DES model development process

As discussed in *Chapter 2*, SD and DES both claim a wide range of applications but exist as two distinct streams, with little communication between them. The model building processes of each were discussed, and although both modelling methods are distinct, they do contain several similar core elements and principles. A framework to follow that is compatible with both the SD and DES methods is needed to undertake this research, and will be an outcome of this research (following reflections made prior to, during and post the project). Looking to the literature for established modelling frameworks ensures that personal preference is minimised. Such a framework would provide modellers with a suitable process to embark upon that encourages the consideration of more than a single method.

5.6.2.2 General modelling frameworks

A widely accepted modelling framework is presented by Landry, Malouin and Oral (1983), shown in Figure 34. This simple iterative process is a simple representation of modelling that emphasises the iterative nature of the process and the four key elements a modeller will use to develop and validate models.

The characteristics and model building processes of SD and DES were discussed in chapter 2. The similarities and differences between the processes were highlighted and although both modelling methods are distinct, they do contain several similar core elements and principles. These similarities tie with the established general OR modelling-validating framework presented by Landry, Malouin and Oral (1983) shown in Figure 34: to understand the system and use conceptual modelling, to code the model(s), to perform validation, and to experiment; whilst acknowledging that it is necessary to cycle through these stages.

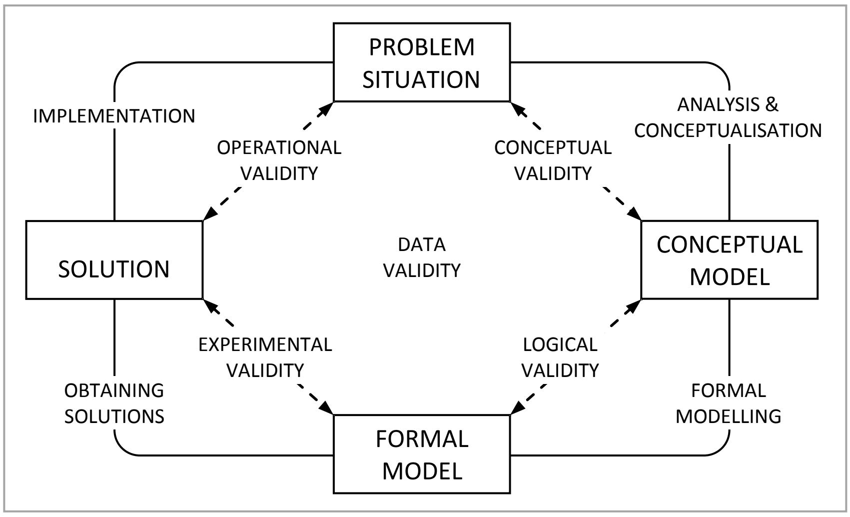


Figure 34: The modelling-validating process (Landry, Malouin and Oral 1983, p.212)

5.6.3 Proposed Modelling Framework

The proposed framework, shown in Figure 35, is based on the modelling guidelines of SD and DES and in light of the literature review. It takes the form of standard model building processes put forward by many authors (Mitchell, 1993; Pidd, 2004a) with the key distinction being the appreciation of mixed method designs and existing projects at the heart of it. It incorporates the model building processes of both SD and DES and asks the modeller to reflect on mixing method when transitioning between the stages of the process.

This framework is not proposed as the one and only way to embark on a mixed methods project. It provides a process not far removed from other simulation development frameworks to acknowledge that mixing methods may not be the most desirable project methodology in every situation, but that mixing methods should be considered when choosing a project methodology and throughout the modelling process. Practically, that is to say that, mixed methods should be an option for a modeller when embarking upon any project, and in the same way that a modeller is encouraged to continually assess if the view of the problem system they are modelling is appropriate, it is encouraged that the method(s) chosen are reflected upon for their value to the project. Mixed methods should sit alongside isolated methods as the set of options for project methodology.

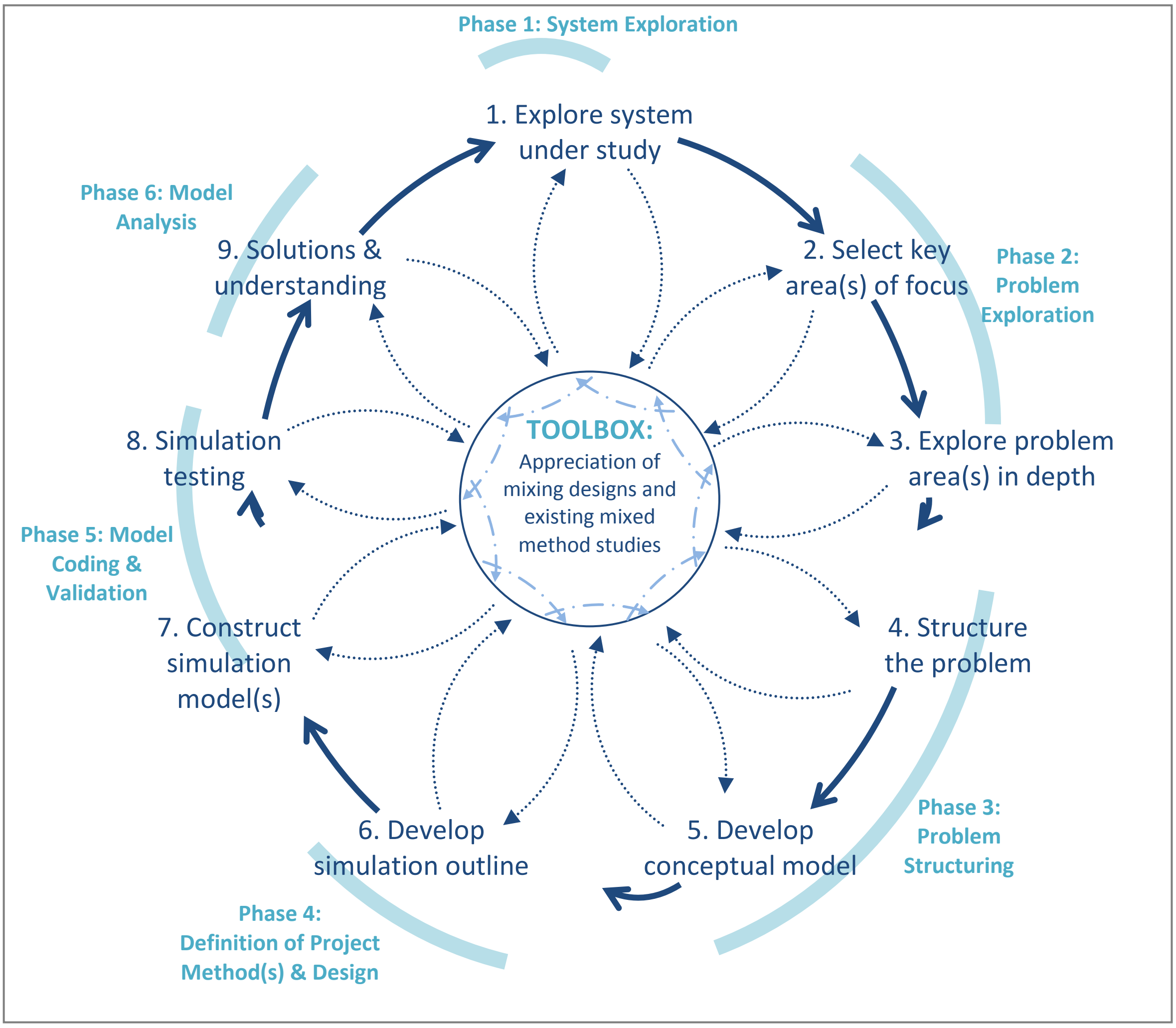


Figure 35: Proposed model development framework

5.6.3.1 Aims of the proposed framework

The proposed framework specifically separates exploring the system and exploring the problem. This is because, as discussed in *Chapter 2*, choosing what to model (model conceptualisation) is *"the most difficult, least understood and most important task"* of simulation modelling (Robinson 2012, p.1909). Problem holders often do not have a clear view of the problem, do not know specifically where the problem lies in the system and/or the system has many issues requiring exploration. Because of this, it is proposed that mixed methods should be considered throughout the whole modelling process. Even once the project method has been selected it may be beneficial to continue to reflect on whether the most appropriate method has been utilised, whether value may be added to the project by using more than one method, and if so, how this method should be used within the project.

If a modeller is knowledgeable of a method they are aware of the disadvantages or limitations it holds; if a modeller is inexperienced then they ought to seek out methods which support their skillset alongside being beneficial to the project. A modeller selects a project methodology based on how they perceive the problem system and this perception is liable to change over the duration of the project. Placing mixed method designs at the heart of the process acknowledges that the project methodology is liable to change over time as modellers should not become restricted by their method preferences

The framework is planned to provide a structured process to allow for clear exploration of the system by following a general OR modelling process that is both DES-like and SD-like. This is facilitated by a process that encourages the modeller to cycle back to previous phases when it seems necessary or appropriate to reflect on the methods adopted and, if mixing is thought to be appropriate, the form the mix will take (the design of the mix). At the heart of this is an appreciation of designs for modelling that the modeller should look to throughout the process. This encourages the modeller to clearly define the system and the problem area(s) whilst maintaining an appreciation for designs to deal with the problem(s).

5.6.3.2 Steps of the proposed framework

The framework in Figure 35 consists of six core phases with the central toolbox of mixed method designs and existing projects at the heart to reflect upon throughout which are described below. The six core phases of the cycle progress clockwise but it may be necessary to move back a stage to re-assess/re-explore.

As noted by Curtis, Dortmans and Ciuk (2006, p. 1300): *"The essential first step of any OR investigation is to ensure that the 'right problem' is studied"*. In the SD model development processes this consists of familiarisation, problem articulation and conceptualisation of the system from a messy system into a structured mental model and in DES this contains tasks such as problem formulation, objective setting and model conceptualisation (discussed in

Chapter 2). The literature review highlighted the importance of conceptual modelling within the process of both DES and SD, and that DES may benefit from the additional attention SD modellers pay to conceptual modelling (discussed in *Chapter 3*).

Phase 1: System Exploration is undertaken to examine the system that is considered to have issues, to air a wide variety of views from many stakeholders and work to define the focus for the study. Within this phase it is necessary to explore the system from a broad perspective with the aim to explore issues and air views.

Phase 2: Problem Exploration consists of selecting the area of focus and then exploring the issue(s) in depth. The boundary of the system that will be explored is defined at this point. Figure 36 illustrates moving between system exploration (on the left hand side of the diagram) to selecting the area of focus (red dashed ellipse). This may consist of more than one area but is intended to help the modeller more clearly depict the problems in the system. The time and emphasis required for *Phases 1* and *2* will differ from project to project depending on how well the project is already defined. During the initial project, these phases will require significant emphasis to reveal the areas of concern within the system. However these may require less focus during other modelling projects whereby the problem is well defined.

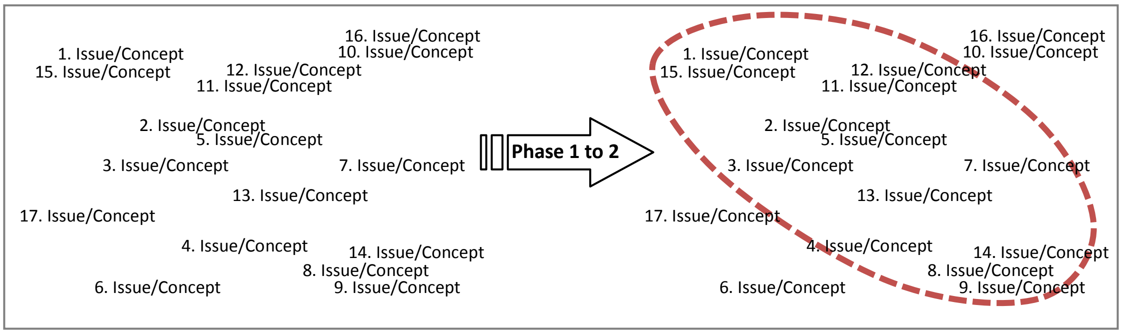


Figure 36: Process moving from Phase 1 to 2 of the framework

In general, the selected area would be the specific problem(s) that the client requires insight into. However, in this research, this also needs to be an area that provides sufficient scope for the use of SD and DES. This necessity to select an SD and DES-like problem to explore could be regarded as a limitation of the research if the researcher needs to continue to push to find such a problem. However, the organisation has agreed to participate in the research and has previous experience with both DES and SD, with the client interested in applying both to their issues.

Phase 3: As discussed in *Chapter 3*, choosing a project methodology should be informed by the problem and system. *Phases 1* and *2* of this framework capture the initial exploration, whilst phase 3 more formally structures the problem to establish what methods might be useful. Having determined the size and shape of the system under study and the problem space the next step is to explore the *potential* for the application of mixed methods. This phase encourages the modeller to examine the suitability of methods to address the problem. It highlights the attention that should be paid to method selection: selecting a method then exploring the problem system may lead to conflict between the method and the aims of the project, as discussed in *Chapter 3*. This emphasis on method selection is not found in the DES and SD literature as their model development processes work under the assumption that the method is already selected, but represents the broader OR modelling advice for fit between the problem, the system and the methodology (Chahal and Eldabi 2008b, Pidd 2003).

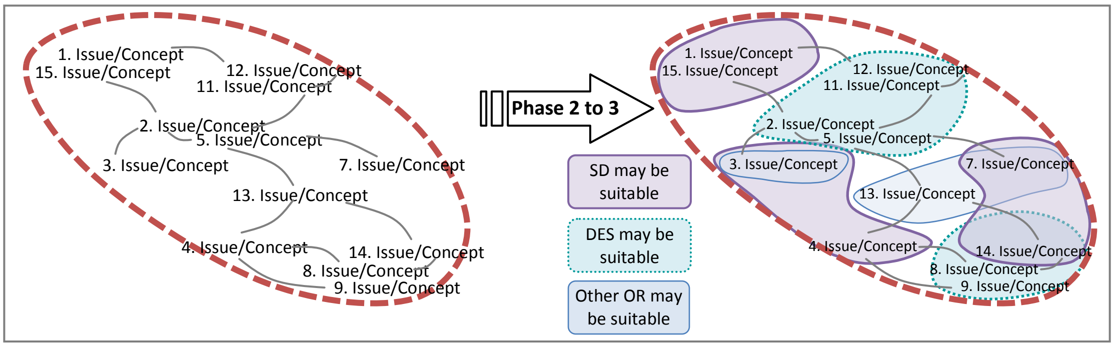


Figure 37: Process moving from Phase 2 to 3 of the framework

Figure 37 illustrates how themes may be highlighted and consideration given to appropriate methods to address the issues within the themes. Methods overlapping, or multiple methods suited to the problem may indicate there is potential value for mixing methods. This exploration of how the system and the problem might be modelled highlights the methods under consideration, the potential overlap of methods and the possible benefits to be had from combining modelling methods.

Phases 1 to *3* may be combined if group workshops could be conducted with stakeholders, following the strategy of group model building (Ackermann 1989, Vennix et al. 1994). However, how these phases are completed may be dictated by aspects outside of the modeller's control such as company politics and stakeholder availability, and it may be necessary to conduct individual interviews.

These phases represent the conceptualisation of the system in light of the problems sought to be explored. This phase results in a conceptual model of the system providing detail to select the modelling method and initial design of the project. This is a representation of the systems area of focus at the perceived preferable level of system aggregation, containing enough detail about the system to be of use to help determine the modelling method(s) that will be used in the projects (*Phase 4*) whilst demonstrating the structure of the system under study. In practice this requires the problem to be structured, using a conceptual modelling method common to both methods. Although each method has its own distinct group of diagrammatic representations, common ground can be found in problem structuring methods as they have been used with both DES and SD.

Phase 4: *Definition of Project Methods and Design* is the point in the process where the method or methods to be used in the project are defined. Given the insight into the problematic area(s), the modeller is then able to choose appropriate or indeed preferred methods for the issues that make up the problem area based on those identified in *Phase 3*. If more than one method is suited to the problem to be explored then the modeller should state how the methods will be used together: define the mixed method design. This phase serves two purposes: to provide a point in the process for the modeller to reflect on what method(s) will be used, and to clarify how the method(s) will be used to address the problem by providing a conceptual model of the mix to inform model coding (*Phase 5*).

Phase 5: *Model coding and Validation* follows the definitions of the conceptual model which details how the method(s) will be used in the project (the mixed method design) from *Phase 4*. In this phase the computer model is constructed and populated with data. At this point in the model development process the practicalities of the mixed method design might need to be assessed, and clarification given to the interaction between model elements: the feasibility of the design is examined

Phase 6: *Model Analysis* based on the problem(s) defined and the intended use of the model revealed during the structuring phases. Consideration must be given to the mixed method design to ensure adequate testing is conducted and appropriate conclusions can be drawn. Analysis is a common task within both the DES and SD model development processes, and the phase should be undertaken informed by the principles of both methods: to develop understanding.

5.6.3.3 Application of the framework in this thesis

This framework, inspired by Landry, Malouin and Oral (1983) and the mixed methods cascade developed by Howick et al. (2008), forms the model development process of the project within this thesis. It is reflected upon throughout the project and altered based on the modeller's experiences of using it is practice.

Just as there are numerous model development processes for DES and SD modelling respectively, this is not proposed as the only way for a modeller to undertake a mixed SD and DES project. The framework is not far removed from the modelling processes of each of the methods we are interested in mixing, and draws insight from a practical example of mixed methods that explicitly considers the model development process. It is not intended to be a substantial departure from general modelling processes. It is intended to be suitable even if a modeller choose not to mix methods, but selects only DES or SD. This illustrates that mixing methods is able to fit within existing modelling frameworks by encouraging reflection on the options (the mixed method designs).

5.6.4 Summary

This proposed modelling framework is a general modelling process with an appreciation of mixed method designs at the heart of the cyclical process. The intention is that these designs are borne in mind throughout a project: when the problem is being structured the modeller should try not to become committed to the use of a single method and should openly consider the options available for the given system and problem context. The framework is designed to allow for clear exploration of the system and its associated issues, and regularly reflect on mixed methods when undertaking a modelling project.

As was noted at the start of this section, the proposed framework is not distinctly new: it is an extension of the general cyclical modelling process proposed by Landry, Malouin and Oral (1983), coupled with the insights gained through the literature review into the DES and SD model development processes (*Chapter 2*). Additionally, the proposed framework places a large portion of the work within the model conceptualisation phases, with model coding 5^{th} of 7 phases. This is to capture how SD modellers are focused on conceptual modelling (Tako and Robinson 2010), continually cycling between the problem and the model being developed; and the recommendation from the DES community to not underestimate the value of conceptual modelling (Robinson 2007, Robinson 2012), as discussed in Chapter 2 and Chapter 3 respectively.

The main difference between the proposed framework and other model development processes is the toolbox at the heart of the process. The researcher proposes that a modelling project should be embarked upon with a keen appreciation of mixing methods to open the mind to the possibility of combining. This appreciation is often borne from experience, but the purpose of the toolbox of designs and project examples is proposed to extend, facilitate and guide this.

5.7 Discussion

This chapter has introduced the mixed method designs and model development framework which will be used to conduct the project within this thesis.

5.7.1 Mixed method designs

The objective of the first sections of this chapter was to present the work undertaken to develop a relevant set of mixed method designs that are able to be used to describe projects which mix SD and DES. They have sought to show how the proposed designs can be used to describe projects, demonstrating their applicability to document a range of mixed methods projects. To simply describe a project as hybrid, multimethodology, or mixed is not enough to convey the processes undertaken in practice and how it may be of use to the reader. This has led to a gap in the literature that there exist no clear guidelines or suggested modelling development frameworks to adopt when considering using more than one method within a project (mixing methods)

The mixed method designs presented document a spectrum of mixes of DES and SD. The mixing of SD and DES may progress through several steps as illustrated in the mixed method designs. Initially comparisons may be drawn (*Parallel*) or two models developed in succession (*Sequential*) when the need is apparent. However, following these initial steps of mixing, it may be beneficial to further consider the impact of aspects of one model being included within the other (*Enrichment*), where the two separate models can feed one another to close the system (*Interaction*), or finally that the two models should be fully integrated to remove the delineation between the two methods and create a single model consisting of DES and SD features (*Integration*). In addition to the design of the mix, the order in which method are used or their dominance throughout a project and what view of the system each of the methods take summarise the project methodology, delineating two projects which use the same mixed method design but utilise the methods differently.

The designs presented are not necessarily on the same level, or independent from one another, but can provide a language to encourage thought. A group of designs have been defined to put under a mixed methods umbrella, allowing for comparison of works that adopt similar designs and analysis of the processes undertaken, proposing a set of designs (terms) at a suitable level to enable generalizability and comparability of mixed methods. The designs presented are not an exhaustive list of possible permutations and combinations, but present a range or characterisations which may in turn be further divided into subcategories.

The applicability of the mixed method designs has been explored by reviewing a sample of published projects of SD and DES but they may similarly be of use in the wider multimethodology field. The designs are based on theories presented within the multimethodology literature and further work may explore their applicability to a broader range of OR methods.

It is the purpose of these designs to encourage use of mixed methods and help the modeller to address concerns raised in the literature regarding paradigm permeability or incommensurability, lack of clarity and confusion. Designs are proposed that range from maintaining the separation of paradigms, to the softening of boundaries to allow crossover.

5.7.2 Method selection

Modellers embark on projects with their own personal filter on the world. Their education, experience and creativity may guide them on how to undertake a project; how they view the system and its problems; and may ultimately lead them to a method they are most familiar with. Existing frameworks for model methodology selection do not explicitly represent personal preference or encourage the consideration of multi-methodology work thus not factoring in the possibility of combining paradigms, methods or tools.

5.7.3 Model development framework

The framework proposed is informed by the modelling processes of both the SD and DES methods. The framework demonstrates the importance of system and problem exploration to inform conceptual modelling, and that the process should be cyclical in nature, allowing the modeller to reflect on the work conducted and modify the models in light of new insight.

5.7.4 Summary

The aim of this chapter has been to propose a toolbox of applicable, relevant, and useful transferable designs to draw upon to inform the selection, design and description of a mixed methods project. The mixed method designs, system view and method dominance are characteristics of mixed DES and SD projects that are proposed to provide methodological clarity when reporting completed work and enable modellers to take forward general lessons. Further to this, it is proposed they are also useful during the methodology selection and design stages of projects, and this has led to the development of a framework to reflect upon when considering combining the modelling methods and inform methodology selection.

This work seeks to fill the gap concerning *a lack of methodology clarity* when presenting mixed methods work with a focus on SD and DES combinations. How can we contrast projects and learn lessons if there is uncertainty as to how the methodology was implemented? Although all projects are unique, finding points of commonality enables a researcher to make connections between ideas, theories and experiences (Hart 1998), and ultimately to pass on understanding. Mixed method designs are proposed as a suitable range of initial options to enable modeller's to obtain a clearer view through the fog of multimethodology. By providing a coherent toolbox of designs we provide structure to the methodology selection and design decision process, enable practitioners to comparatively evaluate existing works and inform further thinking.

This chapter has explored the mixed methods literature to propose a set of mixed method designs to illustrate how DES and SD have been successfully mixed in projects. These designs are proposed as archetypes of mixes of DES and SD; tried and tested examples to inspire modellers which may reduce methodological and paradigm concerns by acting as illustrations of bridges across paradigm boundaries (Mingers and Brocklesby 1997 – discussed in Chapter 2), encouraging the wider use of multimethodology. Cultural and cognitive concerns impact the feasibility of multimethodology studies as organisations and individuals may not be open to the idea of the mixing and so clear representation of the project design and methodology employed is necessary.

The set of mixed method designs presented in section 5.4 are proposed to form a toolbox of options for modellers to consider when undertaking modelling projects. The mixed method designs are placed at the heart of the method selection framework (Figure 33) with the view to encourage the selection of methods that fit with the problem and the system, and the model development framework (Figure 35) to represent the model development process requiring frequent reflection on the design of the mix. The mixed method designs have been shown to be able to describe mixed DES and SD projects, and are suggested to be applicable as a reflexive tool when undertaking modelling projects to explore the applicability of mixing methods.

This chapter has sought to present a common language for use when reporting and analysing mixed methods projects. Further to this, it is proposed that these mixed method designs can be valuable to inform the methodology within a project and along with the selection factors can form a toolbox of ideas to sit at the heart of the selection framework, for the modeller to reflect upon when exploring the problem and the system to determine the methodology.

Mixed methods continue to be a hot topic, but guidance as to how to undertake the process of a mixed methods project, and adopt general lessons, remains sparse. The adapted framework for methodology selection seeks to address this gap, acknowledging the consideration that should be given to mixed methods. The designs and sample projects are proposed for use to inform a modeller's personal preference and inspire the consideration of mixed methods.

The following chapter introduces the organisation which forms the backdrop to each project, providing an overview of the Beatson and its suitability as the context for this work. It discusses the system exploration phase, as described in the modelling framework, and the initial problem exploration undertaken to select appropriate projects to apply the mixed method designs within.

6 System and Problem Exploration

6.1 Introduction

Chapter 5 proposed a model development framework that incorporates a toolbox of mixed method designs to refer to throughout the process. The chapter covered the initial theory development consisting of an examination of general frameworks to inform method selection, and the development of a toolbox of mixed method designs with which methods may be used together. The model development framework recommends that this toolbox is reflected on during all phases of modelling, from system and problem exploration, model conceptualisation and model development, to validation and analysis.

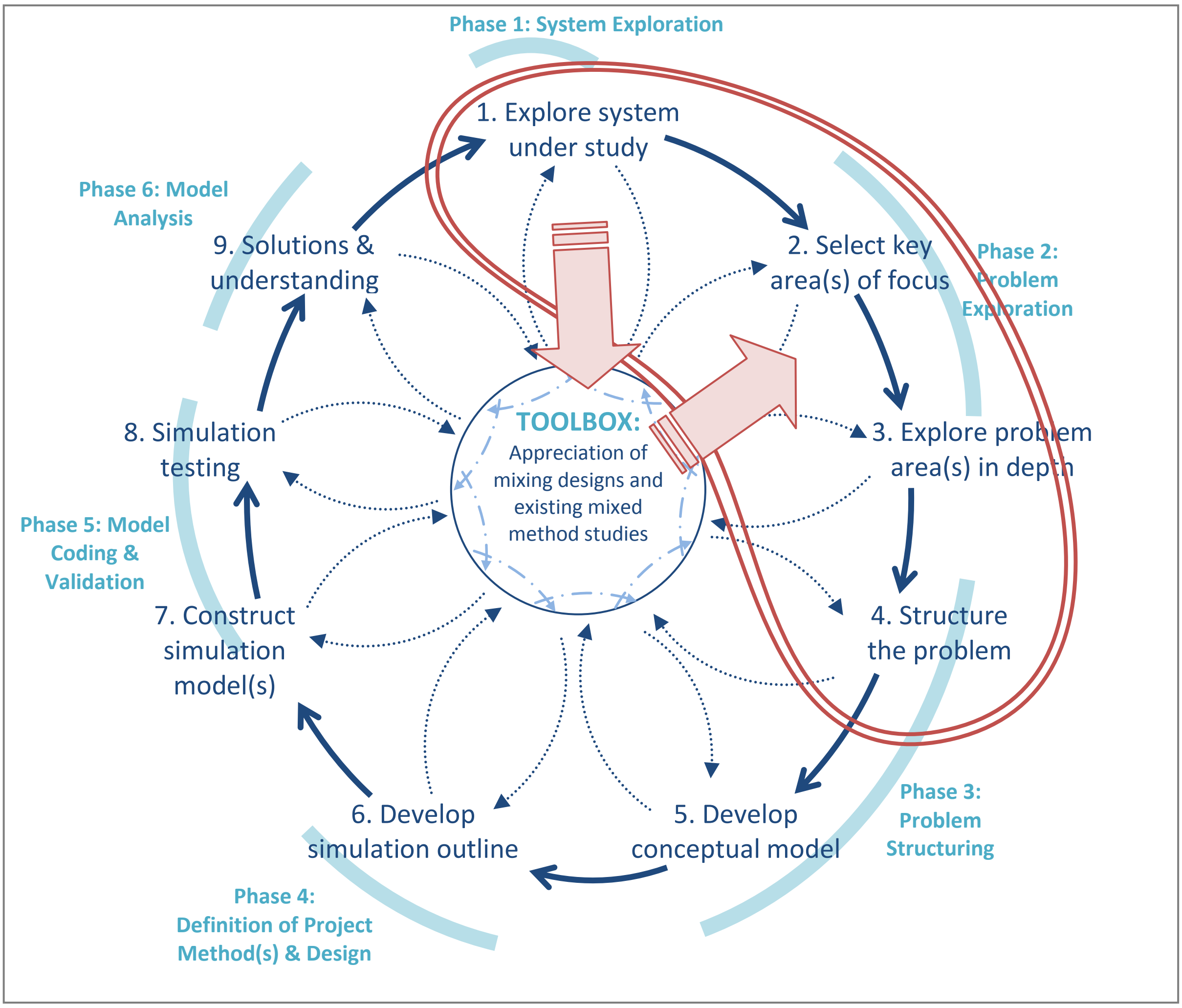


Figure 38: The proposed model development framework – content of Chapter 6 highlighted

This chapter will describe the initial stages of the project to explore how the mixed method designs and model development framework presented in the previous chapter can be tested and further developed in practice to produce a robust and practical framework to support mixed methods modelling. It introduces the organisation within which the project takes place to develop and test the framework and mixed method designs, and the initial system exploration and problem definition undertaken (phases 1 and 2, and beginning of phase 3; shown in Figure 38). These stages of the action research project will be discussed considering both the perspective of the modeller and the researcher to ensure a robust research methodology and that the project adds value for the client organisation.

6.2 The System: The Beatson West of Scotland Cancer Centre

The setting of this project is the Beatson West of Scotland Cancer Centre, Glasgow, which plays a major role in the treatment of cancer in Scotland (referred to as 'the Beatson' from here on). The Beatson is Scotland's largest cancer treatment centre[22], providing an essential service serving a population of 2.5 million (46.5% of Scotland population) (www.woscan.scot.nhs.uk). The centre focuses on non-surgical care with treatments, and each year handles over 8,000 new patients, over 15,000 courses of chemotherapy and 6,500 courses of radiotherapy whilst maintaining some of the lowest waiting times for patients receiving treatment to remove the cancer completely in the UK (www.beatson.scot.nhs.uk).

This project is concerned with the processes involved in the planning and delivery of treatment of cancer, using radiotherapy, at the Beatson. This project has been undertaken at the Department of Radiotherapy Physics with the Head of Radiotherapy Physics, Garry Currie, acting as primary contact for the project. Before examining the Beatson and its processes in any detail, background information will be given concerning cancer in general, the treatments available and, more specifically, radiotherapy. Definitions of medical terms used throughout this thesis are outlined are included in the *Glossary*.

6.2.1 Background to cancer

The Oxford English Dictionary defines cancer as *"disease, in which there is an uncontrolled proliferation of cells"* (OED 2012). It is not a single disease with a single treatment; it is a group of over 100 distinctive diseases each displaying different characteristics and requiring different treatment (www.cancer.gov). It is possible for cancer to be treated through the use of chemotherapy, radiotherapy, surgery or, in the majority or cases, through a combination of these. The Beatson provides all of the radiotherapy and much of the chemotherapy for patients with cancer in the west of Scotland.

[22] Second largest in the UK

Radiation Therapy (Radiotherapy) employs high-energy radiation from x-rays, gamma rays, neutrons, protons, and other sources to shrink tumours and kill cancer cells. It intends to cause as little harm as possible to normal cells by aiming the treatment at the affected area of the body and is planned particularly carefully. Numerous advances in technology are making it possible to aim radiation more precisely than in the past putting a large emphasis on the importance of planning. This is expected to increase the effectiveness and reduce the side effects of radiation therapy.

The method of treatment can be dependent on the *intent* of the treatment to be given to the patient. Radical treatment intent is the term used when the cancer is treatable and treatment is focused on removing and eliminating the disease. Palliative treatment refers to treatment intended to alleviate symptoms, reduce pain and/or improve quality of life.

The number of cancer cases in Scotland is projected to rise from 30,000 per year between 2006 – 2010 to 35,000 per year between 2016 and 2020 (NHS Scotland 2006, Scottish Government 2008). As such, an important issue for the Beatson is to ensure that their capacity is able to meet the demand for the service. Further to this, the spread of incidence according to cancer type is expected to change, with some cancer types experiencing marked increases. Changes in the incidence of cancer types has an impact on the service required, as the cancer type is a determining factor when deciding the patients route through the process and the equipment used. In essence, the expected changes in demand may have an impact on the equipment needed and consequently on the time a patient waits for treatment.

6.2.2 The radiotherapy planning & treatment process

A patient is directed through a complex process with many activities needing to be carried out before treatment can begin; Figure 39 shows a simple flow diagram of main tasks in the radiotherapy planning and treatment process.

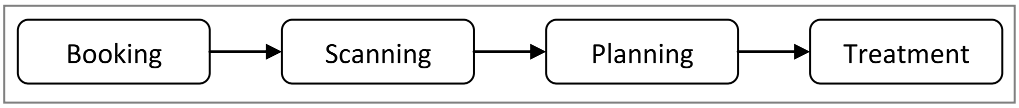


Figure 39: Simplified representation of the radiotherapy planning and treatment process

Booking is the first stage of the process but it does not involve the patient. The booking slip, which the patient's consultant has completed, provides details including the patient's information; age, address, general health, type of scan and the treatment required.

The ***Scanning*** (or simulation) stage provides images on which the planning is based; it is the point where the patient physically joins the system. The time spent on this activity depends on the type of cancer, the type of scan carried out and whether radical or palliative care is being undertaken. The decision between whether radical or palliative treatment is provided is influenced by factors such as the site of the cancer and the stage at which it's at, patient's age and general health, and the availability of resources.

Planning is undertaken by skilled radiotherapy physics staff. The time taken to complete the numerous stages within planning can range from under a day to almost a month's work.

The Therapeutic Radiographer is responsible for the delivery of ***treatment***. Patients attend treatment for a number of fractions with each fraction being equal to one visit. Fractions take place at the same time and on the same treatment machine on subsequent days for the required duration.

6.2.3 Changes and pressures on the system

The demand increases and changes in the numbers of cancer patients of each cancer type will impact the Beatson. These changes are likely to alter the main routes through the radiotherapy treatment process and the equipment required as the site of the cancer is one of the determining factors. This implies that staff and machine resource requirements will increase and future waiting times could be affected. The centre needs to consider how the current setup of the system will cope and need to alter with these changes, and what can be done to ensure timely treatment for all patient groups.

The purpose of this modelling intervention is to aid understanding of the system to allow for experimentation and analysis which may lead to changes being made in the system. This is with the view to provide insight at both the operational and strategic levels.

The following section discusses the stages and the processes embarked upon when applying the developed framework (as described in *Chapter 5*, *section 5.6*). The methods used to explore the system and the problem themes elicited during this process are discussed. The section concludes with consideration of several possible projects to continue testing the framework on by exploring how SD and DES may be used in conjunction to provide insight.

6.3 Steps of System Exploration

As discussed in *Chapter 5*, the intention of this phase of the framework is to look at the system that is considered problematic, taking a broader perspective than might have been experienced had a method been selected very early on. It is the aim of this phase to explore the system, to air a wide variety of views from those with a stake in the system and work to define the focus for the study. The process undertaken in this phase is based on the variety of methods that have been used with SD and/or DES in mixed method modelling projects previously.

The following sections discuss the overall approach to this phase of the process and the options that were considered. The necessity of documenting the process is considered alongside the need to progress to the next stage of the framework and undertake a useful modelling project for the client.

6.3.1 Problem Structuring Methods

Formal problem structuring methods (PSMs) were considered for use within the frameworks first phase for the integration of SD and DES. Specifically under consideration were Soft Systems Methodology (SSM), Strategic Choice Approach (SCA) and causal mapping, as a part of Strategic Options Decision Approach (SODA) as all have been successfully and frequently used with multimethodology projects using SD or DES[23]. Each of these are participatory methods that use *"a model as a transitional object"* (Eden and Ackermann 2006, p. 766) and show promise for use within the framework. Each method assumes that preferences and perceptions differ from person to person. This means that the problem definition is not straightforward but is itself problematic. It is important to understand the different views of the issues each of the stakeholders may hold. They are also noted as being particularly important when operating at levels above the merely operational where the issue is not so much how to do something, but more about what should be done.

Such methods share the idea that models are developed to allow people to think through their own position and consider possible actions, whilst endeavouring to bring together these multiple views generating debate and insight (Pidd 2003). The outcomes of each of these methods are intended to be primarily learning about the system and how it functions, rather than focused on hard outputs. Therefore this project seeks to utilise such a method to

[23] This is discussed in *Chapter 3* and the relevant papers are tabulated in Appendix 10.2

complete the first phases of the model development process by exploring the system and defining the problem to be explored: the conceptual modelling.

Soft Systems Methodology (SSM): It has been documented in the literature that SSM has a track record of use with both SD[24] and DES[25] before (as shown by Howick and Ackermann 2011). This methodology offers a multiple step process to achieve action, the first of which is to explore the problem (Williams 2008). The most common tool for this step is a rich picture: a general term for a diagrammatic representation of relationships in a problem system which could be abstract or literal.

Strategic Choice Approach (SCA): An incremental approach that is interactive between the various stakeholders, used in face to face workshops of a decision making group (Friend and Hickling 1997). A goal of the approach is to prioritise and make decisions, and so may be too focused to use in its entirety to provide overall insight into a system prior to problem selection and conceptual modelling.

Strategic Options Development & Analysis (SODA): In principal SODA is more individualistic than SSM as it looks at individual views of the world through mapping. The method looks at *"eliciting individual representations, weaving them together into a single composite model and then representing the model back to the group for review and further work"* (Ackermann et al. 1994, p.4). The method makes it possible to make sense of large amounts of information, permitting the exploration of both detailed and holistic properties (e.g. hierarchy to identify and explore option packages). It is also possible to see how changes in the character of one issue may have repercussions for another.

Several PSMs were considered, specifically SCA, SSM and SODA but the complete method of each may not be necessary; only tools from the initial phases of each PSM might be adopted to provide a structured method to transparently capture the system and the problems. SSM and SODA are effective at articulating the problem situation, whereas SCA is a method that may be viewed as too focused on making a decision at the end. The researcher sought a PSM to support the use of simulation methods. This research will apply the first part of one of these methods (the structuring) only, not a fully encompassing method, as a gateway to mixing simulation methods.

[24] Examples reviewed from Coyle and Alexander (1997), Lane and Oliva (1998), Paucar-Caceres and Rodriguez-Ulloa (2007) and Vos and Akkermans (1996).

[25] Gunal and Pidd (2005) and Kotiadis and Mingers (2006) both support DES with SSM

Rich pictures for problem exploration within SSM would be applicable to complete the first phases of the framework. Rich pictures may be defined as *"anything visual that can present the situation"* (Williams 2008, p.65). However, the amount of information hoped to be captured during the initial stages of the project requires a clearer definition of how the information will be captured. As the likelihood of holding a group session reduced, it was necessary to utilise tools that would provide a structure for data capture that enable individual interviews to be merged within a common structure. Further to this, the potential acceptance of the tool by the client organisation was a consideration. The definition of the problem(s) in the system needed to be captured in a matter that would provide useful outputs to the problem holders. Many stakeholders come from a highly technical background and may not see the value to be held within the rich pictures, preferring a more rigid, structural approach which is able to demonstrate causality, which was found in mapping.

Mapping has been used with both modelling methods of interest[26] and often forms part of wider problem structuring methodologies. It appears to offer the most open and flexible approach for the project, whilst providing a structured means of gathering information in the system exploration phase and collating multiple views. The researcher intends to use the approach to elicit insight into the system under study and better define the problems faced. During the process it is possible to structure the system and define boundaries, but enforcement of the need to agree upon decisions is not made until the latter stages of the process.

The next section describes the types of mapping used and the overarching process to the mapping undertaken for this project.

6.3.2 Mapping

Mapping has been selected as a key component in the initial phase of the project as it is designed to focus on the beliefs, values and assumptions an individual has about a particular issue. It is designed to provide a process through which additional richness can be ascertained and the maps produced are immediately useful to both the mapper and interviewee. Several mapping processes are considered for the problem exploration phase of the framework which could be used to develop a directed map of the system.

[26] Mapping has been used: with SD in interventions described by Ackermann, Eden and Williams (1997, 2003) and Howick et al. (2008); and in a DES study, described by Sachdeva, Williams & Quigley (2007).

Concept Mapping is used to represent the relationship between concepts to organise knowledge in the form of a map. It may be an undirected or directed concept map where links can be articulated in phrases such as ‘gives rise to’, ‘results in’, ‘is required by’ or ‘contributes to’. They are more free form than mind maps[27], as multiple hubs and clusters can be created. They can be used to communicate complex ideas or to facilitate the creation of a shared vision and understanding within an organisation.

Cognitive maps are used to construct and accumulate spatial knowledge to reduce cognitive load and enhance recall and learning of information, representing this knowledge graphically (Spicer 1998). It is a technique designed to capture the person's values and perceptions. Unlike concept mapping, the process is not constrained by a formal structure but can follow a natural conversation able to capture interrelationships and implications that remain disconnected in linear notes (Ackermann, Eden and Brown 2005). The maps ideally contain clusters of structures that take the teardrop shape as represented in Figure 40, demonstrating the goals and the means for achieving them.

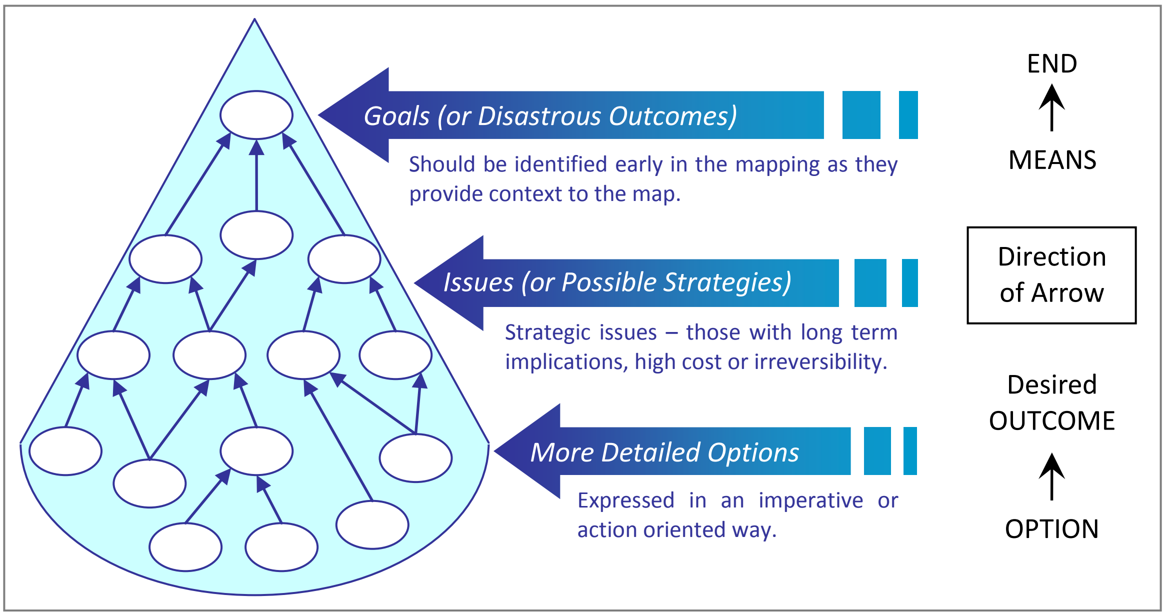


Figure 40: Some Guidelines to Cognitive Mapping (based on Ackermann et al. 2005, p. 33)

The added value to be gained through cognitive mapping is through the identification of characteristics of the situation, determining what makes the situations problematic and helping to reveal central beliefs. It provides a way to identify concepts that have the most impact on the goals, or those that require more options to be considered. In a group setting, the technique can facilitate reducing the impact of individual personalities and interpersonal

[27] Mind maps are free form diagrams consisting of words, thoughts, ideas, tasks linking to a central keyword designed to generate ideas (mindtools, 2010)

dynamics, whilst developing ownership of the problem through participants dedicating time to the problem(s).

A **Casual Map** is *"a word-and-arrow diagram in which ideas and actions are causally linked with one another through the use of arrows. The arrows indicate how one idea of action leads to another"* (Bryson et al. 2004, p.4). Causal mapping is a suitable approach to apply when looking to explore muddled, complicated, dynamic work (Ackermann and Eden 2005) where everything is interconnected as it provides a means to formalise the structure. It is particularly applied to management challenges and how to manage them. A causal map can illustrate what, how and why: what to do in the areas of concern, how it might be done and why (as the arrows indicate causes and consequences) (Bryson et al. 2004).

Each of these mapping tools is useful to the project. All three will be utilised to provide the modeller with a structured process to progress through when bringing together the multiple views of the system.

6.4 The System Exploration Process

This section will discuss the work undertaken to explore the system which informed the selection of a problem theme. The selection of participants with the assistance of stakeholder mapping, the method of acquiring the participants views of the system and the mapping process are discussed.

6.4.1 Stakeholders

In order to explore the system it was necessary to identify appropriately representative stakeholders from the system to use the above discussed mapping techniques with. Stakeholder mapping was undertaken to enable the modeller to consider which system stakeholders had interest in and impact on the project, and from a research perspective that the process involved a diplomatic selection of participants.

Stakeholder mapping aims to identify and group individual stakeholders, helping to assess the client, but also the domain experts. A stakeholder map provides insight into the stakeholder interest in relation to the project and can help the modeller understand how this interest may impact upon the project. From this, it says something about the expected use of the model and organisational culture. Stakeholders are mapped using ‘Influence’ or ‘Power’ as the x-axis, and ‘Interest’ as the y-axis. A sample map from an NHS rheumatology service (ISIP (Integrated Service Improvement Programme) 2007) was used as a point of reference to assist the development of a stakeholder map of the Beatson for this project. It highlighted that key persons of interest should be senior management and ground level teams who are involved directly in the process. Additionally, it is recommended that the size and shape of the system is taken into account to help inform the selection of interviewees (Ackermann et al. 2005).

A stakeholder map was developed early in the project to obtain an appreciation of the influence and interest parties involved in the project would have. In general, within a simulation study it is necessary to consider three roles: the problem owners/clients, the model developer and the experts being modelled who provide data for the project (Robinson 2008). Although this reference comes from the DES field, it is equally applicable within SD, and stakeholder mapping is equally compatible to SD projects[28].

[28] For example, used by Eden et al. (2008).

The stakeholder map of the Beatson for the context of this work is shown in Figure 41. Of those in the high influence quadrant, stakeholder 15 represents an individual with high influence but low interest in the specifics of this project, demonstrating that when considering participants for the interviews it was necessary to also consider the likely involvement of individuals. We were most likely to gain participation from and useful insights from those who feel they have something to say and the project appeals to. The diagram represents the stakeholders according to their interest and influence on the functioning of the system with respect to the project. Staff central to the core functionality of the system are highlighted in the blue diagonal band. As with the example NHS map, key staff members for the radiotherapy department are of interest for this project. Above the diagonal blue band lie policy makers at the national level who are able to influence at policy level, but are less likely to have interest in operational or strategic issues at the Beatson. Additionally, staff involved in patient transportation can have significant impact on the day to day functioning of the system, but little interest in the strategy of the centre. At the other side of the blue diagonal, support staff, family members and patients all have high interest in the system, but little influence The project is envisaged to be focused on the system function rather than the quality of care and so these individuals are not included (although this may change depending on the problem focus of the project).

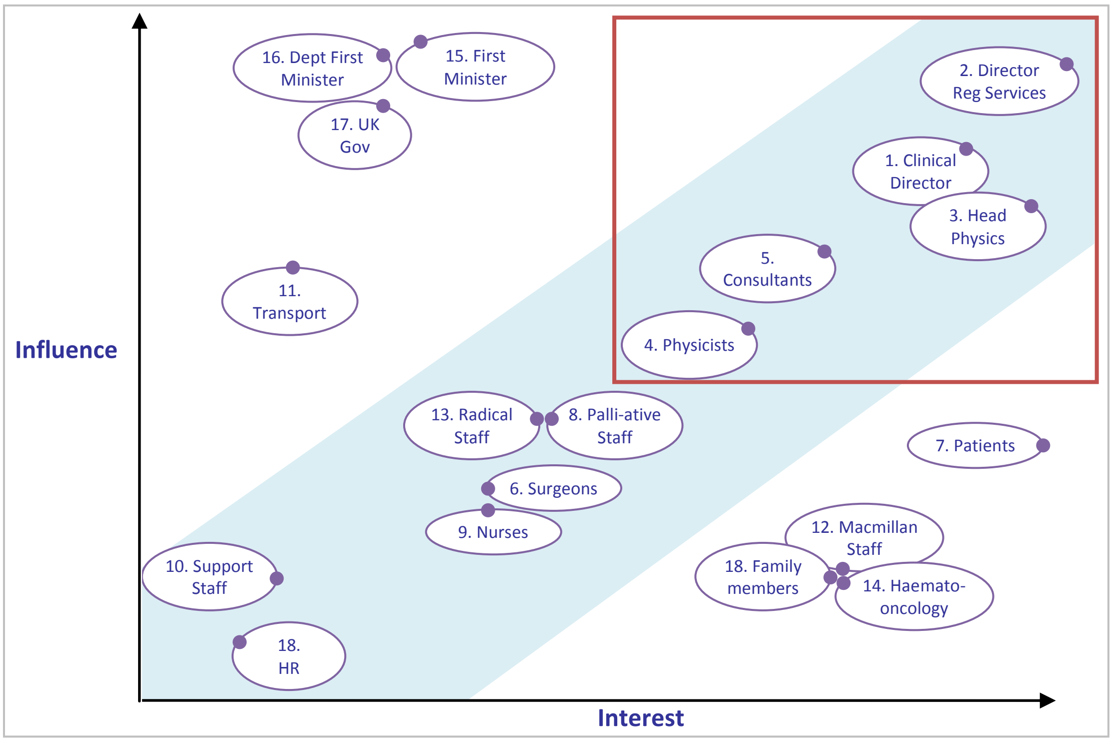


Figure 41: Stakeholder map of the Beatson Project

– Core services are highlighted on the diagonal (blue) and the area of focus for the project is highlighted in the top right hand corner (red)

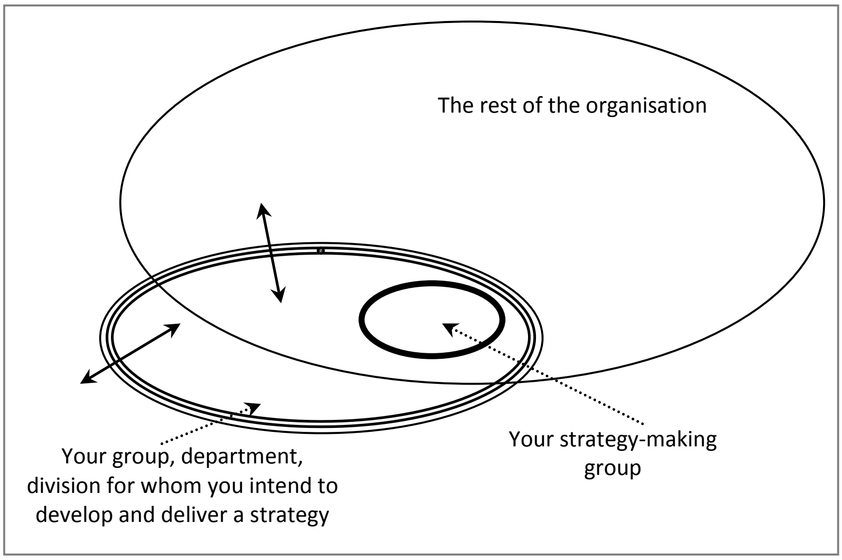


Figure 42: The context of a strategy making group (Ackermann et al. 2005, p.16)

Seven participants were selected based on characteristics that were expected to influence the type of insight and range of focus on the system. Prospective interviewees were selected based on the stakeholder map, informed by Ackermann, Eden & Brown's (2005) advice for the context of a group involved in mapping (illustrated in Figure 42), and using purposive sampling design (Schahill, Harrison and Carswell 2010). Given the nature of the project and the time constraints on those involved in the system, participation was dictated by those willing and able to give up their time. The area of focus highlighted in Figure 41 represents those stakeholders sufficiently knowledgeable about the system and in a position to discuss the strategic and operational functionality of the centre, as well as holding influence and interest for the project. In an attempt to fit in with their workload, encourage engagement and increase participation the researcher was mindful to be highly available for interviewees and flexible with timings. Considering the motives of stakeholders helped to inform the direction of the interview process and illustrate what focus they bring to the problem situation and how their views might differ from others (see Appendix 10.3 for further details).

6.4.2 Mapping process

The design of the intervention was shaped by the client and the needs of the researcher to ensure an appropriate approach to system exploration and problem structuring was used, as advised by Eden and Ackermann (1998), that enabled the collation of multiple perspectives of the system in a manner that was understandable by all stakeholders. The choice to undertake one-to-one interviews or group mapping sessions to structure the issues relating to the system under study may depend on: the task being addressed, the nature of the organisation and the client objectives (Eden and Ackermann 1998, p.1). However, it was ultimately dictated by staff diary density and time pressures.

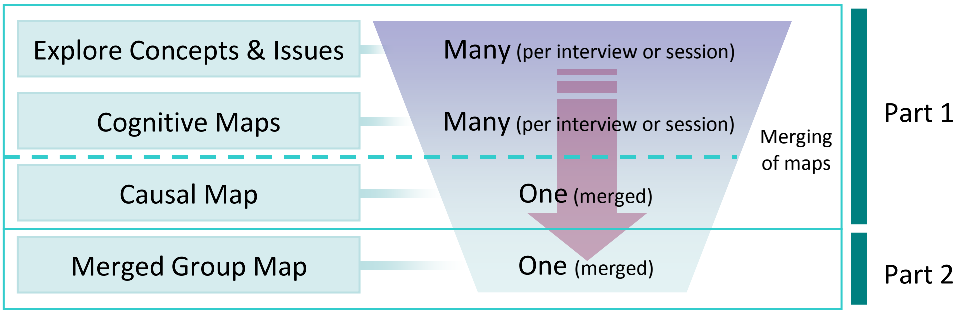


Figure 43: Proposed mapping process to explore the problematic system under study

As well as selecting appropriate mapping tools suited to inform project selection, the mapping process was developed with discussions with the main contact at the Beatson to ensure the proposed methodologies would fit with prospective stakeholders. The tools selected provide the modeller to obtain an appreciation of the personal beliefs, to analyse the different perceptions of the system, assess alternative conceptualisations of the system and generate consensus of the systems view (Mingers and Brocklesby 1997).

The mapping process was designed to progress through the stages depicted in Figure 43, taking individual views, refining and structuring them. This is based on the ideas put forward in the modelling cascade as presented by Howick et al. (2008), but consists of more mapping stages with the modeller encouraged to move from a causal map to a conceptual model rather than moving directly from the causal map to an influence diagram. In this process the modeller maintains a broad view of the system determining area(s) of focus on the causal map and develops this to be a stage one conceptual model. This stage one conceptual model contains the views of the multiple stakeholders which can then be used to share understanding between stakeholders and explore what methods may be applicable to the various problem themes raised.

If the initial phases of the framework can be conducted within a group setting then Figure 43 becomes a two stage process of mapping and conceptual modelling. However, when individual interviews are conducted (as was the case in this instance) this needs to be broken down further to allow for the structuring of individual views, merging and structuring of a combined view.

6.4.3 Interviews

Due to time constraints preventing the undertaking of group mapping sessions, individual sessions were conducted with the interviewer mapping during and after the session. Although group sessions[29] may be preferable, it is noted that individual interviews are effective where a deep and rich understanding of the issues is required (Ackermann et al. 2005).

Interviews are recognised as possibly being an easier entry method that provides the potential to gain commitment to a group workshop at a later date. They offer several advantages over the group mapping sessions, but also have several disadvantages (Ackermann et al. 2005). These are that interviews provide relative anonymity that encourages participants to discuss issues more openly and more thoroughly than may be possible within a group session, and prevent peer pressure from other group members, which guards against members relying on other participants rather than contributing themselves and *"group think"* where members may feel their view is out of step of others and may not express it. They offer the opportunity to obtain a rich understanding of the issues at the Beatson and present a less risky starting point than a full day group mapping. However, disadvantages of individual sessions are:

- individualistic representation of views;
- time consuming for the facilitator to complete all interviews and to merge maps;
- need for topics to be pinned down to ensure individual interviews overlap;
- interviewees are unable to appreciate alternative perspectives.

To manage against several of these disadvantages several measures were undertaken. Mapping interviews and merging the maps enables a more cohesive view of the system to be represented. Presenting the mapping from the initial round of interviews back to interviewees allows the modeller to demonstrate the combined map of the system to the stakeholders to gain comment on the alternative perspectives presented. Finally, the time commitment was outside of the modellers control as this was dictated by stakeholder availability, but it also meant only a select group could be engaged in the project. The interview and mapping process conducted is shown in Figure 44. The process utilises mapping tools from SODA,

[29] Group sessions were the preferred approach but were not found to be possible due to the dynamics within the organisation and the inability to get a date in the diary.

and is influenced by 'shaping' stage[30] of SCA; it is the first stage of many problem structuring methods with the goal to identify a problem foci for the project.

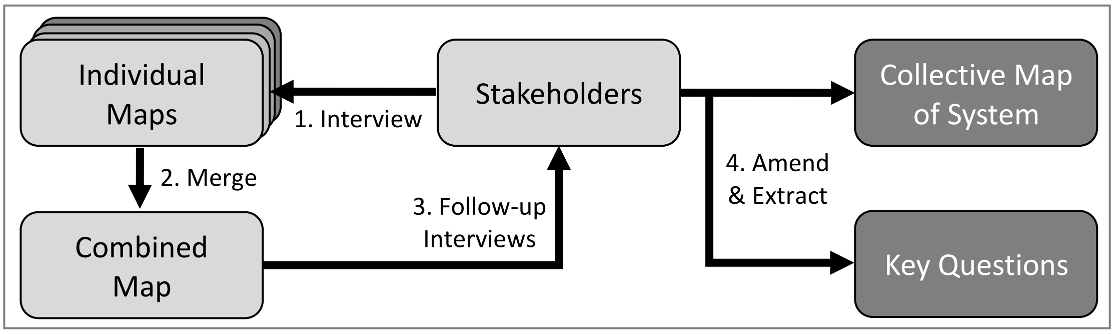


Figure 44: The stakehholder interview and mapping process

6.4.4 Interview process

Individual interviews were conducted with 7 participants selected on the basis of the stakeholder mapping. These interviews were semi-structured and with the aim to explore the system of interest, expose areas of concerns and eventually lead to definition of the problem area(s). The outline for the interviews is included in Appendix 10.4. An open, semi-structured interview design allows participants to talk freely about their hopes and fears for the department, highlighting areas of pride and those which are underperforming.

Interviewees were informed that their anonymity would be maintained which enabled interviews to be recorded[31]. The researcher then fully documented each interview by creating a concept map, one per interviewee based on the audio and notes taken using the Decision Explorer© software[32]. Following the initial documentation of the content of the interviews, the researcher restructured the maps to form clusters of points of interest and arrows to indicate the links between key points and their drivers. Key themes were identified based on how clearly they were described by the interviewee, their centrality to the rest of the map and the emphasis the interviewee put on the topic (if the topic was returned to or mentioned numerous times). These key themes were then used to collapse the maps to gain a summarised overview of the interview.

[30] The 'shaping' stage of SCA involves listing decision areas, sorting and refining decision areas, building a decision graph, highlighting areas of significance, superimposing organisational boundaries, and then selecting problem foci.

[31] Recording enabled the modeller to focus on eliciting as much information as possible during the interview, without the pressure to live document. However, it is noted that this may have influenced the content of the interviews.

[32] Decision Explorer© is the mapping software used to create the cognitive maps of each interviewee, and was used to merge these maps to create a causal map of the system.

These individual maps were then combined to be developed into a causal map of the system. The process involved reviewing the maps to ensure the key points highlighted were representative, and the full maps were brought together into one view. Concepts were searched for similar themes to allow individual elements to be merged. Clusters from the individual maps were re-examined to locate concepts with corresponding meaning, and repositioned on the merged map to provide an overall clustered map.

Following the merging of maps and identification of clusters, the researcher returned to the interviewees to show the merged map providing participants with an opportunity to provide feedback on the concepts and relationships captured, confirm the relevance and importance of the key themes drawn from the mapping process and comment on the direction of the project. Example SD and DES models (shown in Appendix 10.10) were used to demonstrate work previously undertaken within the centre and illustrate the purpose and final goals of the work. These models were intentionally limited in detail but were used to convey the type of modelling work that would be undertaken as those interviewed were not familiar with the methods.

The following section discusses the merged map of the system, highlighting key problem themes identified following the follow-up interviews. It concludes with a discussion of how the problem themes might be addressed using SD and DES, how a mixed method designs may be appropriate and beneficial, and what form this design might take.

Had this not been a research project then the system exploration phase may not have been so formal and structured to ensure an auditable trail. However, it was vital for identifying a project that was important to all stakeholders that also fitted the remit of the researcher: to provide sufficient information to help the modeller identify a project that was suited to the use of SD and DES.

6.4.5 Merged map of the system

Using Decision Explorer© to combine the individual maps resulted in a causal map of the system containing over 1500 concepts. All concepts from each interview map were brought onto a single document. All individual maps had been structured prior to combining into a single document to assist the merging of similar concepts as they were clustered into thematic groups (individual maps created following each interview are included in Appendix 10.6). In these maps concepts which are not directly linked to the body of the map are statements made by the interviewee but which were not elaborated on further and could not be integrated into the overall discussion. Such unlinked concepts were able to be linked when the individual maps were combined to form the merged map and relationships established by other participants were revealed. A key to the styles used to emphasise concepts in the merged map is shown Table 15.

Table 15: Concept styles used in Decision Explorer© mapping

Concept Descriptor	Styling	
Key Point	Navy (14); Bold Underline	**Sample**
Concept of Medium Focus	Teal (14); Bold Italic	***Sample***
Standard concept	Purple (12); Normal	Sample
Standard Inferred by researcher	Purple(12); Italic	*Sample*
Participant airing a personal view	Maroon (11); Italic	*Sample*
Researchers personal view	Red (11); Italic	*Sample*
Informational	Grey (11); Normal	Sample

The merging of the maps resulted in a large and messy map requiring a restructuring. There were some differences in the concepts and relationships discussed by interviewees resulting in a messy collapsed map and so the interview recordings were returned to ensure that the changes resulting from the merging process did not conflict with the views they expressed. All concepts maintained their formatting during the merging process and were assigned the 'higher' weight if there was a difference between interviewee concepts[33]. Additionally, a single concept being raised by multiple interviewees appears only once in the merged map, as do concepts only raised by a single interviewee. This was to ensure that all views were represented rather than a merged view that failed to include some of the possible contested relationships, but overall there was no discernible conflict of opinion regarding the relationships within the system.

Figure 45 represents the merged map of the interview data. The map has been collapsed to only show points of medium and high interest, that are core to building the structure of the system. On examination of the map some key problem themes could be extracted, demonstrating the interrelated nature of the system and questions being posed. The following section discusses the merged map and the issues in the system it highlighted.

[33] An issue identified as a key point by one interviewee remained a key point even when merged with the same concept identified by other interviewees as a standard or medium focus concept. See Table 15 for the levels of concepts used in the maps.

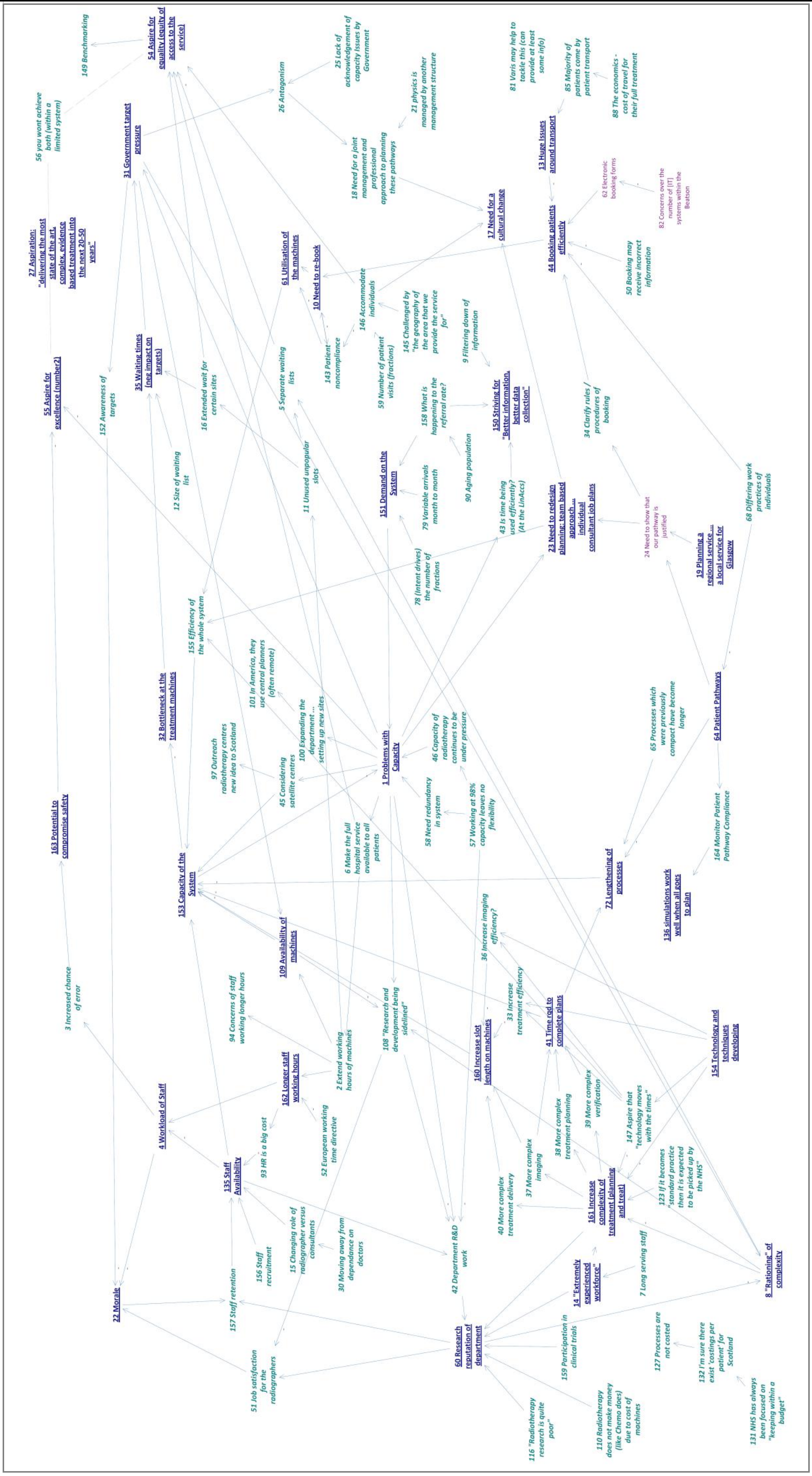


Figure 45: Collapsed merged map containing interview data

6.4.6 Follow-up interviews to discuss the merged map

During and post the merging process it was possible to dig into the details of the map and identify clusters of issues (problem themes)[34]. Feedback was provided to interview participants that outlined the identified problem themes (the ‘to-date’ outcome of the project, illustrated in Appendix 10.9) and requested their involvement in a follow-up meeting. A set of follow-up interviews with the original participants was undertaken following the initial interviews. This was to obtain their feedback on the merged map by discussing the various clusters of issues. This also provided the opportunity to speak with the participants about the two modelling methods to determine if they felt there was use for such methods (see Appendix 10.10 for further details).

There was no discernible conflict of opinion regarding the relationships represented on the map, both when the modeller produced the maps from the interview tapes, and at the follow-up interviews. During the first interviews some interviewees had not identified some links between concepts but after being shown the merged map they appreciated being given insight into the whole of the system, which was an expansion of what they had said in their interview (an extension of their individual map).

As no disagreement with the merged map was raised by any of the interviewees the map remains unchanged. The following section will discuss the themes identified within the map.

6.4.7 Themes of the merged map

All participants raised concerns about the capacity of the system and the ability of the system to provide equitable and efficient care given the demand on the system. The capacity of the system and its ability to function is defined by staff availability (Figure 46). There were concerns that pressures from workload and government targets may impact morale and staff retention and therefore the resource level. Changing the times required to complete phases of the treatment process influences both the capacity of the system and the staff workload and so a delicate balance has to be found. A proposal to extend the working hours of the service is not possible without the backing of the staff and would require careful handling to ensure that morale is not negatively impacted. The merged map is able to illustrate these issues and the relationships between them.

[34] Clusters were identified manually both by the researcher and using the “cluster analysis” feature in Decision Explorer© to provide a complete list of core issues raised by interviewees. Discussion of all of the clusters identified can be found in Appendix 10.8.

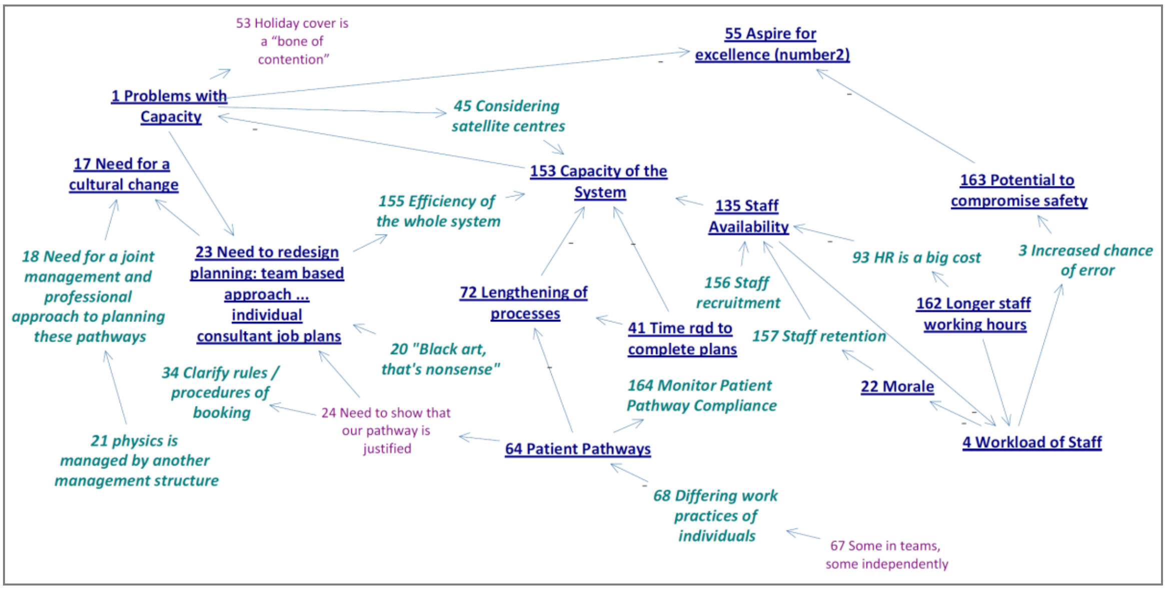


Figure 46: Map of "Capacity & Staffing" problem theme

An additional area where the value of the merged map was observed directly within the interview process was the clarification of the impact of the booking of patients on the functioning of the system. A section of the merged map is represented in Figure 47, demonstrating how the efficiency of the booking processes ultimately influence the capacity of the system and the potential utilisation of the machines. Within the system, the focus is on ensuring machines have high utilisation, but it is the booking process that determines the scheduled workload. Several of the interview participants found value in observing this relationship on the merged map, and could see the knock-on impact of the booking process onto the wider system.

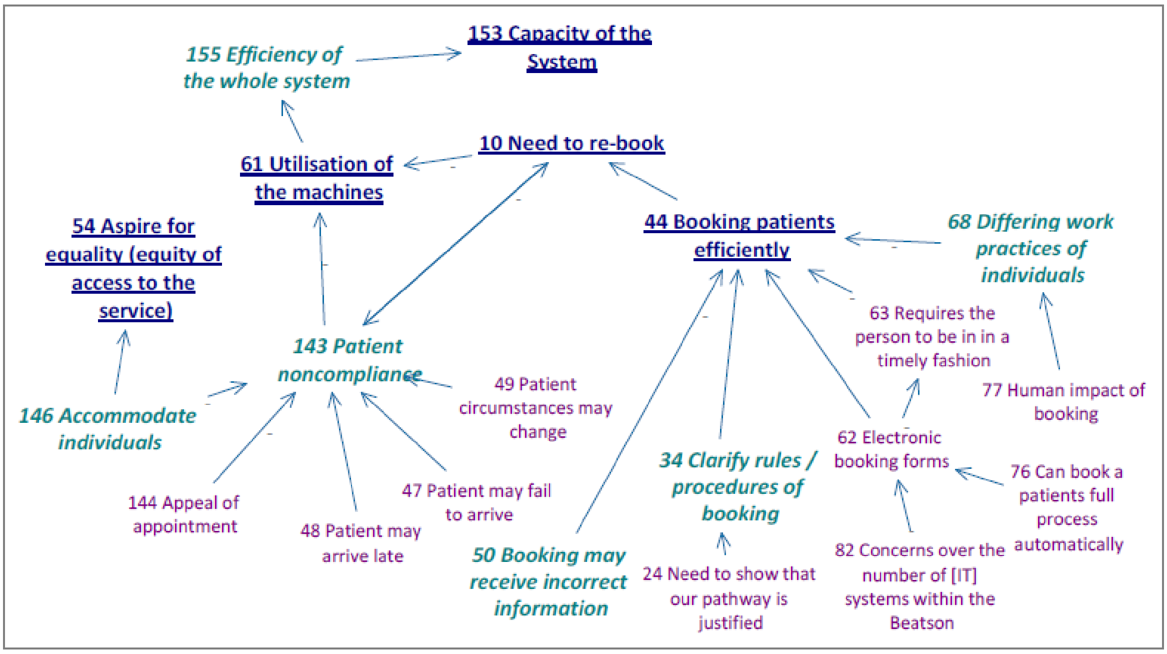


Figure 47: Map of "Booking & Resource Utilisation" problem theme

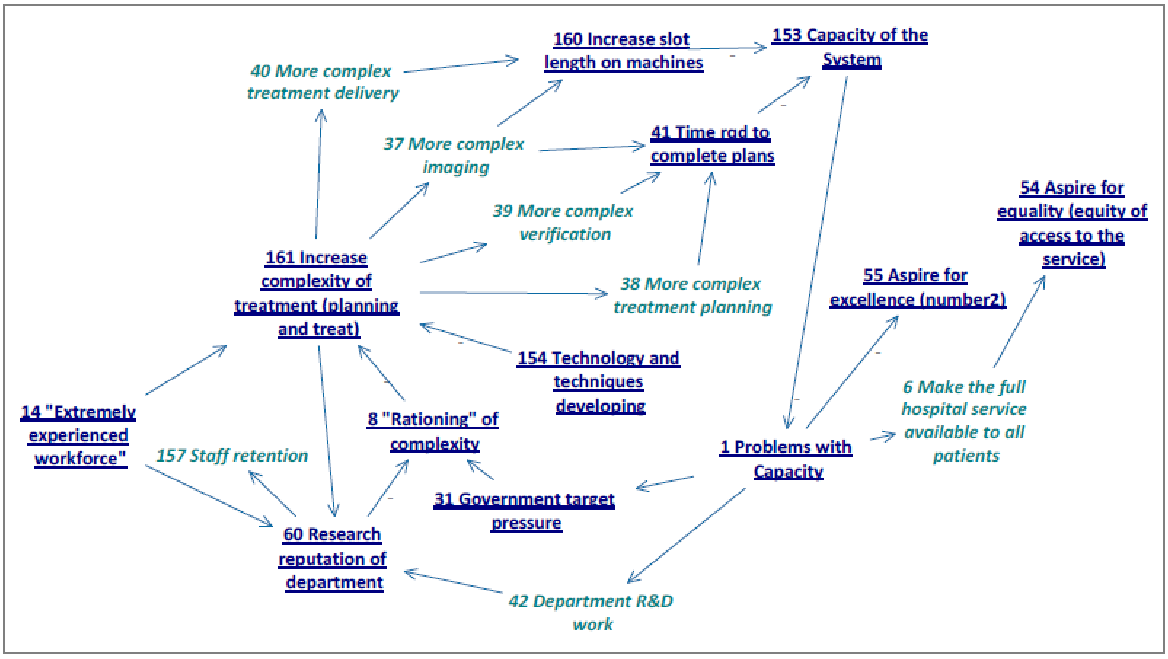


Figure 48: Map of "Complexity of Treatment" problem theme

A further notable cluster to emerge from the merging of the maps centred on the complexity of radiotherapy treatment. The Beatson is interested in understanding the impact of the complexity of treatments on the capacity of the system and on achieving equality – the ultimate goal of the NHS. The causal relationships identified surrounding this issue are illustrated in Figure 48. This area of concern is one specific to physics, but has a knock on effect to the system, limiting capacity from two sides as too complex treatments may lead to a reduction in capacity, whereas too basic treatments reduces the departments research reputation and ultimately reduces the appeal it holds for physics staff, which can have a longer term effect on the system. The level of complexity of techniques that are adopted by the department ultimately feeds into the time spent on the machines and the time staff must spend per plan per patient, impacting the capacity and therefore the centres' ability to meet government targets[35]. However, government pressure may come in two forms: ensuring a timely progression of patients through to treatment, but also ensuring that the best service is available to all and so the rationing of complexity may compromise this.

Directly linked to complexity of treatment regimes is the issue of government targets. This was a recurring concern throughout the interviews, with participants specifically wanting to know how the system is performing against government targets, and what impact these targets have on the performance and capabilities of the Beatson. Ultimately, the targets place a pressure on staff that interviewees believe impacts upon job satisfaction and morale, as illustrated in Figure 49.

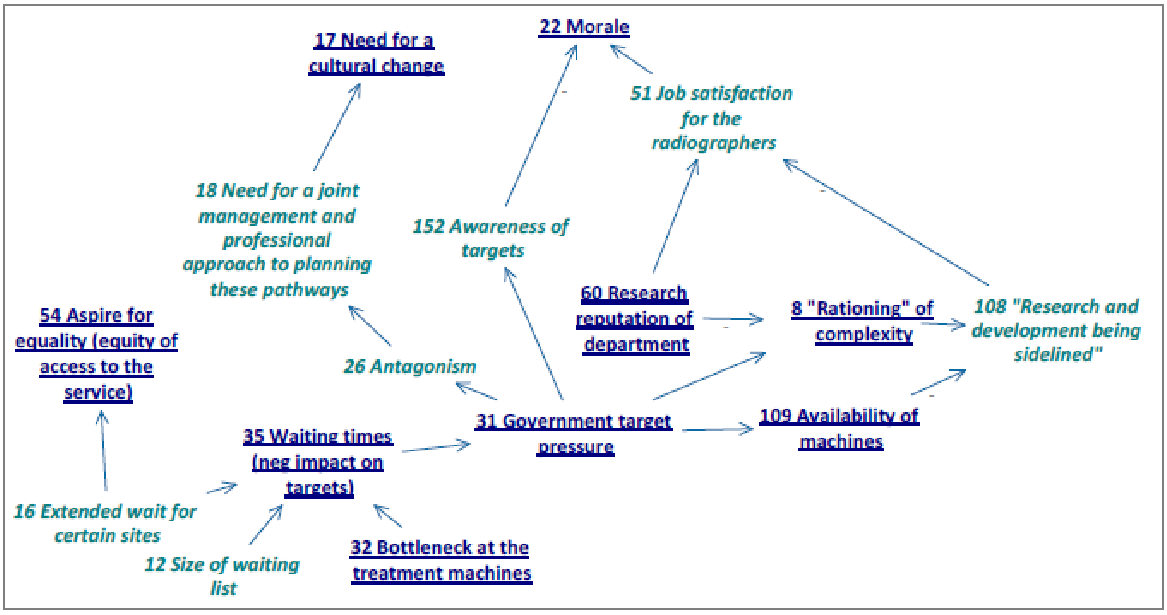


Figure 49: Map of "Government Targets" problem theme

A final problem theme to emerge from the merged map centres on the use of patient/consultant pathways within the Beatson (illustrated in Figure 50). These pathways are used to differentiate between the routes patients progress through the system, and capture consultant availability for each of the required routes. However, there is uncertainty around

[35] 31 day waiting time target for patients to receive first fraction of treatment

how consistently these pathways are used to book patients, if consultants are consistently available as described by the pathways (compliance), and what the overall benefit, or cost, is of utilising these pathways.

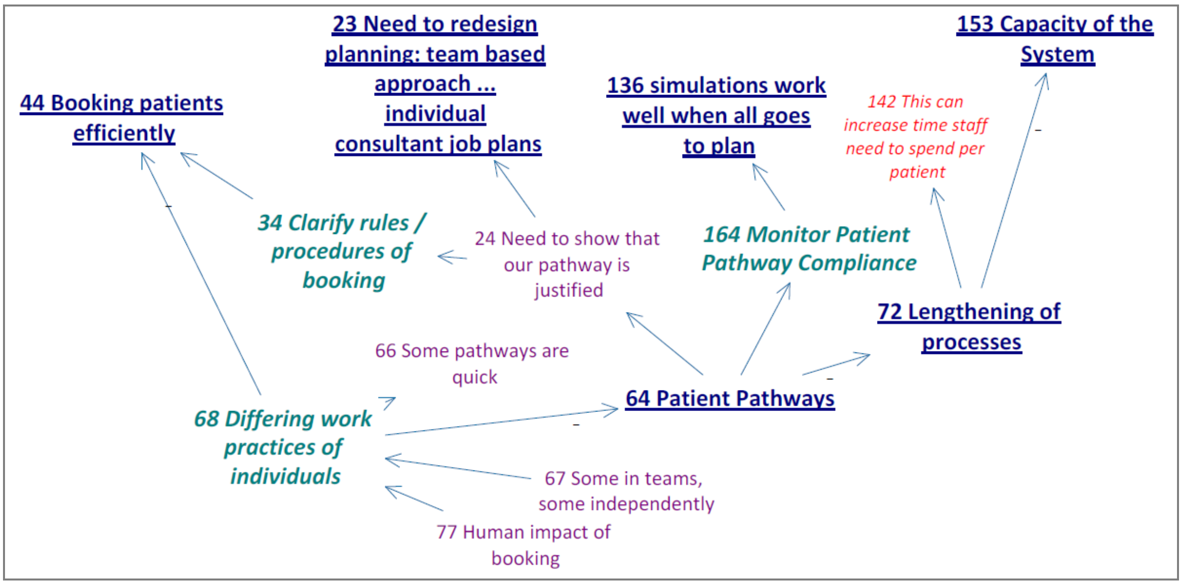


Figure 50: Map of "Patient/Consultant Pathways" problem theme

This section has sought to describe the core problem themes to emerge from the mapping process. The merged map provided a rich view of the system and highlighted the interconnectedness of concepts, highlighting some relationships within the system that had previously been known only by an isolated subgroup.

6.4.8 Summary of system exploration

A structured mapping process for system exploration, inspired by the SODA methodology, has been described. The process enabled many issues to be captured and explored through interviews with staff members. Merging the individual maps enabled the multiple perspectives of the system to be included in the overall system view, and the interconnectedness of the system to be captured whilst also highlighting the centrality of themes and issues.

The merging of the interviews resulted in identification of some of the core areas of interest within the system. The merging process also revealed that some interviewees were able to perceive the links between concepts and describe them, whilst others did not draw links and it was only through the conceptual mapping process and merging of maps that it was possible for them to see a clearer view of the system. The following section discusses some of the themes of interest which emerged from the mapping process and examines which methods might be used to address the issues raised.

6.5 Possible Project Problem Themes

Having examined the merged map to identify problem themes, possible OR modelling methods, especially SD and DES, were considered (see Appendix 10.11). The problems discussed in this section were all identified as potentially requiring the use of DES and SD. Possible suitable mixed method project designs are considered for each theme.

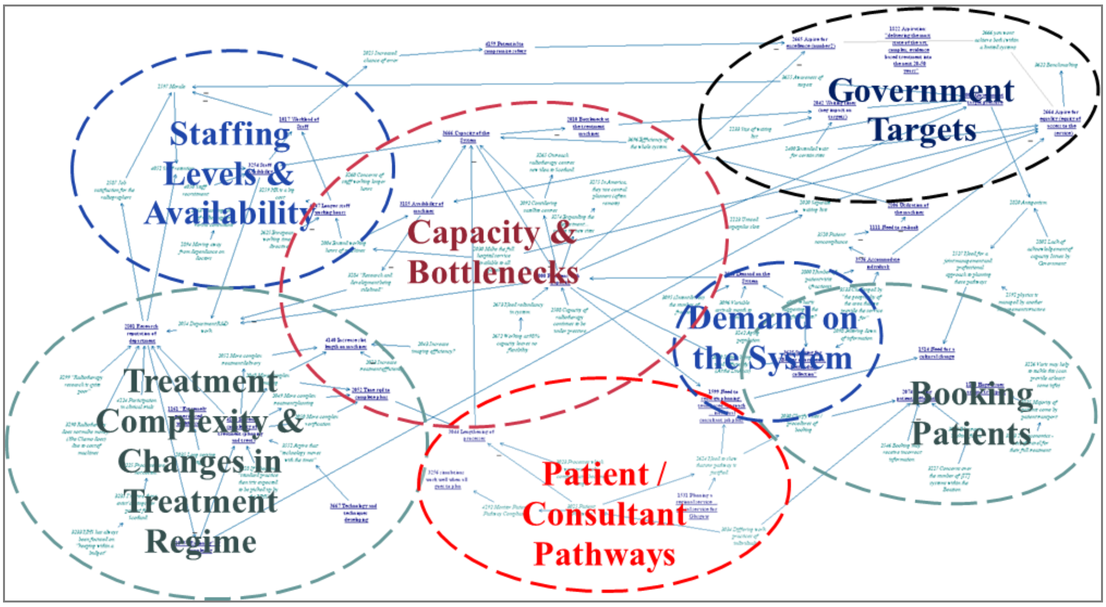


Figure 51: Problem themes identified in the merged map

Figure 51 illustrates the merged map from the interviews with a selection of key problem themes highlighted. Within each of these there are a range of problems, concerns and goals which could form the focus of the project. The following sections present why DES and SD might be applicable of these themes and how a mixed methods project design may be used to provide answers to the questions posed by the interviewees.

6.5.1 Theme 1: Government Targets

As discussed in the previous section, interview participants were interested in how Government targets impact the system: interest in how targets were set at their current levels, how feasible the targets are, how staff within the centre perform against them, and what would happen if the target time for patients to reach radiotherapy treatment reduced. To answer these questions it is proposed an SD model could be utilised to highlight the motivation for targets and the dynamics of targets interacting with those involved in the radiotherapy treatment process. A DES model in conjunction with data analysis could then be used to reveal the performance of the system. It is suggested that the mixed method design of this project is as described in Figure 52.

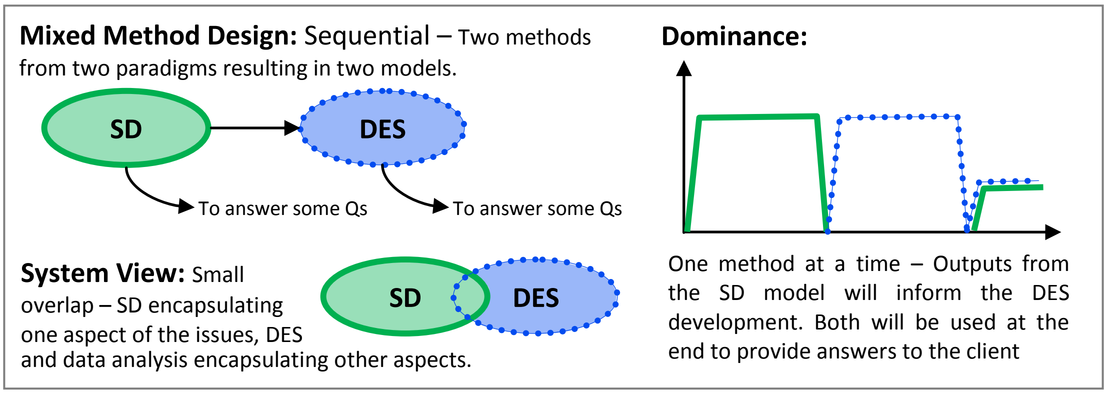


Figure 52: Mixed method design for the problem theme "Government Targets"

6.5.2 Theme 2: Consultant Pathways

Adherence to measures in place to manage the radiotherapy treatment process is of concern to stakeholders. The impact and success of these pathways is not clearly understood and a DES model of the Beatson process with careful and explicit modelling of each consultant's pathway is proposed. This DES could be complemented with an SD model of the process to contrast the impact of stochastic patient arrivals on the system versus being generally available. Two independent models would be able to offer contrasting insights; with both taking the same view of the system to enable direct comparison. Independent modellers working on the project at the same time would enable each modeller to remain completely within a single method paradigm which overcomes conceptual and paradigmatic issues. The proposed mixed method design is shown in Figure 53; with both models have equal dominance and capturing the same system view.

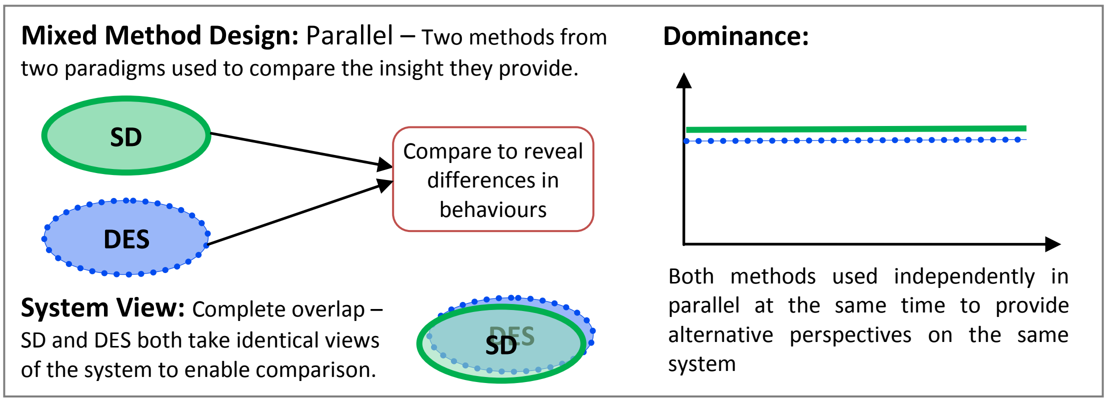


Figure 53: Mixed method design for the problem theme "Consultant Pathways"

6.5.3 Theme 3: Capacity and Bottlenecks

Participants were interested to know what impacts the ability of the Beatson to cope with demand and where bottlenecks occur in the system. Bottlenecks within a healthcare system are often modelled using DES, particularly due to the range of individual requirements for each patient (as discussed in *Chapter 2*). Additionally, demand may be captured using SD, with the possibility of the SD model informing the arrival of patients to the DES process model, and the DES informing the behaviours of referral and population diagnosis. This possible mixed method design is illustrated in Figure 54.

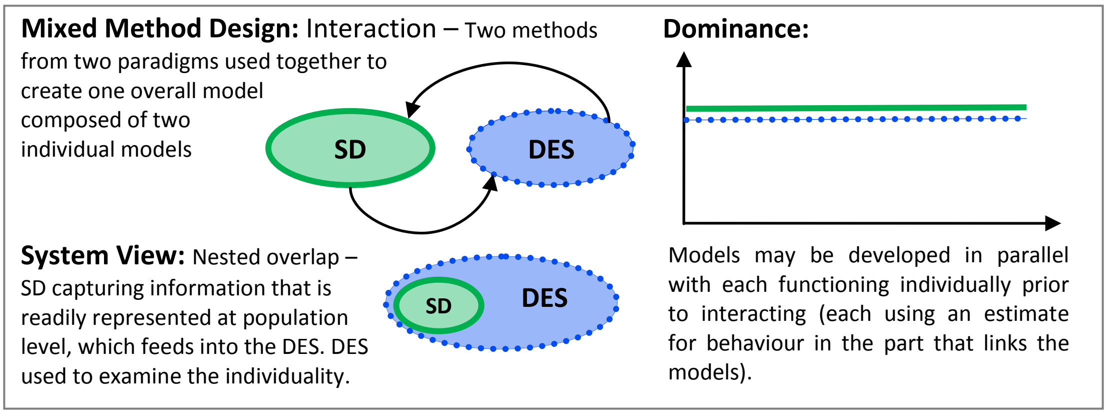


Figure 54: Mixed method design for the problem theme "Capacity and Bottlenecks"

6.5.4 Theme 4: Changing Treatment Regimes

The impact of changing treatment regimes was identified by participants as a significant concern to the future of the Beatson as a leading cancer centre within the UK. The development of new radiotherapy treatment regimes is felt to impact the day to day running of the system but for how long the system can cope is uncertain. It is proposed that a DES model could be used to represent the core treatment processes with an SD providing insight into the drivers of changes in treatment regimes (illustrated in Figure 55).

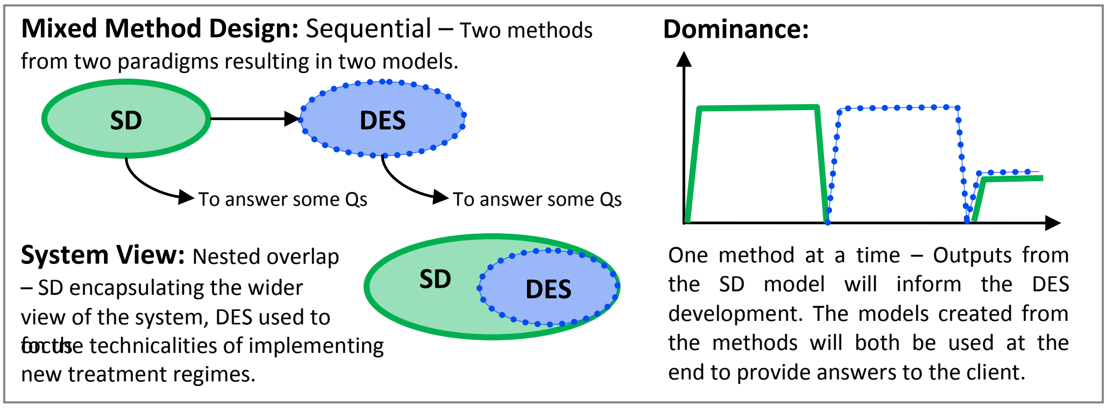


Figure 55: Mixed method design for the problem theme "Changing Treatment Regimes"

6.5.5 Further problem themes

Other problem themes to emerge from analysis of the merged map are detailed below. The full list of problems themes explored and the process undertaken to identify suitable methods are included in Appendix 10.8 and 10.11 respectively:

- **Booking of patients:** Participants identified that a rigorous mapping process would be needed to establish what the current process for booking patients is. Process flow mapping and elicitation of complex processes would help the wider Beatson staff to understand the process; and this could be complemented with benchmarking and adopting best practice from other radiotherapy centres.
- **Staffing levels and availability:** Concerns around this problem theme could be addressed by auditing the current staffing capacity and working rules, complemented by developing an understanding of the processes involved in recruiting and retaining staff (for example through mapping and/or SD).
- **Demand:** This problem theme is traditionally addressed by long term forecasting of cancer incidence, diagnosis and referral behaviours (NHS Scotland 2006). Beneficial insight may also be gained from theoretical models of referral behaviours constructed in SD to represent the feedback processes, and a DES model of the changes in radiotherapy treatment times to observe the implications on resource utilisation.

6.5.6 Summary

In summary, several problem areas exist which demonstrate early potential to use SD and DES together to inform on the questions raised. Each of the problem themes reflects a need to examine the system in its current state, and how it will change over time subject to adjustments. Some, such as the exploration of consultant pathways, emphasise utilisation of the traditional stochastic versus deterministic characteristics; whilst others, such as changing treatment complexity, appear to require the detail and accuracy of DES based on system data along with the feedback representation of SD to be embraced. All of the problem themes discussed would seemingly benefit from SD and DES modelling, but each possibly using the methods with different views of the system, in a different design and at different times in the modelling process.

The themes discussed here are only those which might benefit from both SD and DES. Numerous other interesting problem themes were raised but were not further explored as they required a range of other methods. These problem themes are summarised in Appendix

10.8 and 10.11, along with the methods that were thought to be useful in each situation. The methods assigned are based on the description of the problems presented by the stakeholders and are the modeller's opinion of being suitable. Keywords, characteristics and the required outcomes of each problem help to highlight the possible solutions.

This section has presented possible foci of the project, considered the methods suitable for such problem and proposed initial mixed method designs. Some of these projects may require supportive methods in addition to DES and SD, or may later be found to require only one of the methods advocated, or different methods. DES and SD are not always the most appropriate methods to every problem, and the aim of project can change over time. For the purpose of this research however a project is selected that is highly likely to require the two methods that are the focus of this research. The following section focuses on the problem theme that will be the focus of this project, having agreed this with the client.

6.6 Exploration of the Selected Problem

The previous section has discussed the context and initial system exploration stage of modelling conducted for the case. It has sought to set the scene for this chapter, discussing the broad scope of issues and challenges faced by the Beatson. This section will focus on one of the problem themes revealed in the system exploration phase which was identified to be suited to DES and SD modelling (as discussed in the previous section). It presents the transition between problem exploration and problem structuring of the proposed model development framework (moving from *Phase 2* to *Phase 3*, circled on Figure 56).

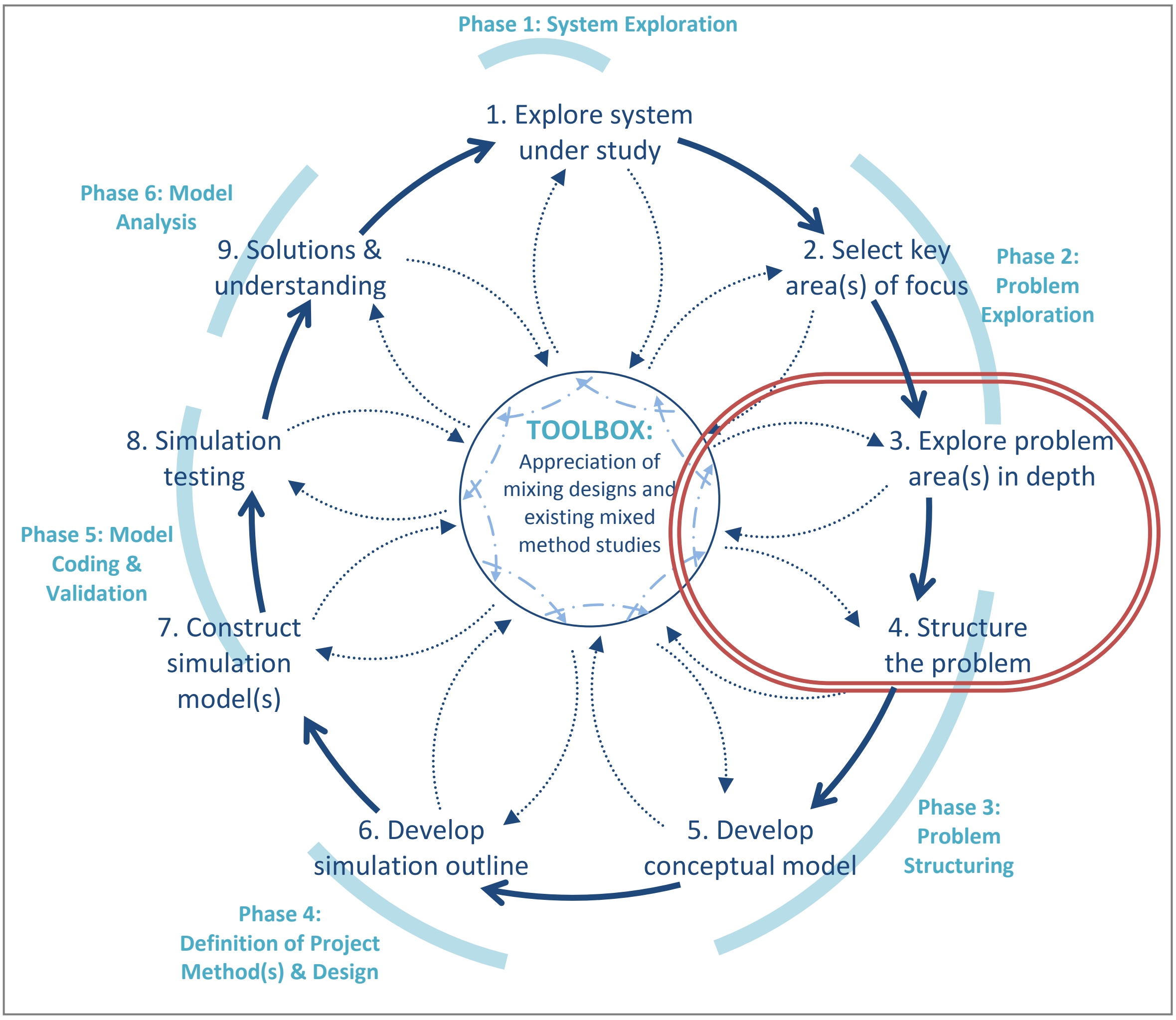


Figure 56: The proposed model development framework – transition between phase 2 and phase 3 circled.

6.6.1 Introduction

Many issues were raised during the mapping stages. Looking in depth at these problem themes the modeller considered the suitability of OR methods to them. The examination of the merged map and problem themes for suitable modelling methods ensured the selection of a project relevant to the objectives of the research, and the mapping ensured the problem was a real issue relevant to all stakeholders. This allowed the suitability of DES and SD to address the range of issues throughout the system to be examined. This was done to highlight the diverse nature of the problems and the broad scope within the system, whilst also demonstrating the clear applicability of SD and DES to the system, and this particular issue.

As discussed in the previous chapter, the possibility of using DES and SD in the project had to influence the selection of the problem. Both methods have been successfully used to model healthcare systems, in particular, with SD to explore the impact of technology adoption (such as described by Sterman 2000) and both methods used to model patient flows within hospital units (DES: Coelli et al. 2007, SD: Lane and Husemann 2008, Proctor et al. 2007, Proudlove, Black and Fletcher 2007, Wolstenholme 1999a).

The problem which will be explored within this project is the introduction of new treatment regimes and the impact such changes have on the centre. This theme was selected due to its centrality within the maps, its pertinence and popularity with all those interviewed and the far reaching links to other themes and issues: the ripple effect to the rest of the system. This issue embodies the balance between efficiency and efficacy.

6.6.2 Problem structuring

The introduction of new treatment regimes due to technological and theoretical developments within the medical physics field have benefits but also present challenges for the Beatson. The centre strives to be at the forefront of research and innovation, to provide the highest level of care for their patients (www.beatson.scot.nhs.uk). However, this is balanced by a responsibility to ensure timely, equitable and consistent care is provided across all patients accessing treatment.

When considering how DES and SD might be used to model the system, the researcher’s experience using both modelling methods, training and understanding from the literature partly guides this decision. However, reflecting on the range of mixed methods in the literature and theoretical designs, as presented in chapter 4, it is possible to expand this view.

Having selected the theme of treatment complexity due to its relevance to stakeholders and suitability to be addressed using SD and DES, this section presents the problem structuring undertaken to explore the problem in depth. The specific questions raised during the interviews in relation to the problem are evaluated. These are used to reaffirm the suitability of SD and DES, and consider the mixed method design: how and when the two methods will be used in the project.

6.6.3 Defining the problem

By returning to the merged map and focusing on the treatment complexity theme it was possible to develop a causal map focusing on the implications of changing treatment regimes and its relationship to some of the key values of the Beatson: equality and excellence. The causal map of the project problem theme is shown in Figure 57 and highlights the interrelationships at work alongside the aspirations of those staff spoken to.

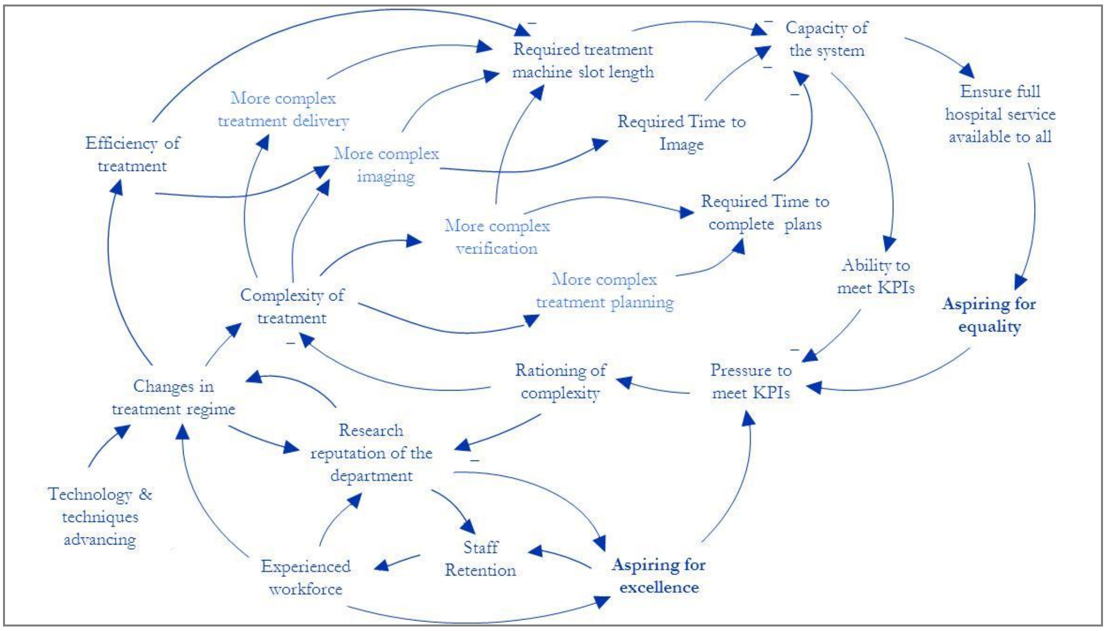


Figure 57: Structuring the Problem – Causal map of "Changing Treatment Regimes"

As technology and research within the radiotherapy cancer treatment field progresses, new modes and regimes of treatment become available for the Beatson to consider including within cancer treatment regimes the centre provides. However, new treatment regimes may improve efficiency (and reduce the time required on a treatment machine for a single dose), or may be more complex and thus require additional planning and treatment time. These changes alleviate pressure on one area of the system (such as at the linear accelerators), but can have a high cost on other areas of the system (such as imaging, planning and verification). Ultimately, these changes impact the capacity of the system and require a balance to be struck between the amount of service that can be provided and the desire within the centre to keep in pace with radiotherapy research and development. The decision to implement new treatment regimes is influenced by a desire to maintain a high standard of care by providing innovative treatment, a desire to retain an experienced workforce aspiring for excellence, but balanced by the need to ensure timely and equitable treatment for all patients.

6.6.4 Examining questions within the problem theme

Although this work is explicitly exploring the mixed use of DES and SD, at this point in the project the range of methods which may be suited to the project are reassessed. It would be naïve to assume that only DES and SD are suitable methods, but it is necessary to ensure the appropriateness of the questions to be answered within the constraints of this research. It is not that mixed DES and SD fits all situations, but rather that a problem that specifically lends itself to both methods is selected.

When undertaking mixed methods, Mingers and Brocklesby (1997) propose consideration of what, how and why: 'what' refers to the methodological stages of a project, 'how' refers to the methods used, and the 'why' refers to the grounds for the methods and the stages. Returning to the interview transcriptions it was possible to extract the questions posed around the treatment complexity theme. This enables clarification of the methods: DES and SD. Assessing these questions also enables the modeller to begin to consider *what* will be done (the mixed method design) and why it is necessary or preferable (the system view and dominance of methods), which are discussed in the next section (6.7).

Analysis of these questions was conducted to confirm the themes of the problems and to consider the methods that may be appropriate to address these concerns. This process enabled the demonstration of the diverse nature of the questions being put forward and the broad range of approaches that might be applicable within the context as other methods (aside from DES and SD) may be more suited. It is necessary to look at the questions to ensure that realistic outcomes and insight are intended to be provided given the methods employed.

The questions sought to be addressed by this project are:

- *What is the current status of the system?* – Where do bottlenecks occur within the system?
- *What resources are needed to implement new treatment regimes?*
- *What is the knock on impact of changing treatment regimes on waiting times?* – What is the impact of changing the mix of treatment regimes?
- *What can realistically be implemented?* – How can we implement new techniques?
- *How are changes in treatment regime affecting us?* – When is the system unable to cope?

- *What would be the impact of a policy change regarding treatment regimes (such as a move to standard plans)?*
- *How are patients impacted by the availability of regimes?*

These questions fall into two broad categories: what happens within the system when new treatment regimes become available, and how does it influence the experience of patients? There is a need to explore the system at a strategic level, namely the decision processes and resulting system behaviour, and at an operational level the impact on the day to day running of the system. Specifically, both DES and SD are needed to address this problem as SD would allow the modeller to explore the dynamics of government targets interacting with the Research and Development reputation of the Beatson and the learning processes involved in changing treatment regimes, and DES can be used to assess the day to day impact of making changes and what resourcing implications such changes will have. Both SD and DES have explicit roles to play within this project, with their purposes tightly coupled and overlap in the view of the system.

6.6.5 Summary

This section has structured the problem that is the focus of this project. A causal map developed from the merged map illustrates the relationships within the problem theme and illustrates the potential to use SD to represent this wider system view. The questions raised by interview participants are summarised and further highlight the suitability of DES and SD to this problem. The following section presents the initial mixed method design, system view and method dominance that will be used within the project, based on the understanding of the problem system developed so far.

6.7 Conceptual Modelling: Mixed Method Design (1)

The previous section described the problem focus for this project and the suitability of the methods. This section considers how the methods might and will be used. This phase of the project explicitly reflects on the mixed method designs developed in chapter 4 to consider how the methods could be used together in the project. The intention of this section it to discuss and consider, given the problem at hand, what methods to use at what stages of the modelling project and how to utlise the methods. Figure 58 shows the current phase of the proposed model development framework highlighted. This section discusses the link in the framework to the mixed method toolbox to consider a suitable mixed method design for the project

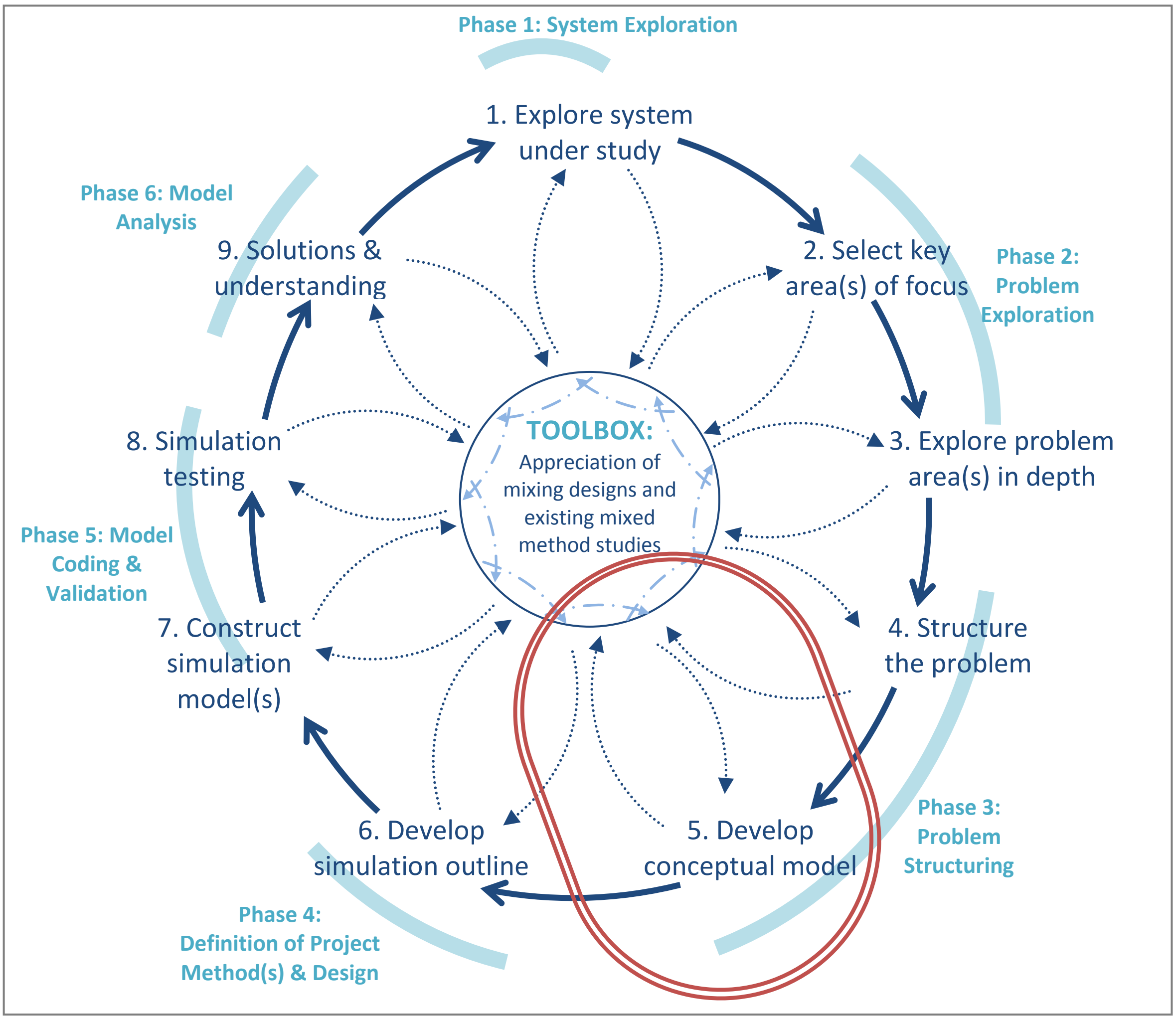


Figure 58: The proposed model development framework – conceptual modelling stage circled

As discussed previously in this document, exploration of the problem and the system led us to focus on the impact of implementing new, more complex treatment regimes on the ability of the Beatson to maintain throughput and waiting times. Within the problem structuring stages it became apparent that both SD and DES modelling could add value to the client and address the problem themes raised. However, it was not obvious if these two models could or should function independently or if it was necessary or desirable for them to interact.

6.7.1 Justification of methods

This problem theme, as discussed in *Section 6.5*, was selected following exploration of the methods which may be used to address the problem themes identified in the merged map (see also Appendix 10.11). Explicit consideration of the questions posed in relation to the project further confirmed the applicability of DES and SD to this problem theme.

Although the methods may be used in various ways on this project, discussions with the client following problem selection emphasised the desire to model the problem at a strategic and operational level. It appeared that both DES and SD could provide insight into the system, with the broader (strategic) questions suited to the SD method (discussed in *Chapter 2* when comparing classic views of DES and SD). DES is a viable modelling method for this issue, but SD is more commonly applied to this situation, with more literature and supporting case studies. The understanding of the situation developed during the problem structuring stage highlighted the apparent feedback processes (illustrated in Figure 57), which could be explored using SD.

Given the nature of the issue being modelled, the project appeared to lend itself to a SD model representing the systemic changes, and a DES model capturing the core patient flow through to treatment in order to capture the stochastic nature of this element of the problem. The variability in time to reach treatment between patients is of interest, but the variability between technology adoptions was not discussed in the interviews (the focus was on the overall impact of new treatment regimes). Each new treatment regime is different due to newly available technology or research but the aim of the project, identified from the merged map, is to explore the impact of implementing such new regimes, giving a flavour of the impact, rather than prescribing the intricacies of each regime. Therefore, stochastic characteristics are a key requirement when modelling the flow of patients, but stakeholders are interested in the dynamics (knock on impact overall) of changing treatment regimes and the feedback processes influencing decisions (the strategic level of the problem). This implies the need for two methods to be used. This could be achieved by two independent models or the integration of two methods into a single model, or characteristics of one method used to enhance another.

6.7.2 System view & method dominance

Starting with a broad scope but limited detail provides the modeller with the opportunity to create simple models to capture some of the core dynamics within the system. The view of the system that each method would be required to take, the scope of each method, is illustrated in Figure 59 with SD taking a broad all encompassing, but less detailed, view of the system, and DES focusing on a single aspect of the system: the radiotherapy treatment process.

At this point in a project it is too early to decide how dominant either method will be so the modeller embarked upon the project considering each method equally (see Figure 60). No preference is given to either method and they are expected to have equal roles within the project so value from either method is not overlooked.

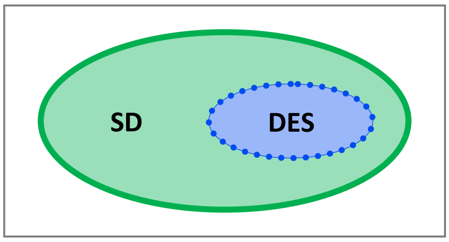


Figure 59: View of the System (Mixed method design 1)

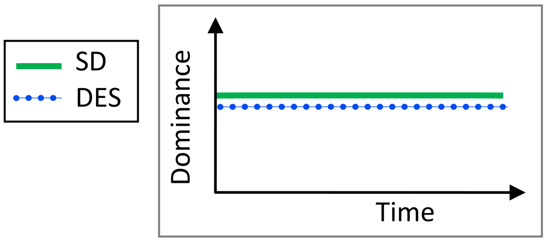


Figure 60: Dominance of Methods (Mixed method design 1)

6.7.3 Selecting a mixed method design

The suitability of each mixed method design is examined in turn by considering how each could be applied to the project and comparing them in turn.

Isolationism: The first option is that only a single method is utilised. This design would allow the modeller to remain within a single methodology and philosophy and present a single model to the client. However, as is discussed above and in the previous chapter, both SD and DES have been identified as potentially having useful roles within the project. Undertaking the project only using a single method, without enrichment from SD, would require questions and issues to be discarded and/or the scope to be restricted.

Sequential: If applying this mixed method design to the project a SD model might be developed first to enable exploration of the drivers of changing treatment regimes, followed by the use of a DES model to explore the impact of new regimes on patient treatment times, in a similar manner to Brailsford and Hilton (2001). Using this design would result in the development of two models with the SD model highlighting the dynamics of new regimes, and this insight could be transferred into the DES, influencing their implementation. This would enable the modeller to examine the two models independently, whilst also transferring insight from the first (SD) in to the second (DES).

Parallel: With this design, both methods would be undertaken independently to provide insight into the problem, which would imply that the order in which the models are developed is not important. This design involves no transfer of insight between the models (only reflective insight post the modelling process). This design implies that either method may be undertaken first; there is no preference. The outputs of each model can be independent, the modelling methodologies for each method can be readily adhered to and the resulting models will be manageable. However, this design allows for no transfer of insight over the course of the project, only at the end and may lead to oversight. As only a single modeller is available for this project, this design would not be adhered to strictly – the models would be developed in sequence and it is unavoidable that what is learnt from the first model would influence the development of the second. The goal of this project is not to compare two views of the system, but to create complementary insights with each method addressing different questions and so a design that encourages transfer insight and/or data between methods may be more suitable.

Enrichment: The enrichment of SD with elements of DES is proposed as a suitable form of this mixed method design, over the enrichment of DES with SD due to the boundary of the system more clearly lending itself to SD. This is because the complex broader system with non-linear and uncertain relationships, feedback, judgemental data and informational flows (illustrated by the influence diagram: Figure 57) lends itself to the SD method. The aspects highlighted for exploration using DES are restricted to those within the Beatson building, the operational process flows. These aspects are commonly modelled (both in the literature and in practice) using DES to allow the representation of individual patients, resources and machines, and probabilistic interactions influencing the performance of a system. This mixed method design would enable the modeller to capture important stochastic patient behaviours within the overall representation of new technology adoption. This design would result in a single model, but there is the danger it would become an over-complex model or fail to capture the detail required due to the complex operational processes within the Beatson.

Interaction: The above discussion of a sequential design highlighted the potential benefit of transfer of insight between the two methods. This design commences as two separate models that can be joined later in the project and so the decision to revert to this design can be made at a later stage in the project if it is deemed suitable and advantageous. The influence diagram of the problem theme (illustrated in Figure 57) demonstrates potential benefit of the explicit exchange of insight between the models, as there is feedback between policy decision to implement new treatment regimes and the operational impact on patient treatment times. This design may reduce the workload on the modeller by reducing overlap between the models but this is offset by the effort required to align the views of the system and model content to ensure transfer of insight and data between the models.

Integration: If the problem theme formed an indistinguishable whole, where the elements which displayed characteristics of each method could not be separated into a manageable number of groups then this mixed method design would be a suitable way forward. Within this project, however, all the questions posed are related and interlinked but it is possible to separate them into two groups: one for each method. For this reason it may be possible to maintain some distinctions between the two methods and form two models containing different features and details of the system (the *Interaction* design described above). An *Integration* design may commit the modeller to a complex integrated model early on so was not selected as a starting design – but it may be that it is returned to later.

Each of these mixed method designs may use a variety of system views, but this project describes problems that would benefit from SD taking a broader view and DES capturing the detailed patient flows. Additionally, the dominance of methods alters depending on the mixed method design undertaken and is uncertain at this point in the project.

6.7.4 Summary

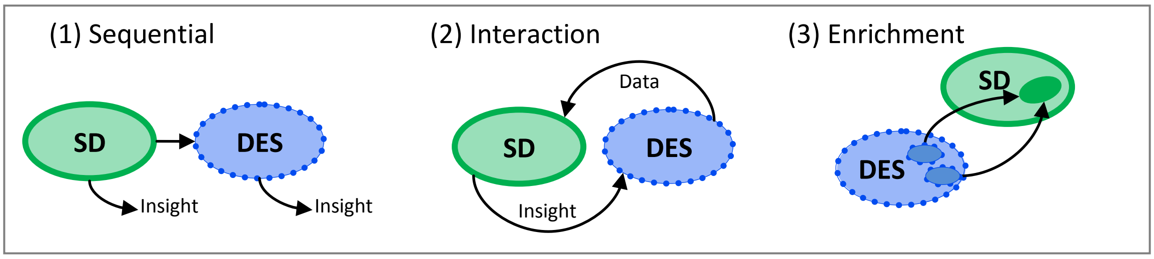


Figure 61: Several viable mixed method designs (Mixed method design 1)

At this point in the project the most appropriate mixed method design is unclear, and three designs have been identified as suitable for the project (illustrated in Figure 61). *Sequential* and *Interaction* require the production of two models. In a *Sequential* mixed method design the models can be completely independent (but will likely pass insight from the SD to the DES). In an *Interaction* design, the two models need to be developed with the view to passing information or insight between them. As such they need to be complementary or supportive of each other. The final option under consideration, *Enrichment*, would produce a single model that adopts some beneficial features from SD.

Through using the designs it has been possible to explicitly consider the various options of how the problem could be modelled and what implications these options have on the outputs of the model, the insight it would be able to provide, and the modeller's workload. On the face of it the *Enrichment* mixed method design would be a time efficient design as it involves the development of a single model to test and analyse. However, the inclusion of characteristics of an additional method would lead to a large number of system elements to be included which is likely to be a time consuming task and conceptually complex. The problem is not sufficiently understood to know which method should be enhanced with the other.

For this project, *a Sequential* mixed method design is selected because it is one of the simplest forms of mixing and encourages the modeller to remain within the paradigms of each modelling method. It does require the development of two individual models, which can be time consuming, but the design does not require the modeller to alternate between methods which can be challenging for the modeller to move between paradigms. This design allows the problem to be explored from the theoretical perspective of each method whilst the overall model development process encourages the modeller to consider alternative methods and the possibility of mixing. As further understanding of the system is developed then it is possible that *Interaction* and *Enrichment* may be used but at this stage it is unclear.

Although a *Sequential* mixed method design implies that order is important, at this early stage in the project it is believed that the process embarked upon and the results obtained would be the same irrespective of the order in which the models were developed; SD then DES or DES then SD. At the current stage of understanding of the project the modeller has sufficient information to begin to develop either model and SD is selected as the client is unable to visualise this method, but is supportive of DES. However, this project was undertaken by a lone modeller and so a *parallel* design was not practically possible. It was necessary to choose which method to begin with, and the design is referred to as *Sequential (order unimportant)*. The structure and level of detail of the causal map of the problem in focus presented similarly to an influence diagram. Additionally, the structure of the planned DES model could be conceptualised by stakeholders, but several were unconvinced regarding the use of SD. It was decided that SD was the first method used to encourage engagement with the method. The stakeholders were already engaged with the idea of a DES and so if this modelling was undertaken it was worried they may only want to focus on the aspects of the problem theme planned to be explored using DES. The SD model was also thought to be able to provide value to the development of the DES through representation of the drivers to changing treatment complexity. Although the first model to be developed will be using SD, it may or may not be the dominant method for this project.

6.8 Chapter Summary

This chapter has presented two phases of the modelling process: system exploration and selection of a problem area that fulfils the requirements of the research alongside the client's requirements. The chapter has discussed the initial system exploration stage and how the resulting problem themes might be addressed using mixed methods by reflecting on the toolbox of designs at the heart of the modelling framework. Problem themes from the mapping, possible projects and how these projects might be modelled using SD and DES have been discussed.

The problem area selected is the issues relating to changing treatment regimes as a result of new research in the radiotherapy field. Both SD and DES could be used to address both sets of questions posed. How the methods could be used within the project has been discussed.

Chapters 7 & 8 present the simulation development stages of the modelling process from the modeller and researcher perspectives respectively. Chapter 7 presents the simulation development from the modeller perspective to the client of the project. It focuses on the models developed, analysis conducted and insight garnered. Chapter 8 reflects for, in and on the process with regard to the researcher role within the project to outline the additional considerations made in order to fulfil the research requirement of the project.

7 Beatson Project - Modeller Perspective

This chapter discusses the modelling project which was undertaken to explore the issues relating to changing treatment complexity within the Beatson. This chapter presents the models developed throughout the project from the modeller perspective. The focus of the modeller perspective is to produce insightful, relevant models that meet the client's requirements for the project. Therefore the model development process undertaken and the models produced to address the questions posed are described.

The models developed are presented alongside the role they played in answering the questions posed by stakeholders in relation to the changing treatment complexity problem theme. This is followed by discussion of the data available about the system and the validation process undertaken, although these both took place alongside the model development iterations to ensure that appropriate, useful and valid information was included and generated. The model analysis and outputs generated are presented and the chapter concludes with discussion of the impact of the models and the modelling process on stakeholders' views of the system and what benefit the mixing of methods has offered.

7.1 Introduction

The models were developed in a stepwise cyclical process, forming three stages of model development which will be discussed (illustrated in Figure 62). This diagram is structured to represent the spiralling process with each model iteration of each method being a development of the previous rather than a completely new model.

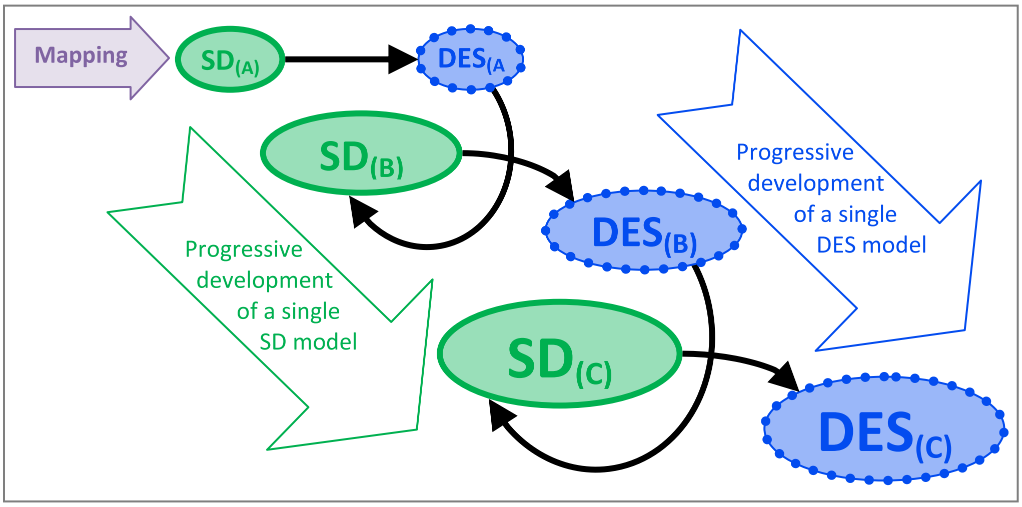


Figure 62: Cyclical modelling process undertaken in the Beatson project

The three model development cycles progressed by reflecting on the value and relevance of the models and the mixed method design prior to each cycle. The process is represented as a spiral as new models were not created from scratch after each cycle; after each iteration the value of the models and the mixed method design selected were considered and adjustments were made to the SD and DES models. The next three sections describe these model iterations detailing the progression of both models, the insights garnered at each stage and the reason for the next iteration. Each cycle covers the three stages of the model development process with reflection on the toolbox highlighted in Figure 63.

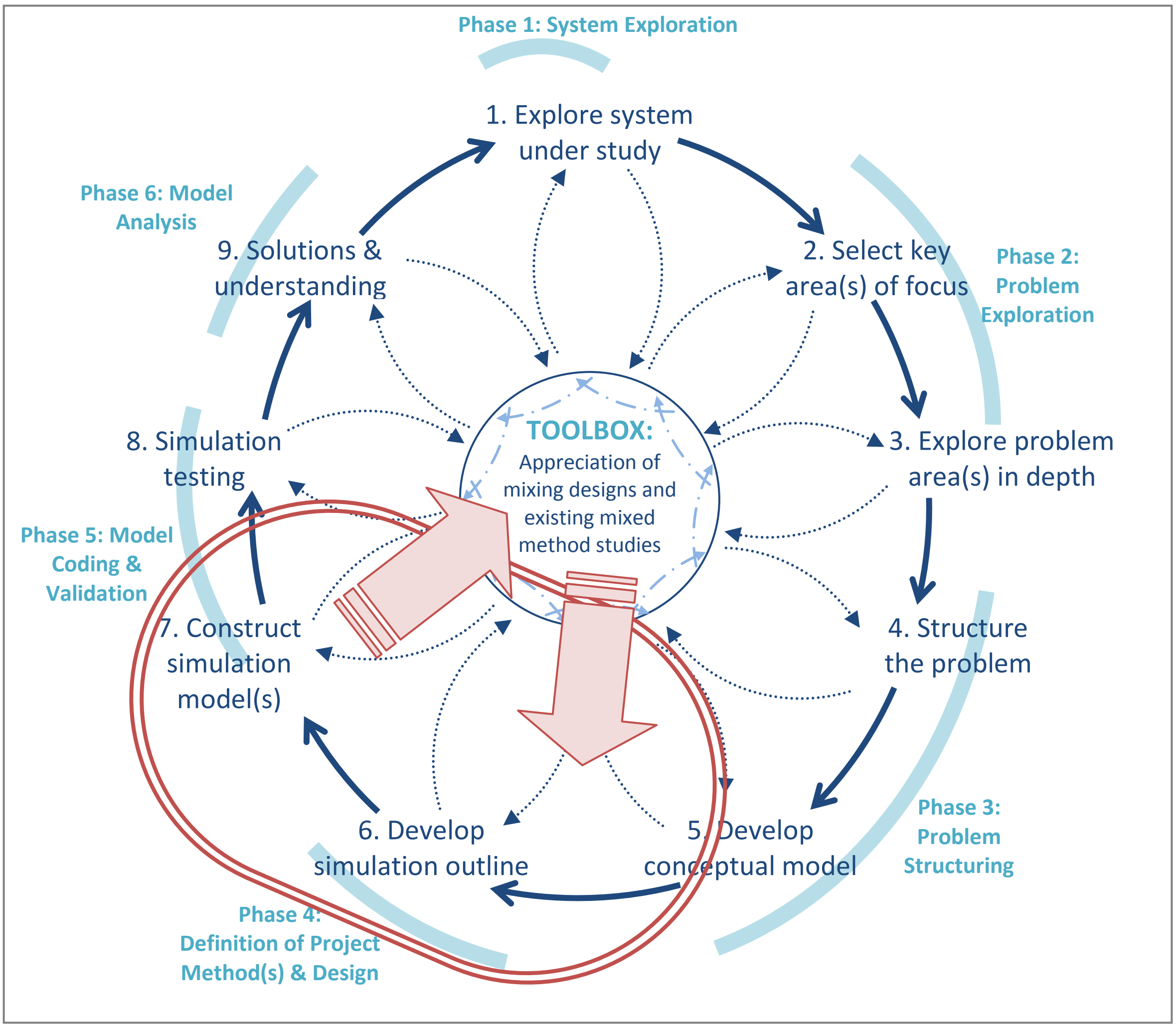


Figure 63: Stages of the Modelling Framework described in sections 7.2 - 7.4

7.2 Modelling (1): Preliminary Models

This section will discuss the development of the conceptual models and the first phase of modelling. The section concludes with reflections on the value of the models and mixed method design of the project.

7.2.1 Introduction

As discussed in the previous chapter the mixed method design of the project was *sequential*, with the SD model created informing the development of the DES model. SD was selected to be the first method used on the project as a higher level of acceptance of the DES method emerged during interviews with stakeholders and the value of SD needed to be demonstrated early in the project to ensure buy-in of both methods was achieved. The two models created in this iteration each represent key aspects of the system and capture two key relationships of interest: the impact of changing treatments, modelled using DES; and the likely reaction to manage this impact, modelled using SD.

7.2.2 SD (model A)

The first SD model created focused on representing a single feedback loop in the system: how the system adjusts its adoption of new technology if they are not meeting government waiting time targets. The dynamics of innovation and technology have been modelled in the SD literature (such as Morecroft 2007, p.165) and these examples were used in conjunction with the merged map to inform the understanding of the behaviour within the Beatson. The merged map of the system revealed the relationship between the need for the system to efficiently deliver treatments in a timely manner and the desire to provide state of the art care. This creates a picture of the key measures of interest and points of concern within the Beatson[36].

The preliminary development of the SD model is a simple representation of the main feedback loop which forms the decision making process to introduce new treatment regimes (illustrated in Figure 64). This initial model focuses on the belief that new treatment regimes will increase the workload on the system and reduce the overall capacity resulting in increased times to treatment. The Beatson ultimately have to provide a timely service for all patients. If the time for patients to reach treatment do not meet the required targets then it is necessary to reduce or retract the implementation of new (more complex) treatment regimes.

[36] SD model A began life as the sample model given to stakeholders at the follow-up interviews as an illustration of SD modelling within the context of their system.

As a result the model emphasises the need to manage the time to treatment to ensure it remains within appropriate levels by limiting the inclusion of new regimes.

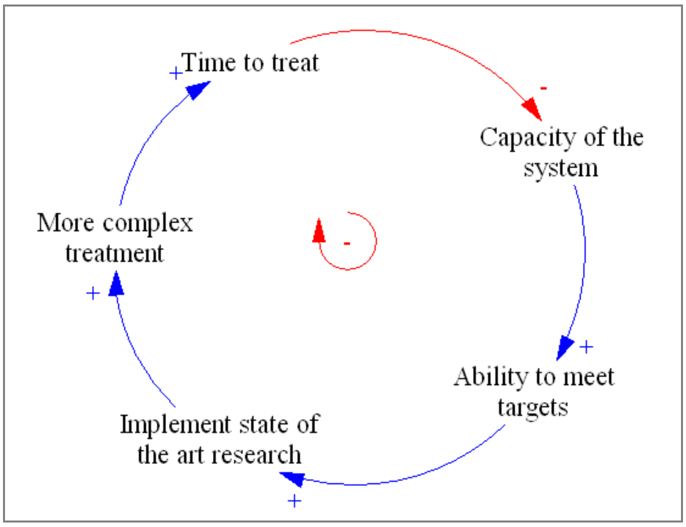


Figure 64: Simplified main feedback loop of the Beatson modelling project

Within an SD modelling process, conceptual modelling often involves the development of the dynamic hypothesis and reference mode. As discussed in *Chapter 2* the reference mode and dynamic hypothesis are representations of what will be explored over time, and what is suspected to be happening to influence this. When considering this it is necessary to consider the time horizon to include sufficient past and future behaviour to represent delayed effects. The reference mode asks for the modeller to consider what we want to explore over time (Meadows 1980).

In this project the reference mode is described as the changing time for patients to reach treatment given the changes to time required to complete the treatment process as a result of more complex treatment regimes. Within the Beatson the number of complex plans being completed by radiotherapy physics is perceived to be on the increase, thus effecting the time a patient takes to complete the treatment process by increasing the workload on physics staff. However, data that captures this is unclear as the complexity rating of plans is subjectively assigned by staff, and may reflect how their perception of a difficult plan changes as they become more familiar with a new treatment regime (discussed in section 7.5.1: Data analysis). This is represented as a graph over time in Figure 65, and although the exact shape of the graph is largely unknown stakeholders believe it is increasing. The dynamic hypothesis of this project, the hypothesis for the underlying mechanisms behind this reference mode, is that capacity is impacted by the adoption of complexity. Additionally, the merged map of interviews and the causal map specific to this problem theme illustrate the dynamic hypothesis of the project (Figure 45 and Figure 57, *Chapter 6*).

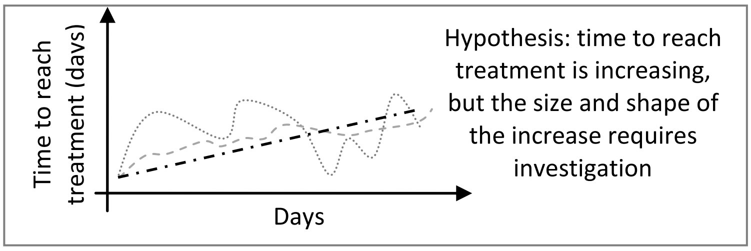


Figure 65: SD model reference mode (the shape of which is unknown, but three possibilities are shown)

The model is based around one goal seeking loop, shown as an influence diagram in Figure 66. The goal seeking behaviour of the model is to meet targets set for waiting time, whilst trying to introduce new treatment regimes (represented here by an increase in treatment time). The desired state of the system is labelled *Government target*, and the discrepancy (*wait index*) results in corrective action (*change in treatment time*) which improves the state of the system (*waiting list*). This model captures a year to allow for multiple monthly reports on system performance. From the healthcare modelling literature, this is similar to SD models where the time units are days of a year, and in contrast to DES models which capture model at the detail of minutes within a working week. The model includes a delay between the waiting times experienced by patients and the systems response to excessive waiting. This results in oscillation due to the delayed effect of responding to status updates of the system.

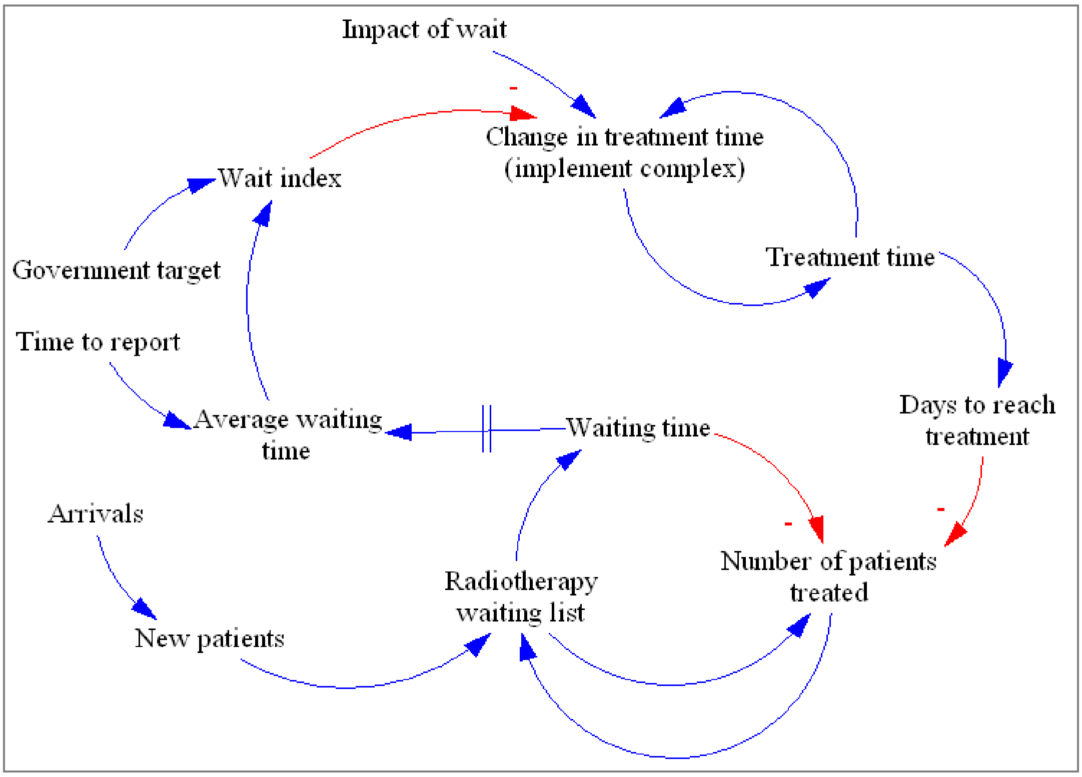


Figure 66: Influence Diagram (SD model A)

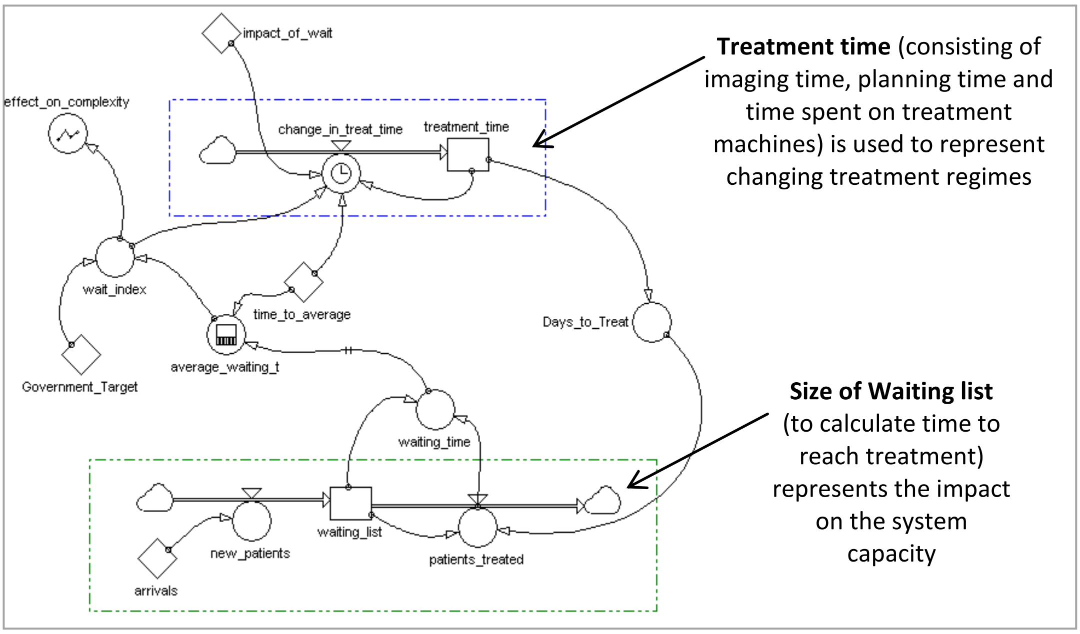


Figure 67: Stock & Flow Diagram (SD model A)

This model is shown in Figure 67 and illustrates the goal seeking behaviour of the system. The complexity of treatment on offer alters in response to monthly reported waiting times to ensure time to reach treatment meets the government targets subject to the demand. The model illustrates the impact of reacting to the waiting times experienced by patients on the decision to adopt more complex treatment regimes, which will in turn influence the time required to complete treatment (Figure 68, left and right images respectively). This first model seeks to capture the relationship of reactiveness: the cancer units' tendency to react to key performance measures (in this case patient waiting time). If the waits experienced are high then the unit will endeavour to reduce the time spent treating to fit with the government targets by reducing the range of complex treatment regimes (such as standardising patient treatment plans). This is achieved by reducing the range and/or complexity of treatments offered within the unit. The reporting of waiting times is however subject to delays: reporting average performance per month. This delay leads to a dampening effect on the system, where the effect of additional complex regimes or the decision to simplify regimes is not observable for 30 days.

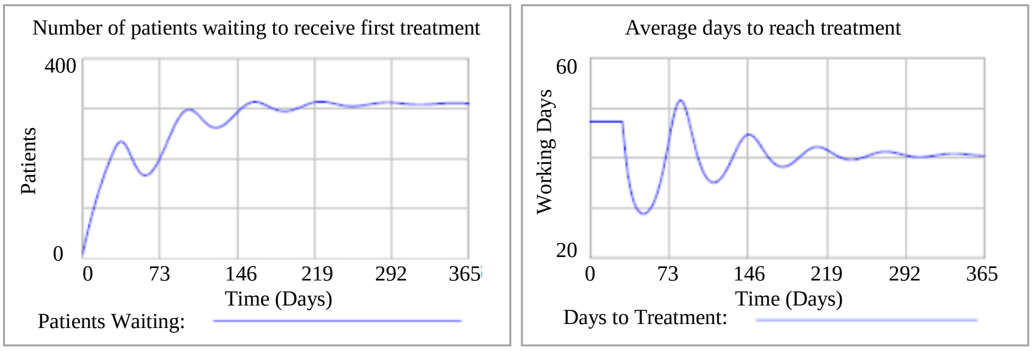


Figure 68: Graphical Outputs – Number of patients waiting for treatment and Treatment Time (SD Model A)

The model isolates the introduction of new treatment regimes to practices within the Beatson, so that the model represents the adjustment of the mix of treatment regimes (from simple plans to complex regimes). It illustrates an issue discussed by all of the stakeholders interviewed: that the targets are met by balancing the system. It represents the necessary behaviour required to achieve the 31 day time to treatment target: that if standardised or simple plans were used then the system has more capacity to treat patients and targets can be met. However, this is an oversimplification of the system that does not provide the whole story. In reality implementing standardised plans or only providing the simplest treatment regime have longer term implications on the functioning of the unit, such as the research reputation, which need to be further explored.

The SD model developed raised further questions about the functioning of the system. The impact of changing treatment regimes on the day to day functioning of the planning and treatment process is uncertain. The model failed to tell the whole story so further insight was required into the practicalities of adjusting the mix of treatment regimes and the appropriateness of the estimated effects on time to reach first treatment within the SD model.

The DES model was developed to provide a different view on the issues within the system, with the aim of providing a complementary perspective.

7.2.3 DES (model A)

The two core values of the Beatson which emerged from the merged map of the system were equality and excellence. The above described SD model illustrated that improvements in research excellence (through inclusion of more complex treatment regimes) could require a reduction in the system performance (time for patients to reach treatment). In order to address the objectives of this project, DES is used to examine the impact of changing treatment regimes on time to reach treatment, and illustrate the impact on equity of treatment.

The conceptual model for the preliminary DES model was informed by the simple five stage radiotherapy process. This process was identified from the merged map and) with the inclusion of the Pre-treatment checks (for quality assurance) which was highlighted in the interviews with stakeholders. This model seeks to represent the radiotherapy planning and treatment process in a simple, aggregated representation of the system with resources at each stage of the process allocated identical parameters with average characteristics. This model represents the flow of patients through the process subject to the various resource constraints. The model contains the five key parts of the radiotherapy planning and treatment process of the Beatson. The model is shown in Figure 69 and an overview of the specification is provided in Table 16.

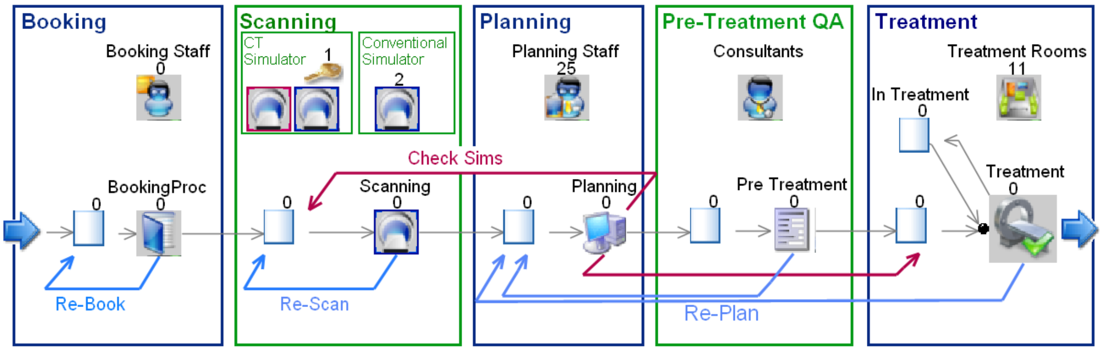


Figure 69: DES model A – the core Beatson processes

Table 16: DES (model A) summary of characteristics

Model Detail		Specification
Model entities		Individual patients
Arrivals		Negative exponential inter-arrivals with uniform patient characteristics
Servers	*Booking*	Servers restricted by the staff available. A portion of patients require rebooking.
	Scanning	Patients may use the CT simulator or one of the Conventional simulators. Re-scanning of patients is needed in some cases to represent no-shows and genuine re-scans.
	Planning	Waiting time at planning stems from the fixed number of planning staff available to complete plans. A portion of patients require more than one plan or for a plan to be re-done.
	Pre treatment	Only a small portion of patients currently undertake QA as this is related to IMRT uptake. Consultants are required to be present for the duration of the QA appointment.
	Treatment	11 possible treatment rooms, with patients requiring a series of treatment fractions each with a day in-between.
Time frame		The simulation runs for 58 weeks consisting of 6 weeks warm-up to populate the model with patients and 52 weeks of results collection.

Each stage of the process is represented by a queue and a single server. It is not broken down into individual tasks; the total time to complete each stage is modelled. This model allows the exploration of how patients progress through the system and provides a sufficiently detailed view of the system to facilitate data extraction and analysis from the IT systems. The model explicitly demonstrates the re-booking, re-scanning, checking and re-planning of patients and how the system behaves should the time taken to complete these stages alter. Staff and machine constraints are included in the model but not the individual characteristics of each phase and/or resource.

Populating the model with data from the Beatson IT systems highlighted the aggregated nature of the model and that individual characteristics would be needed in order to investigate the impact of changing treatment regimes as new regimes would affect sub-groups of patients (such as by intent or cancer type). Experimenting with this model highlighted that the system is running close to capacity, and that changes to the system require careful consideration of any knock-on impact. The scanning and planning stages experience bottlenecks given the resource constraints assigned. However, the availability of consultants does not fully capture the constraints of the system (as the consultant/patient pathways stipulate individual consultant availability for specific stages of the process). Therefore this model will be adjusted to be able to represent the detail necessary to answer the project questions.

The aim of this project is to examine the knock on impact of changes to treatment regime across the whole of the treatment process. Although this model captures the broad system, different treatment regimes can only be represented by adjusting the time spent within the scanning, planning, pre-treatment and treatment phases. This would be an underrepresentation of the complexity of the planning processes involved and fail to provide insight from the model at a practicable level of detail to the Beatson management team. This model needs to be extended to include further detail in the planning phase to represent the various pathways to treatment a patient may be allocated to and how the mix of these pathways affects the overall functioning of the system

7.2.4 Summary

The above section has presented the two initial models developed within the project. The SD model presents the goal seeking behaviour within the Beatson to meet government targets for the time it takes patients to reach their first treatment fraction. The model demonstrates the balance between implementing new, more complex treatment regimes which will increase the amount of time required by the Beatson prior to treatment, and the time patients will wait due to the demand placed on the unit. The DES model captures the key elements of the radiotherapy planning and treatment process. This model was used to illustrate for the client the main points of pressure within the system (simulation and planning), and facilitate the extraction of data for analysis from the IT systems.

These first models were created at a high level of abstraction to explore and structure the problem allowing the client to refine their project objectives. The key objectives of the project are what happens within the system when new treatment regimes become available, and how does it influence the experience of patients? The general impact can be explored using these models, but the extent of the impact of changing treatment regimes is not fully represented. These models were discussed with the client to determine the appropriateness of the issues captured and allow the modeller to determine performance indicators of the system. This discussion revealed the models to be insightful but not yet capturing sufficient elements of the system to answer the key questions posed during the problem structuring.

These models were created with a sequential mixed method design in mind, but the order in which they were developed was not originally seen to be important. However each model still fails to capture the system issues in sufficient detail and with sufficient scope to answer the client’s questions. The following section presents the next phase of modelling to refine the scope of the project, expand the view of the system captured by the SD model and add further information into the DES model. The SD model (A) was not yet telling the whole story but because it captures a wider view of the system than the DES (A), the understanding developed in this model was likely to be transferable to the DES. The next step in the modelling project was to return to the SD model to make adjustments which in turn inform the development of the DES.

7.3 Modelling (2): Refining Scope and Relevance

This section discusses the second phase of model building which expanded the SD model to the required boundary of the system and populated the DES model with data gathered from the Beatson. The mixed method design is reflected upon and altered, and the models are adjusted given the feedback from the client and objectives of the project not yet being addressed. As with the first phase of model development, the toolbox of designs is used to re-evaluate the role of each of the two methods being used within the project

7.3.1 Adjusted Mixed method design (2)

Initially the modeller felt that two independent models could be developed sequentially for this project. The aim of the SD model was to capture the overall behaviour of the system and the aim of the DES was to capture the core elements of the radiotherapy treatment process. The models were developed in order so that the SD could inform the DES. However, the broad view of the DES failed to capture the detail needed to aid decisions relating to changing treatment regimes and the SD model did not capture all of the dynamics around changing treatment regimes. This meant that changes to the models were needed with the SD model expanded to capture more system dynamics endogenously, and the DES was given further detail. The modeller perceived the DES to now occupy a larger portion of the view of the system, illustrated in Figure 70, such that the DES captured a larger portion of the system already represented in the SD: a reduction in the difference between the system views of the two models than originally thought (in Mixed method design (1)).

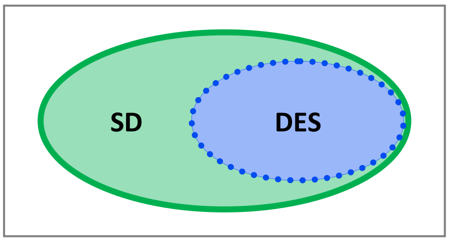


Figure 70: View of the System (2)

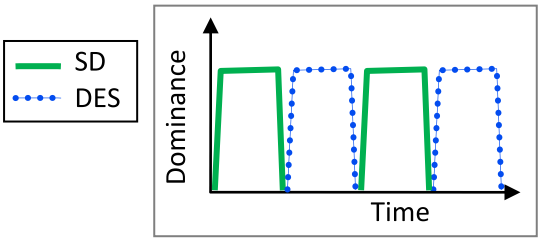


Figure 71: Dominance of Methods (2)

For this second iteration of modelling, the two methods are assigned equal dominance in the modelling project (with neither taking priority over the other). However, it was decided that a second iteration of model development was required, and insight has transferred from first iteration of modelling. The dominance of the methods in the modelling project remained equal (Figure 71) but the diagram now reflects the second iteration (see Figure 72).

The preliminary models were built sequentially but the modeller saw the need to return to the SD model to make adjustments which would inform the development of the DES. The methods are used in sequence with insight from the first models informing the second iteration of models. At this stage in the process it was becoming apparent that the models may benefit from interacting directly with one another; passing information from one to the other. This was because the view of the system used for the DES model is within the view of the system for the SD and it appeared feasible to adopt the *interaction* mixed method design. Alternatively, consideration was given to the *enrichment* design (placing the functionality of the DES within the SD) which is why the SD model was modified before the DES.

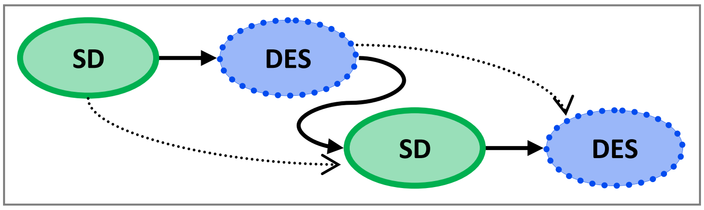


Figure 72: Mixed method design (2)

7.3.2 SD (model B)

The shortfall of the first iteration modelling was that the model did not yet capture the whole story of the dynamics of the system relating to changing treatment regimes. Discussions with the client and examination of the merged map informed second iteration of modelling. The objective was to capture complexity available versus that adopted, represent the impact of new regimes on the determinants of a patient's time to reach treatment, and the working hours of the centre to cope with changing complexity.

Changes made to the model were the inclusion of time in scanning (or simulation), planning, verification requirements, treatment time (on a treatment machine), treatment fractions (the number of visits per phase of treatment), and phases of treatment (the number of plans per patient which indicate the number of blocks of treatment received). It was at this point that consideration was given as to whether it was feasible and useful to change the design of the mix to be enrichment, whereby the system represented in DES model A is implemented in SD model B. Although, the level of detail already within the DES model is most suited to DES specialist software and so the models are kept separate, there is a clear relationship between the two models and the possibility to transfer data between the two.

The second modification to the SD model was the inclusion of a work hour's feedback loop. This loop represents the willingness of the Beatson staff to strive to achieve a prompt time to reach treatment by working longer hours, up to a point. It is a goal seeking loop, resulting in the working hours of staff fluctuating between their contracted hours and an upper limit[37] (illustrated in Figure 73). The result is that the system goal seeks to achieve government targets and strives to maintain the use of more complex treatment regimes by staff work extended hours regularly.

The inclusion of work hours allows the system to adjust the capacity of the system to meet demand. This represents staff within the Beatson striving to ensure a patient reaches treatment in a timely manner, and on occasions whereby the system is under pressure then this acts as a valve to help the system cope. The working hours are viewed as an output variable from the model as it provides an indication of the stress staff are likely to be under. Similarly, if the working hours are consistently above standard contractual hours of staff then it is necessary to reassess the policy of treatment regime adoption.

This model extends the view of the system and magnified the representation of the planning and treatment process from a single stock into 5 core components (scanning time, planning time, number of treatment fractions, time per treatment fraction and number of phases of treatment). This expansion of the model enables different size effects of more complex treatment regimes across the 5 components to be modelled which provides insight into where in the system the effect of new regimes is felt. These 5 stocks model the average time a patient takes to reach treatment using simple queueing theory equations, given the service times and demand. This simple representation enables the model to provide useful insights into the impact across the system as a whole, but doesn't fully capture the expected impact on the stages of the treatment process and led to the modeller returning to DES to generate improved approximations.

The alterations made to the model help to produce practicable model outputs which reflect tangible data used to book, scan, plan and treat patients. The model is grounded to the system it represents by breaking elements of the model down into those that are more easily understood in the context of the system; elements that stakeholders can readily identify with and see how they might change.

[37] Note that this does not represent a policy of the centre, only the willingness of staff to ensure that patients receive timely treatment by putting in extra hours when needed (i.e. a backlog of patients).

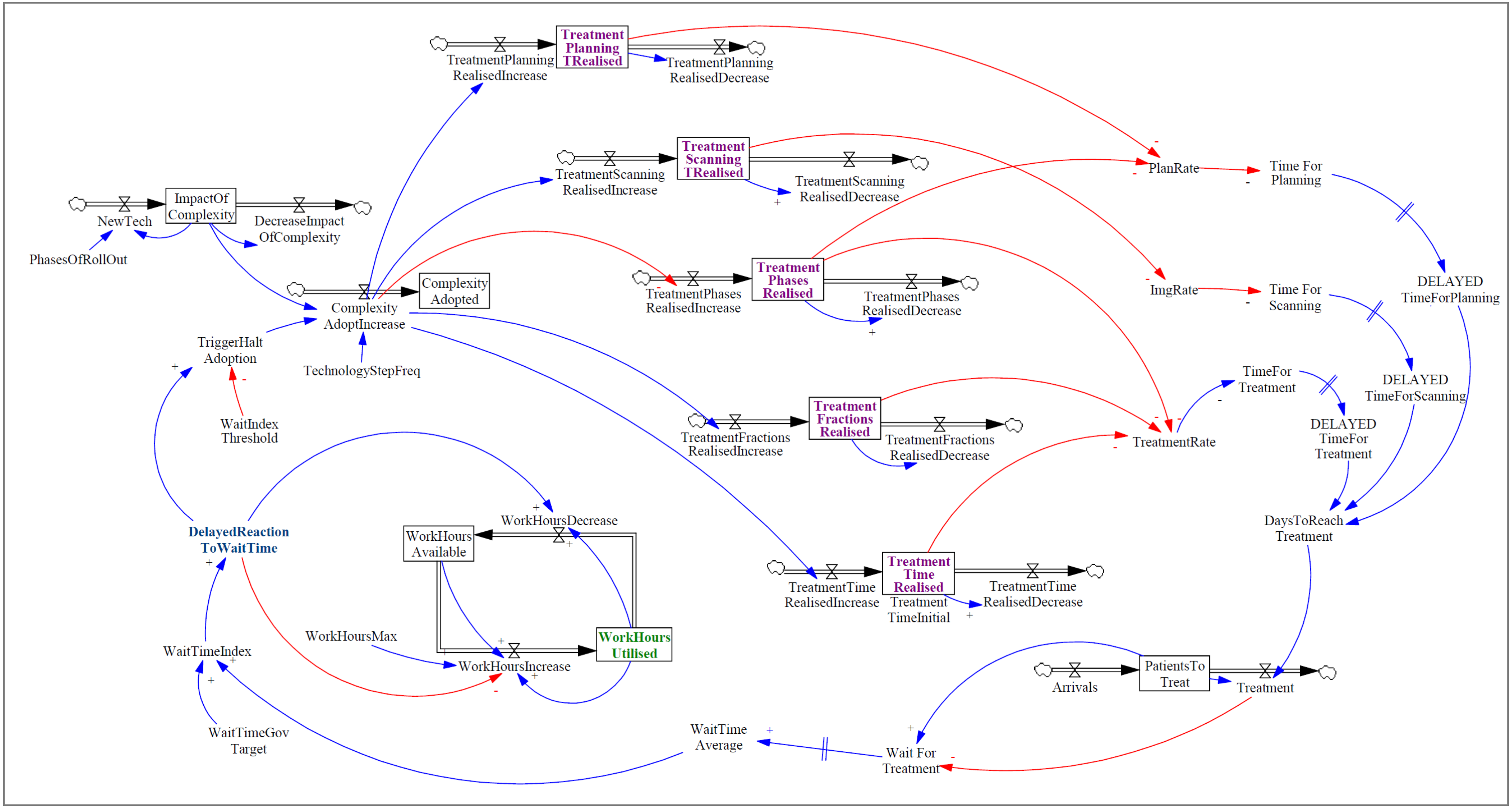


Figure 73: Stock and flow diagram of SD model B

7.3.3 DES (model B)

The second iteration of the DES model breaks down the scanning, planning and treatment phases into more detail to represent the individual resources and capabilities of each machine. Driven by the objectives of the project and discussions with the client, patient pathways were included to denote the various tasks to be undertaken. The three areas of the system which have been expanded upon are highlighted in the conceptual diagram of the system shown in Figure 74.

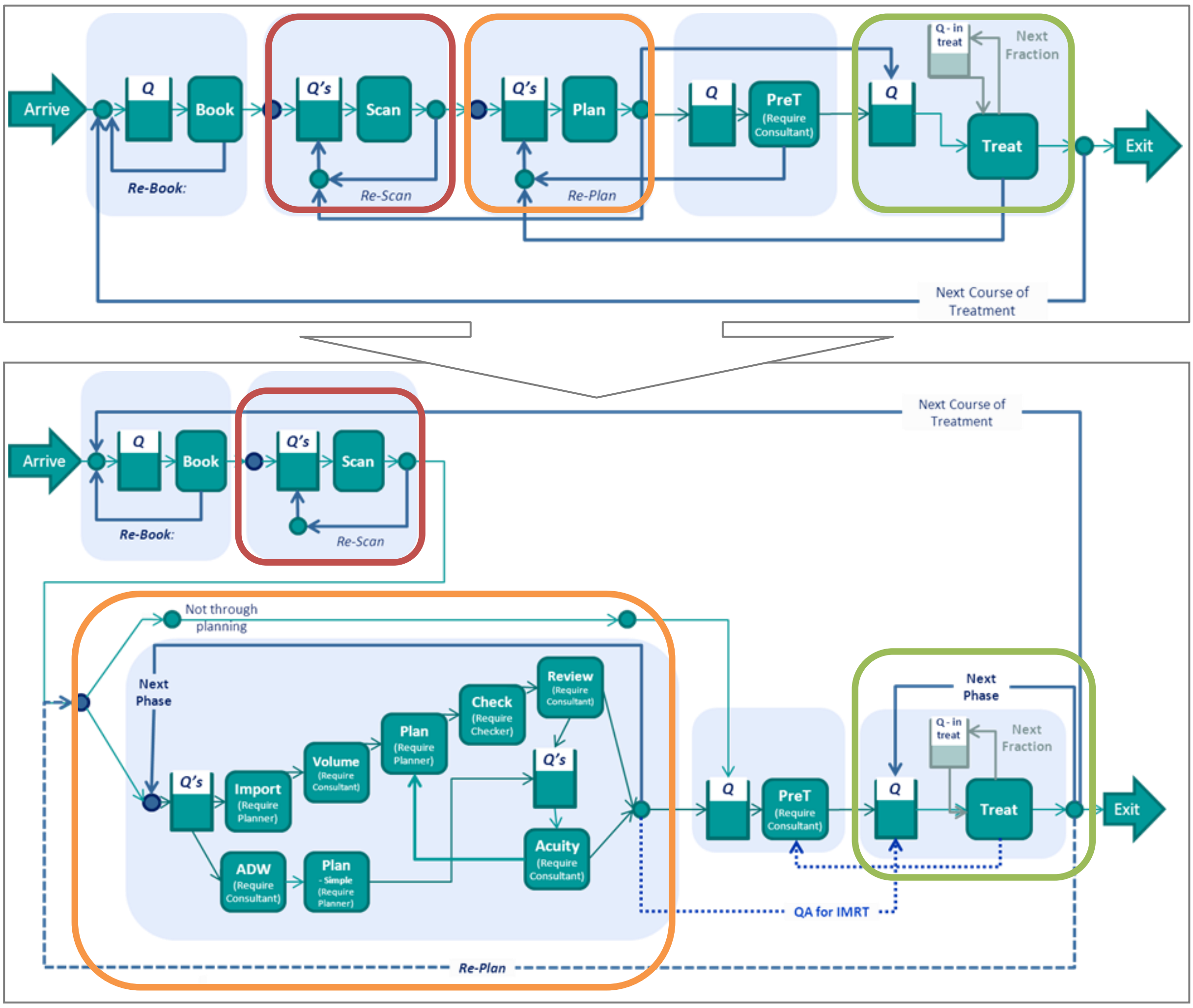


Figure 74: Conceptual model of DES model B.
- expanded areas of the system are highlighted

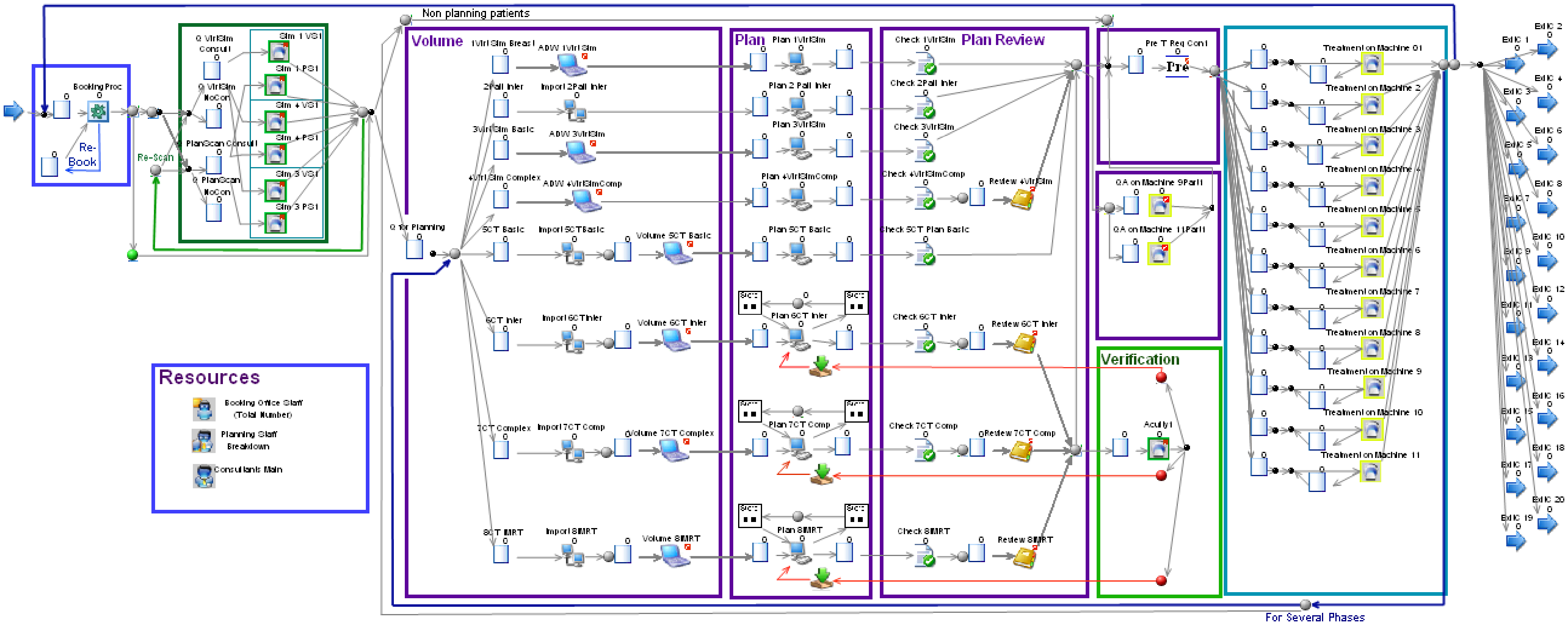


Figure 75: Simulation screenshot of DES model B

DES Model A was failing to capture all of the detail necessary to represent a change in treatment regimes due to a change in the level of complexity of treatment. The model has been adjusted to breakdown the key stages into the pathways a patient may be sent on. The alterations made are:

- Simulation and imaging is now represented by the two types of machines a patient may be imaged on;
- Planning has been broken down into the 8 main patient pathways detailing the different voluming, planning, review and verification requirements;
- The treatment machines are now represented individually to enable the representation of the two machines currently able to provide IMRT treatment, and to model patients during their treatment more accurately by ensuring they are treated on the same machine each time (as is done in practice).

These alterations allow the modeller and client to further explore the impact of changing treatment regimes by adjusting the pathway a patient is sent on and the imaging, planning and treatment times. This model was discussed with the client to establish if it was convincing and provided suitable outputs to answer the project questions. As the system was modelled as running up to capacity there were large queues experienced by some patients. Bottlenecks within the system were identified, some of which were expected, but they highlighted the need to return to the data used to populate the model and consider what assumptions the data is subject to, and how it should relate to the service rates used in the system. Additionally, the discussion highlighted that although consultants are required at numerous points in the system, they are not consistently required by all patients. The model needed to reflect the proportion of time a consultant isn't required as this has a significant impact on the range of times taken by patients to reach treatment, the systems current utilisation and its ability to cope with new, more complex treatment regimes.

7.3.4 Summary

The second iteration of model development has been described in this section. The first phase of model development revealed shortfalls in the SD model. SD model B is used to illustrate that the system has more flexibility with regards to the adoption of new treatment regimes thanks to the willingness of staff to attempt to maintain equitable waiting times for all patients by working extended hours as needed (but up to a point). The DES model has been modified to capture patient pathways to represent stages of the planning and treatment process that change as a result of new regimes and staff timetables.

Throughout this process reference was made to the merged map of the system as it highlights how interconnected the system is. The modeller felt it was important to consider the whole of the system throughout the model development process to ensure understanding of the wider system implications when using two methods to model two different perspectives on the system. The merged map provided the common ground for the two models to relate to.

These models provide insight into the functioning of the system but several questions remain unanswered. An addition to the SD model which would significantly contribute to the project objective would be to capture the differences in the system between what people perceive to be happening (in terms of impact of new regimes), and what happened in reality as the merged map highlighted the varying levels of understanding within the stakeholder group.

7.4 Modelling (3): Requisite Detail

Throughout the process the modeller discussed the models with the client to obtain feedback on their scope and whether they are convincing. At this stage of the project the modeller was able to finalise the view of the system adopted by each method, the dominance of the methods and the roles of each model (the mixed methods design). The client identified parts of the system that are not yet modelled convincingly. The following section details the adjusted mixed method design the modeller adopted for this iteration of modelling and the final SD and DES models produced.

7.4.1 Adjusted mixed method design (3)

The mixed method design, system view and dominance of methods are reconsidered in light of the gaps remaining in the models. The modeller developed their understanding of the system and problem during the course of the project. At the start of the project it was difficult to define the view of the system each method would take. Following the understanding of the system developed, the view of the system is now illustrated using a simple influence diagram with the green circle capturing the system view of the SD model and the purple dotted ellipse illustrating the view of the DES model (shown in Figure 76).

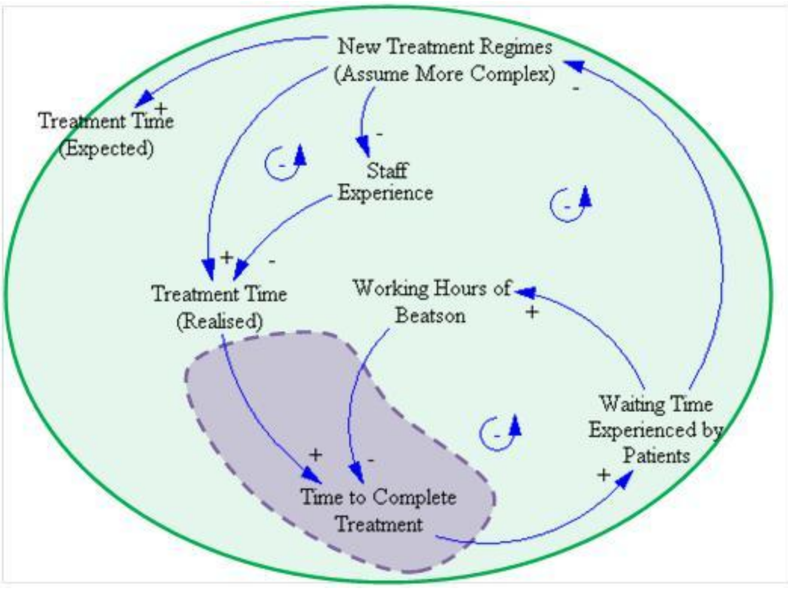


Figure 76: View of the system (3)
- SD Model (green) with the positioning of the DES Model (purple)

Although points of interaction were identified it was felt that changing the models to be an interaction design (dynamically interacting, with the two methods acting as a single model) would add no additional benefit to the models remaining separate. Instead it was sufficient and preferably simple to pass insight between one another. This is not a change from the system view discussed in the previous model iteration, but an alternative representation of the concept is used to emphasise where the models overlap.

Reconsidering the dominance of each method within the process, it is expected that the DES model will be more dominant than the SD model at this point in the project. This was because several scenarios for experimentation in the DES model were requested by the client.

7.4.2 SD (model C)

The final addition to the SD model is the inclusion of a learning cycle. The dynamics of the interaction of new technology and research on the time required to image, plan, verify and treat a patient according to a new treatment regime is modelled interacting with the staff learning process. This feedback process represents the need for training as the average level of knowledge drops on the implementation of a new treatment regime, and then knowledge accrues over time. The inclusion of this cycle enables the representation of the oscillations in treatment times observed in the system by staff as new regimes become common practice, and the effect is observed across the 5 changing levels of imaging time, planning time, number of treatment phases, number of treatment fractions and treatment fraction slot time (illustrated in Figure 77).

This model now captures both what we seek to observe (time for patients to reach treatment, varied over time) and what might be adjusted to change the observed behaviour (staff working hours in the short term, and new treatment regime adoption and training procedures in the longer term).

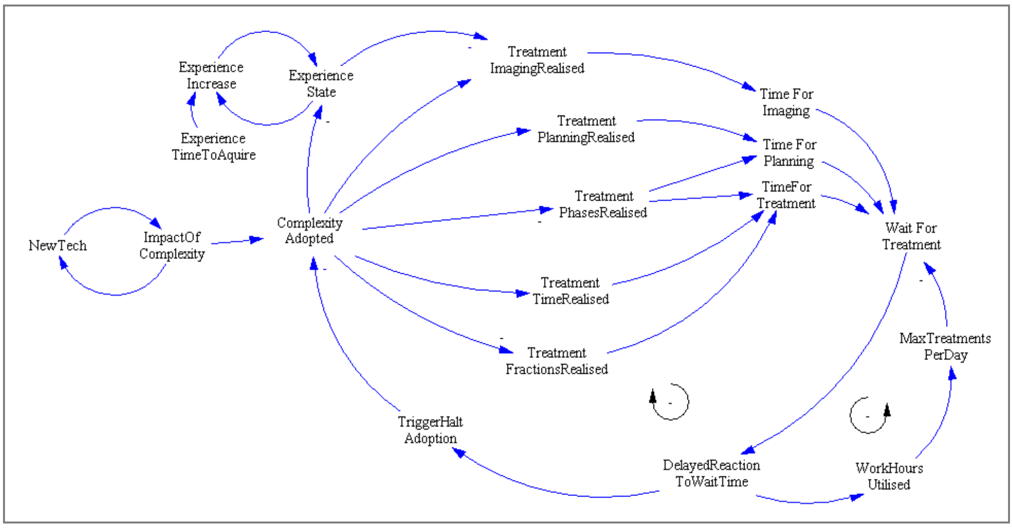


Figure 77: SD Model C influence diagram

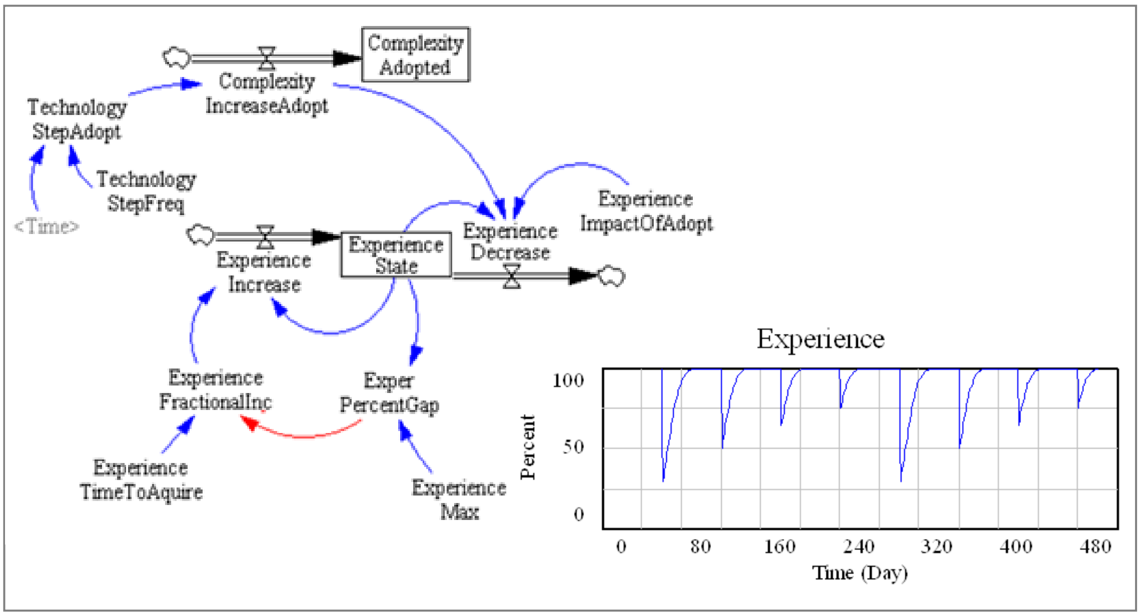


Figure 78: SD Model C stock and flow diagram
– Staff experience interacting with the adoption of new more complex treatment regimes

Figure 78 illustrated the interaction of the new technologies with the level of experience at the centre. The pattern of technology adoption is such that a single complex regime is adopted and then three further regimes of decreasing complexity but of the same type are adopted over 6 months. The result of this interaction on the average treatment time is that the increase in time required per patient is initially larger than expected before falling to the expected level as the level of staff knowledge on the regime increases (illustrated in Figure 79). However, as the time per fraction on a treatment regime increases the number of phases of treatment reduce resulting in the overall effect of a fall in the total machine contact time required with a patient (Figure 80).

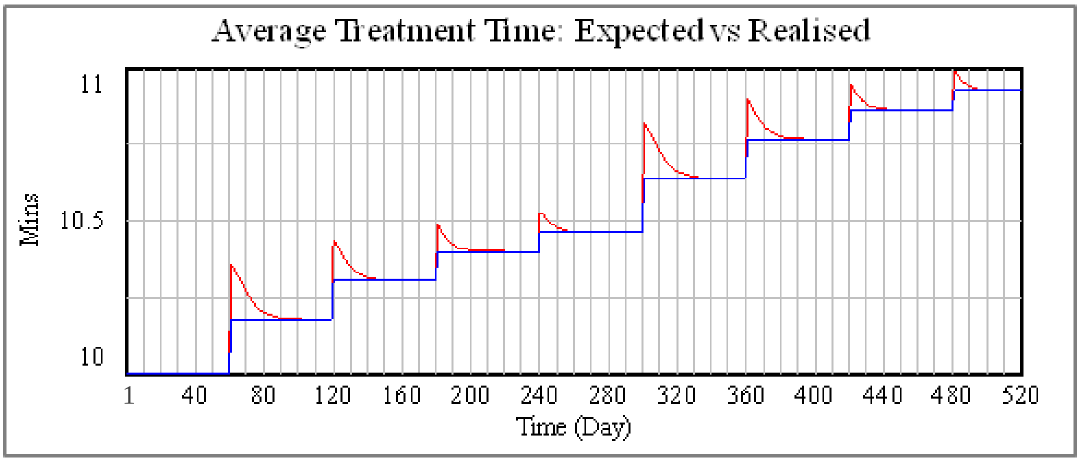


Figure 79: SD Model C output – average patient treatment time as new treatment regimes are adopted (expected versus realised)

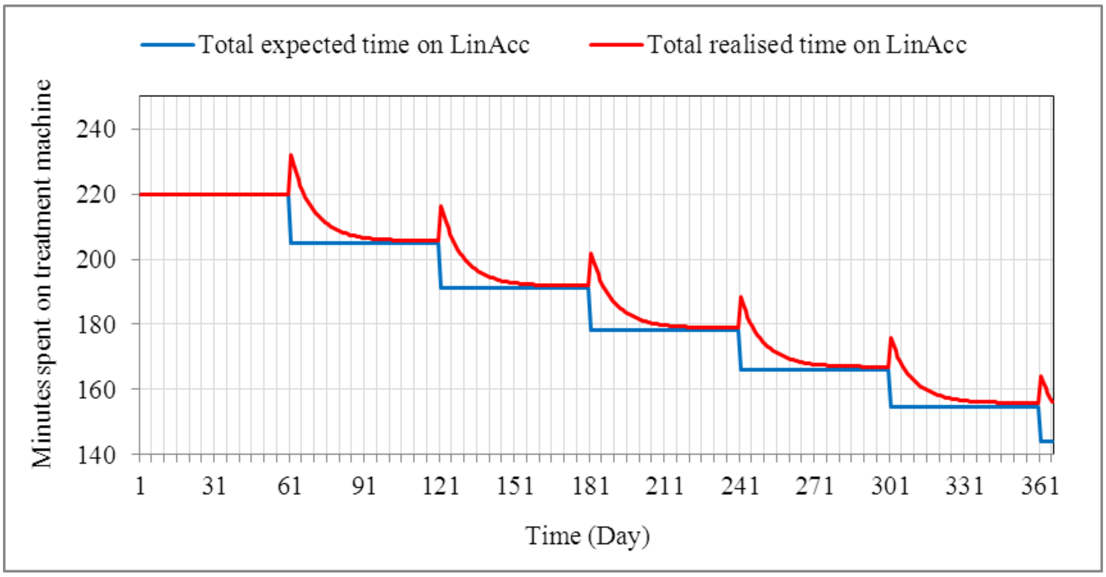


Figure 80: SD Model C output – total time on treatment machines as new treatment regimes are adopted (expected versus realised)

An additional point to make is regarding the use of treatment machine fractions as a performance measure to compare the efficiency and workload on a radiotherapy centre. Due to the changes in treatment regimes the standard length of a treatment fraction is likely to increase and the number of slots used per patient decrease. However, using the number of fractions per LinAcc it might appear that the unit is underperforming in contrast to its peers. Therefore, measuring the number of fractions delivered per machine may not be a suitable measure of system efficiency. It is suggested that the number of minutes delivered per machine is used instead as this would capture longer times per fraction and clearly indicate the total workload placed on the treatment machines.

Within this SD model a simple DES model could be used as a proxy of the behaviour of the core treatment process, but insufficient detail on the stages of treatment would be represented, and the client's questions relating to the impact of new regimes may not be adequately answered.

7.4.3 DES (model C)

The final DES model was developed to more realistically represent the consultants' availability and requirement across the process. Consultant availability, based on their patient pathway timetables, has been incorporated into the model. Requirements for consultants to be present at certain tasks for the entire task time have been relaxed and removed altogether for patients following the most basic routes through planning and treatment. The final model for this project, DES model C, is shown in Figure 81. Table 17 summarises the features of the DES model at each model development phase, and an overall description of the DES model is given (summarising elements included also in models A and B) to provide a complete summary of the model.

Table 17: Features included in the DES model at each development phase

Model Feature	DES Model A	DES Model B	DES Model C
System View	Four stage process	Multistage process (the four core stages split into tasks)	Multistage process
Entities & Arrivals	Individual patients, random arrivals (based on Beatson arrival data)	Individual patients with characteristics (treatment intent and cancer type); random arrivals (based on Beatson arrival data	
Booking	Multiple servers behaving identically		
Imaging / Scanning	Multiple servers behaving identically with identical characteristics, requiring a consultant present	Two types of machine behaving according to their independent characteristics, requiring a consultant present	Two types of machine with consultants required on a subset of patients
	Average service time for each machine type across all patients.	Average service time dependent on the machine, possible to vary by patient characteristics	
Planning	Multiple servers behaving identically requiring planning staff	Broken into stages according to the 8 planning pathways, each with different planning staff requirements	As B, but with relaxed requirements for consultant attendance
Treatment	Multiple LinAcc's behaving identically; average time per treatment fraction and fixed number of fractions per patient	Different treatment machines represented with a patient remaining on the same machine throughout treatment; variable number of fractions, phases, courses of treatment, and fraction times by patient characteristics	
	No QA	Inclusion of QA requiring use of the LinAcc's	QA machines tied to IMRT machines to ensure only one patient per machine

Key aspects of the model are that the four key stages of the process are captured (Booking, Scanning, Planning and Treatment) along with the interactions between these activities. Individual patients are represented with each assigned individual characteristics dependent on: their intent (radical or palliative) and their cancer type (using ICD10 coding). This information is used to determine: the imaging machine used the planning pathway and the number of courses, phases and fractions of treatment. The model has been populated with data from the Beatson IT systems: Aria and TaskPad, or using expert knowledge of the project stakeholders if data is unavailable. A short summary of the interesting aspects of the Beatson data which were identified when analysing the data to populate the model is included in section 7.5.1.

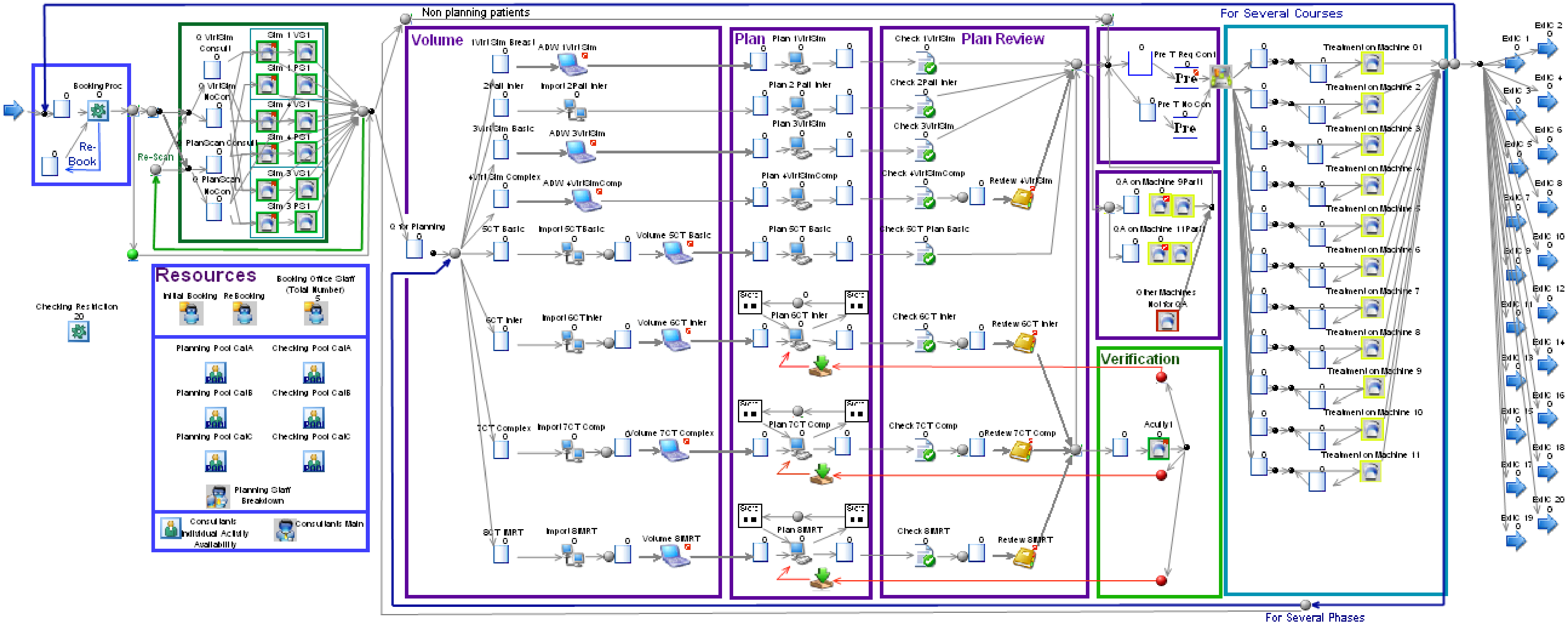


Figure 81: DES (model C)
– additional resource restrictions and consultant timetabling

Several assumptions about the behaviour of the system have been necessary to include in the model in order to manage the complexity of the project and the models developed, or because limited information is available.

- Demand is static in the model (to represent the current situation).
- All phases of treatment are planned prior to commencing treatment. This is a simplification of reality where the first phase is planned, treatment commences and whilst underway the next phases are planned. This simplification enables the modeller to track only a single work item per patient, which assists model analysis.
- Resource availability is subject to shift patterns but remains static throughout a year (no recruitment or commissioning of machines). Any change in the level of staffing or machine resources must be implemented manually to ensure the system works within the financial and physical constraints of the real system (staff are under permanent contracts and no temps are used, and new machines require physical space so should not vary over the modelling time window).
- All consultants are available as and when they are scheduled to be working
- If a patient requires a consultant present at the scanning/simulation machine, they are not able to join a machine until their allocated consultant is available.
- Any re-booking, re-scanning or re-treatment results in the patient using each slot booked rather than missing the slot. This is because a cancellation or a no-show results in the slot being unusable by another patient: the slot is wasted and the resource is unavailable for the duration of the pre-planned slot. It should be noted therefore, when examining model outputs; the quoted number of scans completed includes these wasted slots.
- All patients are attended to on a first come first serve basis at each server. Patients who have received an acuity check take priority over other patients in their planning pathway to ensure timely arrival at treatment.
- There is no maximum time a patient will spend in the system before they leave voluntarily; all patients wait until they are able to be seen.

7.4.4 Summary

This iteration of model development sought to finalise the models for experimentation. Discussions with the client informed the modeller of the final insight required from the SD model and the experimental scenarios to be run on the DES model in order to meet the objectives of the project. Additional detail was required in both models to finalise the models and answer the questions posed about the system.

Specifically in the DES the appropriate level of system detail was required to be able to reproduce the system behaviour sufficiently to enable experimentation. Generalising or aggregating system variables too much would have masked the effects of interactions between stochastic elements of the system. The system is tightly constrained by the resources available and minor changes to the setup could have a significant impact. Consequently, it is necessary to be able to represent minor adjustments to the system to maintain control of the system. Overall, the models offer complementary insights throughout the three iterations of the modelling process, with both methods contributing to answering the questions posed by the stakeholders.

The next section will discuss briefly some of the data analysis undertaken to inform and populate the models, the validation and verification procedure, and model insights generated throughout this project.

7.5 Data Analysis and Model Validation

This section gives an overview of the data analysis undertaken throughout this modelling project and the approach to model verification and validation.

7.5.1 Data analysis

Extensive collation and analysis of Beatson data was conducted to populate the DES model and inform the SD model with the most relevant and accurate data. The modelled arrival of patients; the levels of re-booking, re-imaging, re-planning and re-treatment; and the allocation of resources are all based on data obtained from the Beatson IT systems. This was supported by expert knowledge where necessary to ensure a fair representation of the system was modelled. Analysis pertinent to the design of the models is outlined in this section.

7.5.1.1 Patient arrivals and booking

The arrival of patients into the Beatson is known and can be broken down into 20 separate ICD10 cancer codes. Arrivals are modelled as random over time with patient forms arriving for booking. Booking is the first stage of the process but it does not involve the patient. The booking slip, which the patient's consultant has completed, provides details including the type of scan and the treatment required.

7.5.1.2 Patient Imaging

The time spent on this activity depends on the type of cancer, the type of scan carried out and whether radical or palliative care is being undertaken. The decision between whether radical or palliative treatment is provided is influenced by factors such as the site of the cancer and the stage at which it's at, patient's age and general health, and the availability of resources. The current allocation of all of these determining factors can be extracted from the IT system and is used to populate this phase of DES model B (tables detailed in the Appendix).

7.5.1.3 Radiotherapy planning: using TaskPad data

TaskPad is the system used to plan and track all radiotherapy plans created and delivered at the Beatson. The system is designed to assist the planning process by allowing staff to track if a plan is on schedule and will be ready for the first treatment slot booked.

The Beatson process operates such that the date a patient is booked for their first treatment is selected when the patient first appears in the system, and this dictates the date a plan is due out of planning. Booking staff are able to select an appropriate first treatment date using the *Patient Pathways* which were developed with expert knowledge, and ensure sufficient time is available for the pre-treatment stages. Table 18 and Figure 82 illustrate the information that can be obtained from TaskPad: the time a patient plan waits in a queue at planning, the time taken for the plan to be completed, and the time taken waiting to be signed off prior to treatment. This means that the numbers are higher than the actual time to complete a plan and can only be used to confirm the model behaviour rather than to populate the model. The planning times used in the model will instead be based on the expert judgement of the planning staff.

TaskPad was not designed to yield planning performance measures, and is only able to reveal the total time a plan spent in the planning stage of the process, and this includes time that a plan is waiting for completion. This wait is a reflection of the final due date of the plan, rather than the constraints of the planning stage.

Complexity of treatments is the issue at the heart of this project but is also difficult to capture data on. This is because records hold information on the time and frequency that machines are used, but capturing the planning process can be problematic. Planning is undertaken by skilled radiotherapy physicists who individually plan each patient, and the time to complete this varies depending on the complexity of the treatment regime. The time a plan takes to move through this phase is not equal to the time a radiotherapy physicist spent producing the plan. Variables used day to day by staff to timestamp when stages of the process were completed or when they should be completed by were being used differently by different staff. This issue resulted in the data showing that the time it takes to plan a patient being days rather than hours and minutes as expected. This value represented the time a plan was waiting to be planned and the time taken by a radiotherapy physicist to produce the plan. This discrepancy had no bearing on the patient's level of care or time to receive treatment, but resulted in the modeller being unable to use the data to populate the planning tasks within the model. Recommendations were made to provide clearer instructions for staff using the system which would allow data on this stage of the treatment process to become available in the future.

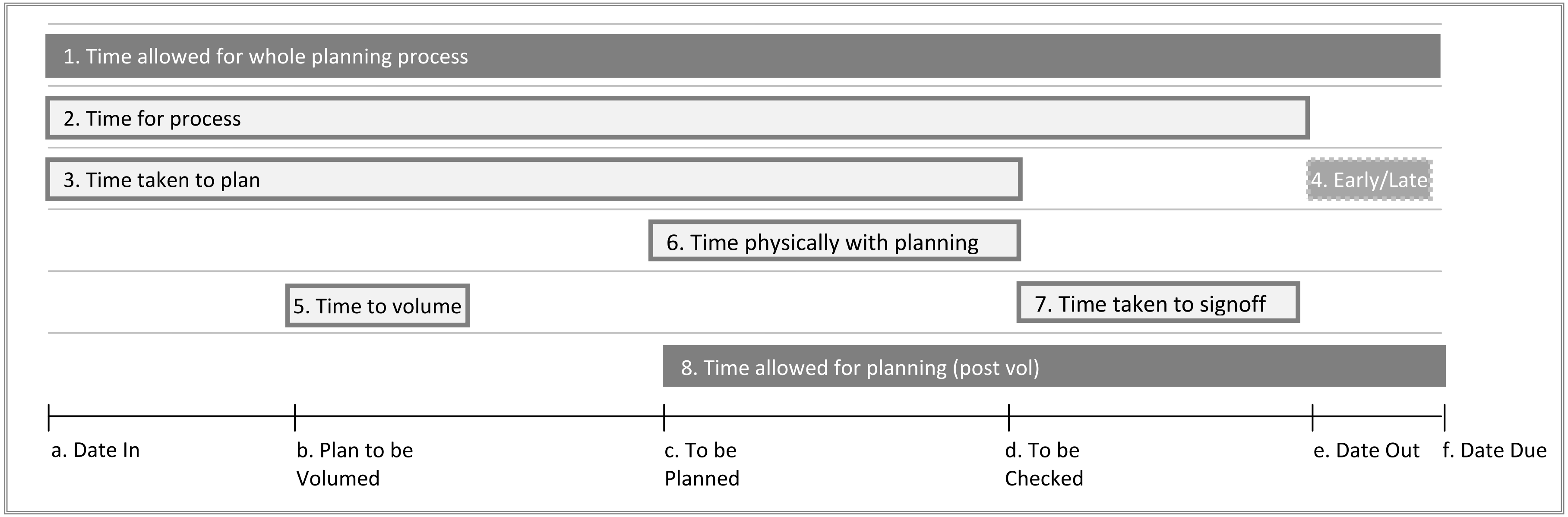


Figure 82: Diagram of data available within TaskPad and what it can be used to represent

Table 18: Summary data producible from TaskPad

Measure Number	Descriptor	Average time (working days)
1	Time *allowed* for whole process	13.88
2	Time *taken* for whole process	14.08
3	Time *taken* to plan	13.86
4	* Early or Late *	0.21
5	Time *taken* to Volume	0.98
6	Time *taken* with Planning	11.8
7	Time *taken* to be signed off	0.01
8	Time *allowed* for planning (post vol)	12.02

7.5.1.4 Plan complexity

Radiotherapy physics staff allocate a plan complexity to each plan they complete as an indication of the time it will take or took to complete. This enables the expected workload to be assessed. Examining the data (illustrated in Figure 83) reveals that more complex plans (c4 and c4+) are remaining steady, with only less complex plans increasing. This may be due to changes in how staff classify treatment plans as complexity is subjective, or due to more plans failing to be allocated a plan complexity. Unfortunately, this measure appears unreliable due to the subjectivity of its allocation stemming from no clear guidelines of what each category means, and the likelihood that as the perception of how complex a regime is changes over time the category which it is assigned may fall. The recording of this variable should be reassessed to include the assigned *'patient pathway'* or some other more objective measure. This data also illustrates the overall increase in the workload placed on the planning staff as more plans are generated.

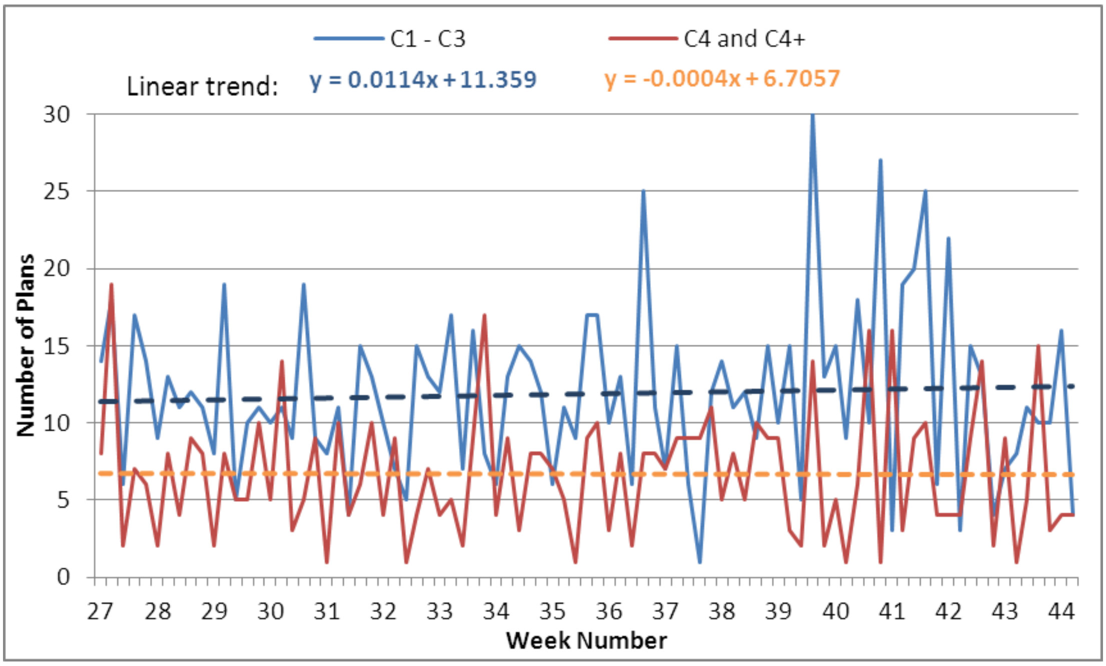


Figure 83: Treatment plan complexity over time

Changing treatment regimes is represented in the DES model by increasing the proportion of patients, by cancer type, sent through the IMRT planning pathway. IMRT is currently the most complex patient pathway available and new regimes would be a variation on this pathway.

7.5.1.5 Treatment

Patients attend treatment for a number of fractions with each fraction being equal to one visit. Information on every fraction delivered on every LinAcc machine at the Beatson is held within their IT system which is used to aid delivery of the therapy. This enables accurate data regarding the number of fractions and length of fraction slot to be modelled and machine downtime to be used to verify the functionality of this stage of the DES model.

7.5.1.6 Summary

Also relating to the planning of treatment is the issue of treatment complexity and how staff assigns an indicator of this complexity to the patient records. An initial assumption of this project was that plan complexity, along with the number of treatment plans required to be produced by planning, was on the increase. However, the data analysis reveals that the former is not occurring as expected. Plan complexity is subjectively assigned and staff may have become more restrained at allocated high categories as time went on, or it may be that those plans without a complexity category (which are increasing) represent high complexity cases, or that staff are not seeing the benefit in spending the time assigning a category. In any of these cases it is recommended that less subjective measures are also recorded (such as the planning pathway a plan was assigned to) and staff are informed of the importance of this record keeping. The data does however show that the number of plans is increasing over time and that measures need to be taken to adopt treatment regimes that manage these numbers.

7.5.2 Validation and Verification

"Simulation as estimation not emulation" (Chick 2006, p. 25)

All models are wrong as all models are a simplification of reality. The focus should be on building useful and convincing models. It is important to recognise that simulation modelling is a tool to aid decision makers; it is not the decision. Stakeholder and client confidence in the models dictates the project success. Their confidence is tied to their involvement, buy-in and ability to understand the model.

(Robinson 2004), in specific reference to DES modelling, concurs that it is not possible to prove that a model is absolutely correct, rather it can only be validated with respect to the purpose for which it was created. Validation and verification procedures seek to prove that a model is incorrect but we seek to prove its correctness and appropriateness (within the given context). As a model builder, we aim to develop confidence in the model; aiming to ensure that the model is appropriate (what is wanted and/or needed), that it is useful (answers the questions posed), and is valid under known conditions (it tells us what we know).

Validation and verification often refers to external validity of models: comparing simulation results with empirical data and how generalizable results are (Davies, Eisenhardt and Bingham 2007). However, a broader meaning is adopted due to interest in the validity of the modelling project: the validity of the modelling process and the models created throughout that process. Therefore, we seek to ensure confidence is developed in the models and in the modelling process used to define and create them. As discussed in the literature review and throughout this chapter, the simulation development procedure is not linear and validation and verification are not conducted as an isolated singular event at the end of a modelling project. Rather looping and iterations in the modelling project all incorporate various elements of validation and verification.

7.5.2.1 Building confidence in the models

Validation involves building confidence to confirm sound and useful models (Forrester and Senge 1980). The purpose of the models developed was not to provide a prediction of absolute values by which to set resource levels and schedules. Models should be useful and illuminating (Greenberger et al. 1976). The purpose of this project was to provide an indication of the impact; therefore where bottlenecks and strain will be felt on the system under the new treatment regime scenarios proposed, not how much of each resource will be needed precisely. SD shows that staff are willing to be flexible and that new regimes will have differing impacts on training needs. This information gives us tolerance and indicative responses to be observed in the DES model; not scope to specifically predict what will happen under each new technology or regime, or the data to populate the DES model to achieve such results. We are limited by what we don’t know. The models offer insight into this grey area, but prediction is only possible if a fixed future is to be explored in detail. A fixed future does not exist however, as there is uncertainty around how research will develop and what new regimes the centre will want to put into place next.

It may be said that there are three broad approaches with which to tackle validation and verification (Sargent 2013): place the model experts at the centre of the process where they decide based on tests completed during the modelling process; ask the model users/client(s) to decide if the models are satisfactory at various stages of the modelling process; or seek assistance from a third party for independent verification and validation. The first approach enables validation and verification to take place in the back room and to be reported to the client or for it to involve the client more directly. The second approach relies on client interaction to ensure credibility of the models. The third approach adopts a third party, with no involvement in the model development process, to independently determine if the models are valid.

In this project, all three approaches have been utilised to greater or lesser extents. Throughout the modelling process the modeller has been engaged with the client and feedback was received on the test scenarios undertaken throughout model development. Additionally, stakeholders have had the opportunity to view the models and feedback to the modeller their views on how credible the models are. Finally, third parties not directly involved in the project had the opportunity to feedback on the models after the third (final) cycle of model development. These third parties were individuals also involved in the delivery of radiotherapy from the treatment of cancer, but from other cancer centres from around the UK, and were therefore able to offer a specialist view of radiotherapy systems from their own perspectives.

Confidence in the models may be tied to the success of a project. Robinson (1994) posits a 4 stage model of success: the model shows benefit, results are accepted, results are implemented, and implemented results are proven correct. In this project, the modeller is confident that stages one and two have been achieved. The models are demonstrably beneficial in both their conceptual and coded forms to encourage engagement about the issues within the system, appreciate the interconnectedness of these issues and provide tools to explore the possible futures of the system. Results from the modelling process have been presented to stakeholders at several stages throughout the modelling process and outputs have been accepted. Implementation however is difficult to define in this project. Implementation has been achieved in that insights garnered from the two models have informed the clients thinking around the problem and alleviate concerns regarding the pressure the system will be placed under. However no single solution to be implemented has been proffered to enable a modeller to cross implementation off the validation check-list (figuratively). Suggestions for improvement made to the client include strategies for future dissemination of new treatment regimes across the patient group rather than an operational plan for a given (single) treatment regime.

7.5.2.2 Evaluating model appropriateness

As discussed above, models should be useful and insightful. For this project we considered Sterman's *"Questions model users should ask – but usually don't"* (Sterman 2000, p.852 – reproduced in Appendix 10.13: Table 35) in addition to discussing the clients confidence in the models. These four broad categories of overlooked, but useful, questions highlight the suitability of the models for their purpose and the time taken to develop confidence in them. Although they stem from the SD field, they are similarly applicable to modelling in general:

Purpose, Suitability, and Boundary: the framework for model development proposed in this thesis and undertaken in this project supports this theme of validation. The careful problem structuring ensures that the purpose of the model is extracted early in the modelling process, the boundary is defined and agreed with the client, and that the aggregation is appropriate to answer the posed questions. Given the use of two simulation methods, the modeller had to carefully select the time frame for each and consider if it might be appropriate to use the same time horizon.

Physical and Decision-Making Structure: These points were all considered during the conceptual modelling and coding stages of the model development process. As these questions posed by Sterman directly relate to SD modelling, several of these points are explicitly represented in the SD model, whereas in the DES model it is necessary to clearly state the assumptions made as some of these features remain hidden in the coding instead of explicitly represented diagrammatically (unlike in SD stock and flow diagrams which represent the delays and feedback).

Robustness and Sensitivity to Alternative Assumptions: Both models have been 'played with' to ensure they react appropriately to extreme and invalid variable values. All assumptions made were discussed with the client (or stakeholders if specific specialist information was required).

Pragmatics and Politics of Model Use: As both of the simulation packages used to develop the models are off-the-shelf and widely used support is easily available and the cost of purchasing a basic version of the software do not restrict access to the models. The models are designed to interact with Microsoft Office Excel for data import and results export as this is commonly found on all work PCs and facilitates quick changes between scenarios and easy project specific analysis. This has been done to ensure the models are as accessible as possible within the constraints of the project, and of the organisation they have been developed for (as price, software installation and software training can be a barrier). Data to populate the models comes from real-life radiotherapy planning and delivery data. This is complemented by expert knowledge when information is unknown or limited, and research papers in the field of radiotherapy treatment development to inform appropriate changes to treatment regimes.

7.5.2.3 SD model validity

The SD model was developed with a focus on capturing the relationships between the variables, rather than the accuracy of the data populating it. It was designed to capture generic dynamic behaviour in a closed system and includes motivations and goals (softer variables that were challenging to quantify). The realism of the model in this context informed the validity. The values used within the model were indicative and based on the changes required to the system to adopt IMRT. Values would need to be adjusted depending on the treatment regimes under consideration and subject to how the technology develops. The model is intended to capture the dynamics of the system, not to provide quantitative forecasts of suitable frequencies of implementation of regimes.

Literature from the radiotherapy physics field was used, along with documents developed by staff in-house at the Beatson, to determine the number of fractions and the amount of imaging, planning and checking specific changes to treatment regimes might invoke. These informed the values implemented into the SD model, along with existing government targets for access to treatment, staff levels and working hours, standard reporting timeframes (such as monthly summaries) and staff training schedules.

System archetypes, previous healthcare studies and standard SD relationships from the SD literature were used to support the development and confirm the appropriateness of relationships and dynamics within the model[38]. These archetypes enable the modeller, and the client, to have confidence in the structure of the model and allow standard solutions to the problems to be instigated.

[38] *limits to success* and *quality improvement* archetypes from Wolstenhome (2003, Figures 3 & 6)

7.5.2.4 DES model validity

As discussed earlier in this chapter, the structure of the DES model was derived directly from the phases of the treatment process, the planning pathways and resource levels. The client was involved throughout the development process and provided feedback on the structure, content and aggregation of the model. Data used within the DES model is discussed in the following section, and system experts confirmed the appropriateness of the values implemented.

The functionality of elements within the model was checked after every new addition to ensure the desired effect was achieved. This was done in the form of testing the model during a simulation run (white box validation) to assess the values elements of the model were using to determine the minimum wait a patient has at each element.

Model outputs were compared to the monthly throughput at the unit (black box validation). These measures included patient arrivals, number of simulations/images taken, number of patients on each planning pathway, number of acuity scans completed, and the number of fractions delivered per year. All outputs were comparable with the real-life system under the base conditions.

7.5.2.5 Summary

This section has discussed the validation undertaken throughout the modelling process which sought to build the clients confidence in the models and the process. Both the qualitative and quantitative aspects of the models were assessed for validity by utilising the data available about the system and the expert knowledge of the stakeholders involved in the project. The structural validity of the models was evaluated with the help of archetypes and common system behaviour in SD, and by confirming that the DES model sufficiently represented the physical patient journey through the radiotherapy treatment process. All models are wrong, but we can seek to make them useful, appropriate and valid in the project context.

7.5.3 Summary of model validation & data analysis

This section has presented a brief summary of the data analysis and described the model validation and verification undertaken throughout the course of this project

The data analysis, conducted over the course of the project, sought to help the client understand their problem system and generate data to populate the models. It also highlighted some issues around the collection of the information, some of the on-going gaps in knowledge in the system, improvements that could be made, and challenges faced for the models as a result of a lack of data available on some parts of the system. Other parts of the system have a wealth of quality of data available which presents an opportunity for data analysis to be conducted to address other problem themes identified in the merged map. The analysis and discussions with the client and members of staff highlighted a mismatch in understanding of the meaning or intended use of several variables in their IT systems and that clarifying these variables would provide richer information about the planning process.

It has been discussed that all models are wrong, but we can seek to make them useful, appropriate and valid in the project context. This may be achieved through engagement with the client throughout the process. This continuous interaction with the client has enabled the modeller to develop the client's confidence in the models and the process undertaken, resulting in models that are tailored to address all of the issues raised around the problem theme.

7.6 Model Analysis

7.6.1 Introduction

This section will summarise the model analysis presented to the client. This analysis is the result of feedback from the client and summarises the insight obtained throughout the modelling process.

The SD model provided insight throughout the modelling process by representing and revealing the behaviours of the system previously underappreciated. The main contribution of the DES model came at the end of the project through the running of several scenarios for the client (detailed in Appendix 10.12). These results are discussed in the following sections.

7.6.2 SD insight

The SD model enables the client to observe the impact of decisions stemming from the feedback structure of the system. Strategies to respond to an increasing amount of time required to prepare and deliver plans can be explored to avoid an overall increase in the time at treatment machines. The potential for changes to treatment regimes to impact staff working through pressure on the system, an increased frequency of training and the need for more staff to be knowledgeable and fully trained for these new regimes can be observed in the model. These changes might be managed by considering the progressive implementation and learning process involved with changing treatment regime, whereby the times required for activities peaks then returns to an expected level (the target level for that regime). The net effect is a progressive decrease in the number of phases required per patient, a progressive increase in time required on treatment machine per session per patient but a decrease in the overall contact time on an expensive resource – treatment machines. This is discussed in section 7.4.2.

The learning curve must be incorporated into strategic plans: The time taken for staff to acquire new skills needs to be factored into the roll-out of new treatment regimes. This is illustrated in the SD model by the difference between the expected and realised new times for each stage of the radiotherapy planning and treatment process as the result of a new treatment regime being implemented within the system. Although the centre currently staggers the roll-out of new regimes, the importance of this and the potential for differences in the expected and realised to negatively impact performance of the system were emphasised in the model.

New regimes increase time to plan: As treatment regimes become more complex, more complex plans are required. Although the number of plans may decrease as the number of treatment courses per patient falls, the total time a planner spends per treatment plan will increase as complex treatment become common place. The reduced number of treatment phases means that these complex plans will be the first treatment plan and can impact upon the centres performance against government targets.

A fraction is not a standardised unit: New regimes reduce the number of treatment fractions but increase their length therefore the total number of fractions a machine provides per year no longer accurately reflects the workload of that machine and cannot be compared across centres. It is suggested that centres should report the total time delivering treatment to account for this shift away from a single fraction size.

Net effect of new regimes is to reduce staff workload: Planning is the only part of the planning and treatment process that experiences an increase in workload. All other parts of the system will eventually experience a fall in demand per patient (although the number of patients will continue to increase). The new regimes offer the opportunity to reduce the number of phases of treatment. And, less phases implies fewer visits to hospital for the patient and overall shorter treatments.

7.6.3 DES insight

The base scenarios reveal that increasing the flexibility of consultant work patterns (to be available at different areas throughout a week) generates a greater improvement in time to reach treatment than sharing patients between consultant groups. Given the data provided, it was not possible for the model to achieve a steady state (as required for analysis) and adjustments were necessary to ensure sound representation of the system.

Increasing patient access to IMRT requires investment in staff and treatment delivery machines (IMRT enabled LinAccs). The system is able to cope with the first marginal increase in access, but all other scenarios require adjustments to be made to the system. Providing access to IMRT for all radical patients requires the time taken by staff to reduce significantly (through investment in training) or more staff.

In the model Acuity experiences queues in all scenarios unless the spare capacity available on at least one simulation imaging machine is adopted for use. This may be due to an overestimation in the amount of Acuity checks performed or of the time taken to complete the check. Planning need to reduce the time taken to complete IMRT plans and/or increase the number of IMRT trained planners in order to cope with even a marginal increase in the number of patients receiving IMRT as the regime is used more widely across patient groups. An increase in the number of treatment machines able to deliver IMRT is needed for scenarios implementing IMRT to over 25% of the current level of radical patients (scenarios 3 to 7). This would be in the form of converting existing machines. These modelled scenarios are a subset of possible future setups of the system which enable the client and stakeholders to confirm or challenge beliefs about the system. Many more possible setups may be investigated, stemming from these investigations

All scenarios have been conducted with at most only a minor reduction in average time to complete “Plan 8IMRT”. A larger reduction in the time to complete this stage of treatment would allow a decrease in time to first treatment across all patient groups. However, this reduction would need to take into account the training needs and learning processes explored during the SD modelling.

Note that this model explored the impact of changing treatment regimes, but has not examined changes in patient intent which may alter as research into cancer treatment continues. Changing capacity marginally can have a significant impact. The system copes on paper, but when the variation in arrivals of patients is taken into account there is the high chance of the system becoming unable to cope and failing to meet targets. In reality all staff will strive to ensure treatment is received in a timely fashion and the best possible care is provided. However, this should be noted as outside of calculated work hours and so proposals such as extending working days are likely to have a greater impact on staffing than may be foreseen.

The sensitivity of the system is due to how close to capacity it is functioning. Any anomalies can cause the system to tip into out of control queue growth. Again, in reality this may be remedied by staff accommodating additional work by working longer hours or by compromising on the roll-out of improved treatment regimes, and each of these has significant disadvantages.

7.7 Chapter Summary

Through the three phases of model development for this project the modeller has reflected on the system view each method will adopt, the dominance of each method and the mixed method design, and discussed the models with the client to ensure appropriate, useful and valid models have been produced. The initial system exploration enabled the modeller to capture a broad range of issues. Using a widely known problem structuring methodology, rather than embarking on the project strictly from an SD or DES viewpoint, the modeller was not restricted to conceptualising the system and its problems in a specific way.

The purpose of the project was to explore appropriate policy changes. This involved challenging stakeholders' beliefs with respect to the impact of changing treatment regimes on the centre. The problem structuring allowed the modeller to present a holistic view of the system to the stakeholders demonstrating the interrelationships within the system and revealing interactions between areas of the system that were not previously well understood. Stakeholders were able to observe the knock-on impact of decisions which had not previously been appreciated.

The use of SD enabled the modeller to depict and begin to quantify the knock-on impact of decisions within the feedback structure of the system. The likely response to an increasing amount of time required preparing and delivering plans and the potential for this feedback to impact staff working was able to be examined. The model developed understanding around the need for progressive implementation of new treatment regimes and the potential impact of the time to undertake training and develop learning across staff. This learning process results in the times required for activities being higher than was initially expected then returning to an expected level (the target level for that regime).

There is a progressive decrease in the number of phases required per patient with the implementation of technologies such as IMRT. Conversely, there is a progressive increase in time required on a treatment machine per session per patient. This behaviour stems from the complexity of the procedures and delivering more complex treatment plans. The net effect is a progressive decrease in the contact time on treatment machines as the total number of machine slots needed per patient reduces. However, the SD model is unable to explore whether the increased amount of Quality Assurance (QA) which takes place on a dedicated machine required, as a result of more complex planned patients, would offset the benefits gained. This is where the DES model is able to provide insight.

The DES model enabled the client to ask more specific questions about the impact of changing treatment regimes. It revealed that, as predicted by the SD model, the impact on treatment and imaging machines does not lead to excessive queues, but the impact on treatment planning is long lasting. Under the current conditions of the model all experimental scenarios would benefit from a reduction in the time taken to plan patients receiving IMRT (time per patient plan) as this part of the process causes significant delays due to large queues building. This would require extra resource within planning and a reduction in the average time for physics staff to produce plans. Currently the technology for planning and delivery of IMRT is still fairly new and as staff members become more experienced in the technique the time per patient plan will reduce.

Figure 84 is used to illustrate the value of the use of mixed DES and SD within this project by highlighting the insights gathered throughout the process.

This chapter has presented the modelling project of this action research study from the perspective of the modeller. It has described the models developed, the outputs for the client, an overview of some of the analysis undertaken within the centre to generate the data for the models and to explore the dynamics of the system, and a summary of the validation and verification process. The next chapter will consider this project from the alternative perspective of the researcher. It will discuss the considerations made whilst undertaking the project regarding the methods used through the three cycles of model development. The project is reflected upon prior to, during and after the project to consider the needs of the researcher within the project.

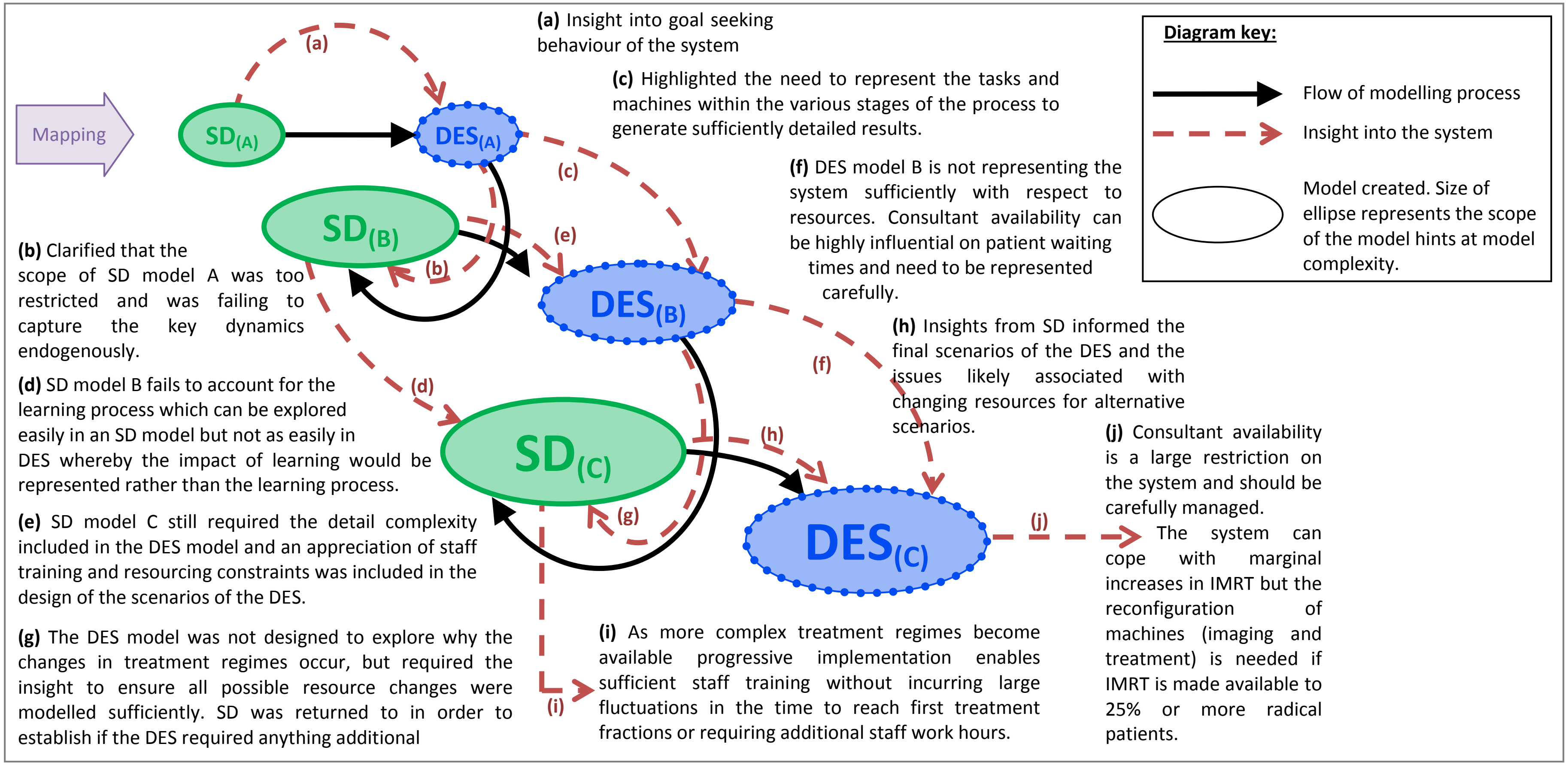


Figure 84: Model development process including feedback of system insights generated

8 Beatson Project - Researcher Reflections

The aim of this chapter is to present the researcher's thoughts prior to commencing the modelling project[39], and the reflections made during and post the project with the Beatson. The purpose of these reflections is to consider the frameworks developed prior to the project, discuss the learning from applying the framework, and present the changes made following this experience. *Chapter 4* (Research Design) discussed the two roles played by the researcher within this action research project: as modeller/facilitator and researcher. This chapter presents these reflections primarily from the researcher perspective, with some discussion of the considerations made whilst wearing the modeller hat during the project in order to highlight the use of the mixed methods throughout. Information will be given about the development of the project, the difficulties encountered and the lessons learnt from these difficulties.

8.1 Introduction

Reflective writing is regarded as *"largely concerned with looking back – but with a view to the future"* (Girot 2001, p.3). Reflections occur in everyday life when a person looks back on what they have done and decided what could have been done to improve performance. It is a method used to ensure that the maximum benefit possible is gained from experience. Reflecting on an experience helps a person to link theory and practice, aiding the integration of prior knowledge to new information, developing understanding. Reflecting on experiences, including mistakes, is an important part of the cycling in action research aiding theory development (Susman 1983).

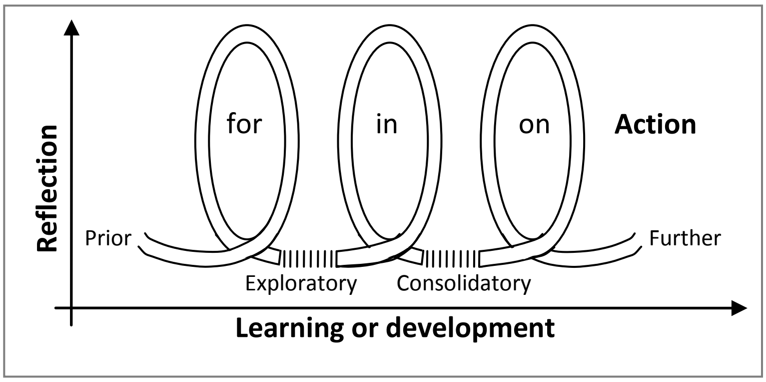


Figure 85: A model for reflection (Cowan 2006, p.53)

[39] The researcher was immersed in the client organisation from early in the research project to become familiar with the research setting prior to the formal system exploration and during the development of the frameworks.

The structure of this chapter will follow Cowan's model for reflection, illustrated in Figure 85. The reflections made consists of: *reflection for action*, the initial thoughts prior to embarking upon the project; *reflection in action*, consisting of several phases of reflection in line with the phases of model development; and *reflection on action*, to look back at the project and present learning points for the future.

The simplest level of reflection is to provide a descriptive account of the events. This should then be expanded by working up through strengths and weaknesses, deconstructive analysis and suggested improvements to future lessons to allow for the maximum learning from the experience. The aim of this chapter is to reflect upon the mixed method framework throughout the action research project and on the research process as a whole. Each of the three main sections of this chapter will endeavour to provide learning transfer in the form of future lessons. The reflection in this chapter is aided by the notes taken during meetings with the client and stakeholders, and audio recordings of key meetings.

8.2 Reflection for action

This section will present the initial thoughts of the researcher relating to the challenges and issues that might arise throughout the project.

8.2.1 The client, the modeller and the researcher

A concern within this research is the role of the modeller versus the role of the researcher, and how this could impact the outputs of the research and the outputs for the client. This research project will take place within a real life problematic system, within which the client has significant motivation to obtain useful insight and solutions. It is for this reason that the project will be undertaken as action research with the client engaging with the researcher and informing the modelling project outputs and in turn the resulting theoretical developments. This project is not intended to be undertaken as a passive case study whereby the framework is tested, but with the view that the proposed framework is reflected upon and adjusted given the application within the system (as is the standard process of action research cycles).

Figure 86(a) is used to illustrate the initial misalignment of the client, modeller and researcher. The client is focused on the answers needed, the modeller is focused on the process to provide the client with answers, and the researcher is focused on the research methodology and required outputs of the research. It is necessary to work towards a situation where the objectives of these three parties do not conflict to ensure a robust research process produces useful insights, illustrated in Figure 86(b) and (c). This could be managed, in part, by the researcher and modeller being the same person; but also by the researcher being actively engaged with and becoming ingrained within the client organisation to develop a sound appreciation of the issues faced, and allowing the client easy access to the researcher, building a helping relationship (Schein 2010).

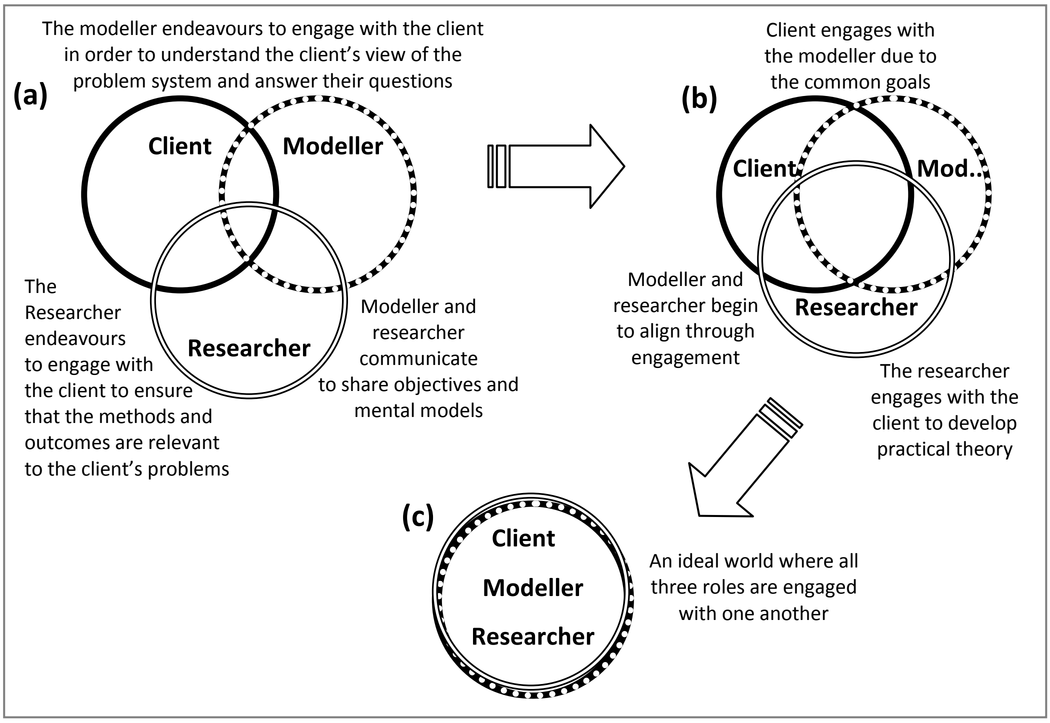


Figure 86: The challenges of client, modeller and researcher engagement to achieve project objectives

Foreseen problems and concerns were the needs and expectations of the client. In general, a client requires the modeller to understand what they want, even when they aren't sure themselves. Communication with the client can play a key role in the success of a project, and is particularly important given the role the project plays as a research output. Failure to communicate effectively with stakeholders and carefully explore the problematic system before choosing the method(s) may result in the modeller failing to capture the system at the desired, appropriate or informative level of granularity (as discussed by Carter and Blake 2004). Therefore it is necessary to build this into the research methodology and factor in time to develop a relationship with the client and engage effectively.

8.2.2 Mixed methods framework

Differences between the model development processes experts in DES and SD each embark upon (as discussed in Tako and Robinson 2008) highlight that it is necessary to undertake a project methodology that does not alienate one method in priority of the other. Healthcare provides a setting rich with complex problems and so the modeller needs to build an understanding and appreciation of the system prior to simulation modelling. Problem structuring methods (PSMs) offer methodologies designed to cope with complex systems and both DES and SD have been successfully used with them in the literature. Similarly, the use of a PSM proactively addresses concerns regarding project complexity which arise in healthcare projects (Carter and Blake 2004). This is in line with Friend and Hickling's (1997) proposition that it is necessary to delve into problems initially prior to working towards decisions. The use of PSMs, specifically concept mapping, is intended to provide an equal footing for both methods during the system and problem exploration stages, enabling a range of issues to be explored.

The proposed model development framework containing the mixed method designs has been developed from the literature to provide a toolbox of concepts to assist the modeller when undertaking a mixed methods project. This framework has been designed to encourage a modeller's consideration of mixed methods throughout all stages of the model development process by placing the designs at the centre rather than at a fixed point in the process. Projects mixing DES and SD described in the literature talk of both the planned use of mixed methods (with the intention of mix from the beginning and the mixed method design tested prior to the real project) and the emergent use of mixing the methods (where the decision was made during the process). It is intended that the mixed method designs will be of use throughout the process: from helping the modeller to explore the system and structuring the problem, to the final stages of model coding and analysis; and to support changes between the methods used in a project (such as from or to a mixed method design).

The frameworks are proposed to ensure transparency of the process for the client. At the start of the project it was useful to be able to talk to the client about how the methods might be used within the system and the roles each may play. From the beginning the modeller was considering mixing DES and SD and sought to bring the client along on the journey. However, at this stage in the action research project the frameworks were still in development. On reflection, this was an important part of the initial engagement process, and more formal discussions around the use of the methods and the mixed method designs may have increased method acceptance.

8.3 Reflection in action

This section presents reflections made whilst undertaking the Beatson project. It is subdivided according to the stages of the modelling project; from system exploration to model outputs. The three cycles within the model conceptualisation and development stages contain two categories: the considerations made by the modeller during the modelling process to clarify the consideration given to various mixed method designs, and reflection from the researcher perspective on the overall process and the applicability of the framework during the project.

8.3.1 The client, the modeller and the researcher

First, the roles of the client and the modeller/researcher within the project are reconsidered. As discussed in the previous section, a modeller seeks to ensure that the project selected fits with the client objectives and needs of the researcher. During the project these potentially conflicting roles were continually reflected upon to ensure that the models developed were useful for the client whilst being appropriate for the research. At the start of the project the modeller aims to become aligned with the client's goals, whereas the researcher has additional goals and objectives for the project. In this project the client was keen to focus on the details of the issues very quickly. The modeller had to manage these expectations and focus on one of the principles of modelling: model simple, think complicated (Pidd 2003). By starting small, and adding, the modeller was able to include important factors in the models at the necessary detail to represent the problem system and answer the project objectives without creating a '*mega model*'.

The researcher was focused on ensuring a rigorous modelling process was undertaken to provide the most transferable insight. The researcher role, in this instance, was not in conflict with the modeller role as the aim of the modeller is to go into sufficient detail to answer the questions posed but no more. The client in this project was interested in the research value of the project which helped to further align them with the researcher and was significant to the success of the project.

8.3.2 System and problem exploration

The interviews and mapping of the system exploration phase involved a variety of stakeholders to capture a range of views, as discussed in *chapter 6*. The key contact at the Beatson had participated in DES modelling previously and so it was necessary to speak to various people from a range of backgrounds to ensure a balanced picture was obtained and the modeller wasn't limited to only a DES-like view. Each stakeholder held in-depth knowledge and personal views of the problem system (the Beatson). They often conveyed that they felt they knew what the issues were and that only the correct way to fix them needed to be identified. However, the differences in the maps created following the first round of interviews highlight that they don't appreciate the extent of the interconnectedness of the system. The stakeholders illustrated the silos of knowledge that is not common throughout the system, and the use of a soft method provided tools to engage with the stakeholders and represent their knowledge of the system in a systematic and scientific manner. This representation (the maps) could then be used to convey this insight to other silos within the system. The stakeholders found value in the mapping of the interviews (one of the participants requested a copy of the map) stating their approval of the process providing a view of the system as a whole. This illustrates the value of taking a broad view of the system and keeping an open mind when undertaking a project, as the choice of modelling method and definition of system boundaries can impact results (Davies et al. 2003). Although the mixed method designs were not applied in practice at this point in the project, mixing methods was borne in mind whilst undertaking the system and problem structuring stages of the framework.

Due to the focus of this research it was necessary to examine the map of the system generated during the mapping process to look at the problems raised, and select a problem theme which appeared to lend itself to SD and DES and was a high priority for stakeholders. This was to ensure that the modelling project remained within the remit of the research whilst being useful to the client (discussed in *Chapter 6*). Several areas of interest revealed during the interviews may have been adequately addressed using data analysis, focus groups or other methods, but the themes in focus were selected for their suitability to be explored using DES and/or SD. During the project the client wants to be sure that the issue selected is the one which is their priority. The use of a PSM enabled a robust process for the selection of a project, ensuring it fulfilled the needs of the client, by its centrality within the issues raised about the system, and the researcher, by its DES-like and SD-like qualities. The system and problem exploration phases of the project have enabled the researcher to select an appropriate project whilst ensuring engagement with the client organisation. This illustrates the benefit of adopting a general OR modelling approach until the modeller feels that sufficient information about the system and problems is known before choosing a simulation method or methods. There is benefit in postponing this decision until after the conceptual modelling, which is discussed next.

8.3.3 Framework reflections (1): Conceptual modelling

The next stage of the project, having selected a problem theme for the project, was the process of developing conceptual models to inform the simulation model(s). The modeller looked to the mixed method designs throughout the process to reflect on how the methods could be used in the project. By considering the mixed method designs in turn the modeller was encouraged to break away from their preconceptions about how the problem should be modelled and forced to at least consider alternatives. Although it is not possible for the modeller to entirely partition their personal preferences for methods, this process provided a structured list of characteristics to consider (the mixed method design, the system view and the dominance of the methods). This benefitted the project as it provided the modeller with clear points of comparison of the designs, highlighted what was known and unknown at this stage in the project.

8.3.4 Modelling reflections (1): Preliminary modelling

The mixed method design selected for the first phase of modelling was *sequential* which was chosen over *parallel* due to the limitation of only a single modeller. It was initially thought that the order in which the methods were used in this project was not important. The modeller could conceptually picture the DES model but remained uncertain about the SD model. However, the uncertainty from the client of what SD would contribute to the project drove the decision to use SD first to encourage buy-in to the method and prevent the project becoming focused only to the view of the client's method preference. It was necessary to maintain the level of engagement with the client achieved to date, but also not side-line the views of the interview participants (from the merged map) as both methods had been identified to have roles to play within the project. The decision to use SD was driven by the research demand rather than the client's method preference. In my opinion, had this been a consultancy contact rather than part of a research project, the client would have commissioned their preferred methods and not had the opportunity to see their system from a different perspective.

On reflection, the order of the two methods played a role in the success of the project. Using a *sequential* mixed method design at this stage in the project enabled the transfer of insight and understanding of the problem from the first model (SD) into the second model (DES). The SD model informed the contents of the DES model and key performance measures, and the understanding developed through the first SD model helped to shape the progress of the modelling project.

Reflecting in the first phase of modelling, the decision to undertake SD first was to acquire a broad view of the system and then develop a better understanding of the system. Had the DES method been undertaken first then the SD method may not have captured as much of the system and its role in the project less significant. This is because it had already been established that the DES view of the system would be nested within the SD view of the system. In the future it is important to establish the extent of the system being modelled and identify the parts of the system the methods would contribute to. It is not advised that SD is always used first: rather modellers should establish the view of the system they believe each will capture and use this to inform the order. If the methods look at different parts of the problem system, with no overlap, or overlap completely (as illustrated in Figure 27b and c) then order may not be important. However, if the methods partially overlap (Figure 27d) or nest then the order should be carefully considered. This point is reflected upon again at the end of the project (*section 8.4.8*).

8.3.5 Framework reflections (2)

The process embarked upon so far encourages the modeller to explore the problem situation and construct hypotheses within two paradigms and broadly approach the problem at hand. This is because the questions to be addressed by the two methods appear separable. At this stage in the modelling the DES model is kept simple to fit with the strategic view of the SD. This allows the modeller to represent the system at a level of detail to facilitate discussion with the client and explore if it is necessary to add further detail: starting simple and adding detail as needed.

For the client, this first iteration of modelling involved producing two basic models; a SD model that captured the first feedback loop in the system to be identified from the merged map and illustrated a key dynamic relationship within the system, and a DES model that represented the main stages of the planning and treatment process capturing the variation in time to reach treatment patients may experience. The two models had a point of commonality: the treatment process, with the SD modelling it simply and the DES able to offer improved insights. This point of commonality meant that the two models were both representing an identical part of the system, but were modelling it with different methods in different ways. This is a specific example of the complementary potential of the two methods. Focusing on this point of commonality helped the modeller to structure their thinking about the objectives of the project and to reflect on what was important to include in the models. Discussing the various possible mixed method designs with the client helped to convey the intention of the models and to depict the roles each method plays in the project. Identifying the point of commonality between the models enabled the modeller to demonstrate to the client the contribution of each model to the other.

This project was becoming longer and more complex than initially expected. As is the case in many modelling projects it is only by getting involved in the organisation and the issues that the modeller is able to get a sense of the problems and the objectives of the project. This meant that the modeller was increasingly able to foresee areas of the system that would be pertinent to include within the system. The process to develop this understanding of the system was time consuming but ultimately beneficial to the progress of the project and to providing useful models. In addition to the modeller's views of the system, the client was engaged in the process throughout providing valuable insights. However, the client frequently sought to increase the level of detail and the complexity of the modelled dynamics which required the modeller to actively assess the value of such reassessed to be able to answer the questions in sufficient detail.

It had been anticipated that the mixed method design would remain the same as it was felt that sufficient information and insight into the problem was known to be able to make that decision. The problem structuring had highlighted the interconnectedness of the system. On reflection this illustrated that the mixed method design of the project was liable to change as understanding of the problem and system developed.

8.3.6 Modelling reflections (2): Considering an *Enrichment* design

At this stage of the project the modeller reconsidered the mixed method design employed and questioned if, given what was known about the problem the most appropriate methods were being used, and are they being used in the most useful way. In any point in a modelling project it may become apparent that additional methods are needed, or (a project already following a mixed methods design) that actually only a single method is required. This section reconsiders in depth the role both the SD and DES methods play within the project, how the DES fits within the SD and if it is necessary to have the models interacting or if an alternative mixed method design, such as *enrichment* of SD with DES concepts, would be suitable.

The first iteration of model development provided useful insight to the client about the relationships in the system. However, there was not sufficient detail in the models to capture the sensitivity of the system to changes in treatment protocol to inform management understanding and strategic decisions, or provide tenable operational solutions. Within the Beatson it is known that new treatment regimes will impact the system but there is uncertainty as to how this technology will change the system and how it could be adopted. The second iteration of model development led to the SD model being expanded to include the impact of new treatment regimes on the time to complete the various stages of the process. Given the nature of the issue being modelled the SD method lent itself to representing the systemic changes, with a DES model capturing the core patient flow through to treatment in order to capture the stochastic nature of this element of the problem (discussed in more detail in *Chapter 7*).

Alternatively, the SD model may be extended to include some DES-like elements to reduce the number of models under construction to one that was explored as a possible or even preferable mixed method design. A detailed discussion is not included in body of this document but can be found in Appendix 10.14 and 10.15.

The SD model (B) created at the end of the second modelling iteration was *enriched* with concepts from queuing theory and DES. Alternative futures for the models were considered, with the DES model being side-lined and the elements of behaviour being captured in the SD model, but this was deemed to require too many assumptions about the dynamics of the system.

8.3.7 Framework reflections (3)

The proposed framework played a significant role in this stage of the modelling by offering mixed method design options to reconsider. When compiling the set of mixed method designs it was difficult to discern any differences in the benefits to the project of that design over another (discussed in *Chapter 5*). The methodology used by the modellers in projects in the literature are described as the ‘most suitable’ or ‘necessary’ implying that there was no other was to meet the project objectives, providing little distinction for this project. However, the designs encouraged the modeller to question why aspects of the system were being modelled in a certain way using a particular method. The characteristics of the design inform it’s applicability to the problem system (discussed in *chapter 5*). Example projects were used to examine the applicability of the mixed method designs but few insights into the different benefits of each design could be discerned; only that the design was deemed the necessary, or only, way for a modeller to represent the system to answer the questions of the project. Interestingly, although the benefits each design are not well established, the modeller was able to discern the value of each design based on the characteristics of the methods they were able to include versus the implications for managing time within the simulation models and the amount of aggregation or disaggregation of the system needed.

8.3.8 Modelling reflections (3): Considering an *Interaction* design

As was considered in the previous modelling iteration, the Beatson process may be simplified to five key stages and behaviour estimated using queueing theory in order to populate the model. Alternatively a SD model may be *enriched* with stochastic elements (DES) to represent queues in an equivalent manner to DES. However, DES enables the inclusion of staff and resource timetables enabling experimentation with schedules, pathways and capacity; all of which are needed to address the project objectives. Developing a DES to further explore this aspect of the system would allow clarification and demonstration of the relationships in the system as required by the client.

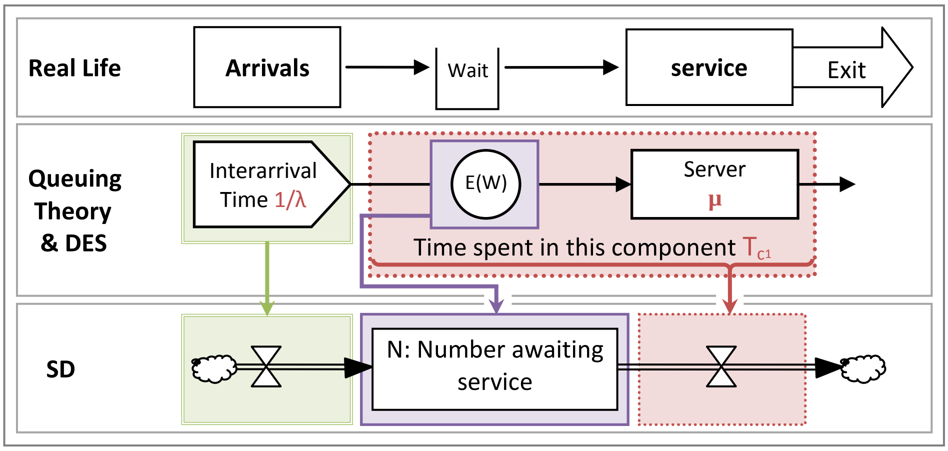


Figure 87: Comparing real life, DES and SD queuing

Queueing systems can be represented in SD but the information required to populate such a model is different from a DES. Figure 87 shows a comparison of SD queues to DES queues. Arrows between the DES and SD representations denote equivalent elements. The elements of Figure 87 are:

- **Arrivals** (**green box**): Often represented as individuals in DES and as a population group in SD. Both models requires the same information of arrival rate [λ] or inter-arrival time [1/λ], but a DES may classically represent this stochastically and assign different rates to different groups of entities.
- **Service** (**red box**): In DES, the modeller defines the time taken to serve a person (or entity); the expected wait [E(w)] is an output of the model due to the space available in the server and the demand (arrivals). However, in an SD model the rate out of the

system needs to be both the time serving and the time waiting; it does not generate the expected time waiting as is done in a DES queue representation.

- **Queue** (**purple box**): While a DES model provides the modeller with the size of the queue and the time waiting per entity allowing them to calculate the average expected wait [E(w)], SD provides only the number of the population remaining within the system (in service or waiting).

Overall, SD requires information about the total time in the system, but DES only requires the service time to estimate the time spent waiting. Both models require two variables to populate these simple models. Arrivals require similar information but the representation of service is different, with SD able to be populated with an output of DES. This illustrates how a DES model can add to a SD model, and highlights the points at which *interaction* would take place or where the SD would be *enriched* with DES. This simple illustration of how the two methods can pass information between one another provides the practical information a modeller requires in order to mix the methods and join models.

Specifically, this is an example of the contribution in the form of hard data DES can pass on to SD models, whether it is in the form of a separate DES model to generate a rate for use in a SD model, or in an *interacting* or *integrated* mixed method design. A discussion of how this could have been implemented in this project, and a more general consideration of mixing DES and SD in this *interacting* design, is included in Appendix 10.15. Additionally, this is an illustration of the insight a DES model can provide to rates within an SD model, and illustrates the different modelling requirements for the two methods. This example proposes a simplified explanation to why frequently DES is used for operational representations of systems and SD to strategic representations.

When representing the radiotherapy planning and treatment process in the Beatson project it was important to understand how the queues built as a result of changes to the resources and service times. Therefore the time patients spent waiting in the system was unknown, so sufficient information was not available to populate the SD model.

All alternate mixed method designs under consideration pass information between the two models, but in different ways:

Soft *interaction* – Models contribute to one another by transferring model insights necessary to meet the objectives of the project. Adopting this design the DES would be used to develop understanding of system relationships, and then represent them in the SD model to generate possible futures. An advantage of this design is that the modeller transfers the insight between models implying that no additional technical skills are needed above their DES and SD modelling ability. It also represents a mixed method design where the modeller learns something from one model and this insight is able to shape the modelling of the second model. However, this design may represent a missed opportunity: it may be possible (and beneficial) for the modeller to consider if data should be passed between models so the data interaction option should also be considered.

Data *interaction* – A more formal mixing of the methods where one method creates input scenarios in the form of parameter data for the next and data is transferred between them. For example: run the SD model over one DES timeframe to give a scenario which can feed into the DES; then, following the DES insight, update the SD policies. The advantage of this design is that the outputs from each model are being fully utilised to inform the other. In this design two models would have to be designed carefully to be coupled, which would illustrate the joined-up view the modeller took of the system. The disadvantage of this design is that it relies on the two models being closely linked, with overlapping system views.

Automated data *interaction* – In this design a SD model automatically feeds a scenario into a DES model, the appropriate number of trials are run within the DES (over the timeframe) and then the results are fed into the SD at each timestep. As with *data interaction* this design requires overlapping system views to ensure points of interaction are identified. Additionally the technical workload of implementing this design may be a barrier to uptake as the number and frequency of interactions between models are likely to justify automating the passing of information.

Integration – Both methods feed data to each other throughout the timeframe of the single model. For the Beatson this design would require extensive data relating to all possible treatment complexity scenarios, and may need a different timeframe. Conceptually this design may be a challenge. This design is described as placing both methods within a single modelling environment and therefore deciding how to model elements of the system (whether to use DES or SD qualities), the level of detail to include and where to set the system boundary may be daunting for poorly understood problems. This design does not appear to be suited for system exploration and understanding; rather it is a design for a system that clearly demonstrates a need to have both methods within a single environment. However, for complex systems this design gives the greatest amount of flexibility for the modeller to move between methods and to change their mind about how system elements are represented.

These designs for mixing the methods were considered prior to and during the third iteration of model development. The models are capable and appropriately structured to enable them to be used together in an automated interactive or integrated design. However, the value of either of these designs was not deemed to be superior to the use of the models *softly interacting* with the transfer of insight. This was due to the limited amount of data available to ensure that all scenarios available within each model when the two interact could be accounted for. The potential additional value for the client over the chosen *soft interaction* design was minimal as they felt it advantageous to be able to engage with single scenarios in the DES model (that were not updating and changing over the simulation *timeframe*) to assess the merits of each scenario themselves. Similarly, the SD model enabled the exploration of different policies without requiring additional extensive data or validation which would be required for an integrated design. Selecting the mixed method design involved a balance to be struck between the time required to develop the models, the mental effort to conceptualise the models and work with both methods, and the perceived value which may be achieved for the client. As with any project, it was possible to add more detail to the models or extend the views of the system represented, but this had to be limited to meet the objectives within the (time) constraints of the project. The characteristics of the mixed method designs provide a basis for this cost-benefit analysis.

8.3.9 Framework reflections (4)

Two separate models are the product of the third iteration of modelling, despite in-depth consideration of a single integrated model due to the explicit roles played by each model in answering the client’s questions. This highlights that care should be taken to only include the detail needed to understand the system at the level required; to disaggregate only as necessary. This can be applied to mixed methods modelling. The technical implications of automated interacting models, or an integrated model design, mean that modellers should take care to develop such models simply because they can.

In terms of the framework, this cycle of modelling utilised the mixed method designs as a checklist prior to the final model coding effort. This was to ensure that the modeller and client were convinced that the most appropriate method(s) for the job were employed; a form of validation of the mixed method design. The mixed method designs provided a means to document what was intended to be implemented, and reflect upon the appropriateness to the client objectives design and the technical requirements to implement such a design.

8.4 Reflection on action

8.4.1 Introduction

The successes and outcomes, observations about the client organisation, the level of buy-in and acceptance achieved, and project outcomes are discussed in this section. These are followed by reflections made and present changes made to the framework and mixed method designs. The section concludes with reflection on the modelling project as a vehicle for research.

8.4.2 The modelling project

8.4.2.1 Successes & outcomes of the modelling project

This modelling project has presented two models representing two complementary views of the system. The models are viewed as complementary as each provides insight which adds to the value of the other model, illustrated in Chapter 7 by Figure 84 which highlights the interplay between the methods, the insights obtained and the complementarity of the two models. There is an element of overlap between the models, with the SD model taking a broader system view but capturing the core elements of the radiotherapy treatment process. The DES model takes a more in-depth view of the radiotherapy treatment process representing the resources and variety of demand, taking the demand as input and outputting key performance measures such as time to first treatment and resource utilisation. Both models have performed specific roles in answering the client's questions. The models present different pictures of the system and provide different metrics, but the results from both are viewed together and are seen to be consistent; that is to say that the model behaviour observed in each is not contradictory. Considering this in terms of triangulation, the two don't offer confirmatory results, but they do work together to provides richer insights than if they were taken in isolation, therefore it may be said that the mixed method designs provides more insight than if two separate models were produced at different points in time.

8.4.2.2 Client buy-in and method acceptance

The client was bought into the modelling project from the start and keen to offer an environment for the research to take place. This provided a supportive environment for the modeller and researcher, making the research possible. Throughout this project the researcher has endeavoured to limit the influence of their personal method preference by referring back to the defining characteristics and benefits of each method when exploring the potential applications of DES and SD. However, the client and each stakeholder also had their own modelling ontology, and preference of methods. In this project, the client was keen to adopt a positivist view and was focused on quantifiable aspects of the system. This meant that their support for and perceived value of the SD model was less in comparison to the DES model. In reference to the SD model, a stakeholder stated *"what you've described is as good an approach as anything else ... it does allow you to go through in a systematic way the influences and impact"*. This statement touches upon the indifference felt towards the SD method as it was felt the DES the necessary method (and the subsequent discussion focused on the detail they felt was needed in the DES). The statement also indicates that SD is recognised as a structured model that enabled exploration of relationships, but another participant that the SD model only demonstrated to them what they already believed to be true about the systems interconnectedness (nothing new). These views presented a challenge for the modeller and further encouraged the cycling between the two models to ensure that one method was not overlooked and deprioritised. This in turn helped to manage the complexity and detail within the DES to ensure that a step back was taken to reassess the project objectives, and ultimately led to insightful, persuasive models.

By the end of the project stakeholders appeared to have accepted the roles of the models, and that the SD model represented some important relationships that impacted upon the DES and so the DES should not be taken in isolation. The two models highlighted that stakeholders with only operational questions and issues need to appreciate the wider system for relationships they may fail to consider. This is not only an outcome of the model but also may be a generalisation for a nested system view.

This project may have benefited from the stakeholder being equally convinced by both methods, but this issue is not unique to this modelling project and occurs in other projects and so it is the role of the modeller, as method expert, to convince the client and stakeholders of the contribution of the methods to the issues they face. Throughout this project the modeller sought to be clear about how and when methods were being used, specifically using the mixed method designs to convey the methodology being used in the current stage of the project.

Positive feedback on the project was received from all stakeholders, but with each finding value in the process at different points (from the initial mapping to the final communication of model results). However, the modeller being a student may have influenced their reaction to the project. The individuals involved all work with students and seek to provide a supportive environment for research and so it may be that the student status of the modeller has influenced the stakeholders such that they remain positive.

8.4.2.3 Usability of the mixed method designs

Throughout this project, I (as the modeller and researcher) considered what mixed method designs would be most suitable to the problem and system. Consideration was given to using queuing theory and DES characteristics to *enrich* the SD model, informal *soft interaction* between the SD and DES models through the transfer of insight, formal *data interaction* between the two models and an *integrated* design. Additionally, it might have been possible to use DES as the primary method and code SD-like behaviours within the model, or embark on a highly DES-based route and just use the SD model for initial exploration. The only design not under consideration was the use of *parallel* models of the same system view to enable comparison of insights. This was because two perspectives on the same issue were not sought by the client. This remains an applicable design for other projects, but in this instance the project required a transfer of insight during the modelling process and the models to capture two different but nested system views. Although some of these designs can be applied easily within off-the-shelf DES and SD simulation software, they should be recognised as alternative mixed method designs. In my experience throughout the project the designs acted as archetypes of mixed DES and SD modelling. Although not as detailed as SD archetypes, they provided a starting point for the modeller to reflect upon.

8.4.2.4 Future projects

Other projects in the client organisation have already been identified as possibly solvable using SD and DES. When undertaking the next project it should be noted that the intention is not to work through the list of mixed method designs and apply each. A future project would involve returning to the merged map of the system to select a problem area for exploration. In future cases the researcher is keen to apply a different mixed method design which influences the selection of a problem area but, as with this project, the design is liable to alter throughout the modelling process.

8.4.3 The client, the modeller and the researcher

At the end of the project the modeller, researcher and client engaged in the process and sought to achieve a common goal: to provide useful, practical insight into the behaviour of the system given possible changes in treatment regimes. The modeller prioritised providing client value and the researcher provides research value by demonstrating the client value obtained through sound research methodology which, as discussed earlier in this chapter, is not necessarily contradictory. Modeller and researcher provide complementary engagement into the process. From the researcher perspective, the value is held in demonstrating the power, usability and applicability of the mixed method design. In future action research projects of this nature into project methods it is necessary to continuously consider the roles of each of these stakeholders throughout the project and discuss concerns if there is poor engagement between these three roles. If the modeller finds that the problem system does not lend itself to the methods proposed by the researcher then the researcher must engage with the modeller and adapt their theory, as is the nature of action research.

8.4.4 The benefits of both SD and DES

Overall, the two models present two complementary views of the system, with each adding value to the other through the understanding developed during the modelling process. In relation to the questions posed around changing treatment regimes, the two models agree on the direction of the impact on the system, with SD able to illustrate the range and scale of the impact of some changes, and the DES illustrating the ability of the system to cope on a day to day basis.

Although numerous articles in the literature propose the benefits of each method, the emphasis of these differ depending on where on the spectrum of soft to hard the applied method lies. The key difference, and benefit to the project, observed by the researcher during the modelling intervention was the different world views of the problem system each method adopts. Although each method may be adapted (*enriched*) to create a method similar to the other, the overall philosophies of each method encourage the modeller to think of the system in terms of two different perspectives. These are often referred to as the operational and the strategic perspectives. These two terms are often pigeonholed to imply that DES and SD are ***only*** applicable to systems that conform to these respective perspectives. However, it should be noted that these terms do not represent two different types of system but rather two views the modeller might take of a system: the operational perspective is one which considers how the system can be made to function (such as what shift pattern needs to be applied), and the strategic perspective is one which considers what makes the system function (such as what is the maximum hours staff should be working).

Within the project at the Beatson, these two perspectives boil down to how the resources could or should be allocated throughout the system to cope with the demand, and what factors impact these resources. This project demonstrates that answers to both are needed to obtain an insightful view on the problem system. Considering only how to allocate the resources (utilising only DES) may have led to poorly informed conclusions. Similarly, using only SD within the project would have required the method to be stretched to include stochastic events, individual entities and detail complexity. Therefore, in this project, trying to apply SD in isolation may have resulted in utilising an enriched mixed method design.

This modelling project utilised SD first, followed by DES as it was intended that the SD model would capture a larger system view. Equally a modeller may choose to use DES first in the same situation to obtain a detailed insight into a smaller part of the system prior to modelling the wider system. The order in which methods are used reflects a modeller's preference, the information available to a modeller at the time and what the project appears to dictate.

A DES model is not always used for operational problems and a SD model is not always used for strategic problems. This project used SD to capture the broader issue of technology adoption. However had another problem theme been selected then this may not have been the case: an SD model could be used to represent the dynamics within a single entity or server in a DES model. Therefore how the methods are used within mixed method designs is also flexible.

8.4.5 Potential of mixed methods

This research project has highlighted that it is often possible to use mixed methods, but the value and explicit need is not always justifiable. In this project there were numerous instances when another method could have been used, or that a more complex mixed method design might have been employed, but if it was actually necessary was considered and the cost of employing a more integrated design was unjustifiable versus the benefits. In this project, the models could be taken further into a single interacting model but this would require further assumptions about the system and would push the data (rather than the methods) further than necessary.

Much as one method may be employed in a project to address a single or multiple objectives (Figure 88A & B), more than one method may be used for similar purposes. Figure 88C illustrates that two methods may be used, overlapping or not, to answer a specific objective. Alternatively, more than one method may be used to address a number of objectives (Figure 88D). The system exploration and problem structuring stages of this project provided real examples of these configurations. Several issues raised might have been addressed using a single method, but it was apparent that others would benefit from more than one method: with a *sequential*, *enrichment*, *interaction* or *integration* mixed method design; or that several methods might be equally suitable to provide comparative insights (*parallel*). The applicability of the range of configurations and the mixed method designs proposed in this research to the Beatson project highlights the theoretical relevance to the real world.

In terms of practice, this illustrates that mixed method designs fall within different categories which may inform how modellers select one. In terms of research, the designs could provide groupings for researchers to re-evaluate their mixed methods projects, and inform the practice of mixing methods.

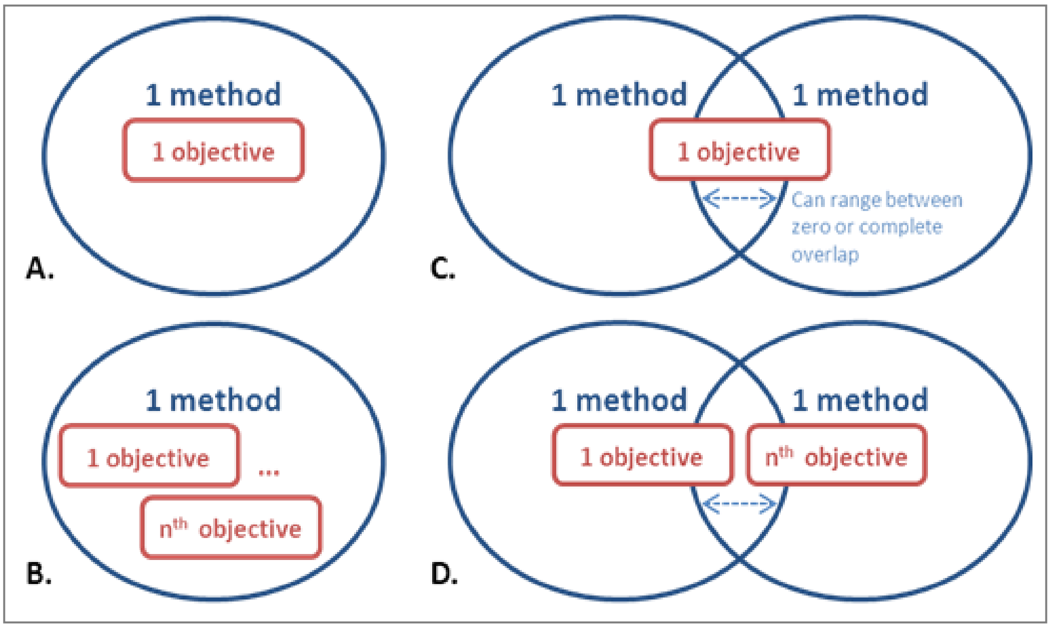


Figure 88: Various configurations of methods to address objectives

Considering the general question of the value of mixed methods there are three types of situation: systems that must be modelled with more than one method, and those which could. Mixing methods seeks to apply the benefits, characteristics, and/or philosophical views of more than one method. This may be due to: necessity, as one method is unable to suitably capture the problem; conformity, as other similar problems have been addressed using such combinations of methods or it is the recommended course of action (according to literature and/or specialist knowledge); or curiosity, as the modeller and/or problem owner/client suspect there to be benefits to be had from utilising more than a singular method.

It is important to appreciate that it cannot be assumed that sufficient understanding of the system and problem have been obtained to determine if the methodology must, should or could benefit from utilising mixed methods. In particular, in the first instance, necessity, it may not be apparent that the insights to be garnered require the use of more than one method. It is also not clear cut which situations best suit a singular "isolated" method, but it is possible to tap into the benefits mixed methods offer and how methods are and could be used together to ensure modellers are suitably informed of the options available to them should the necessity, desire, or curiosity arise. Such designs for mixing methods are intended to inform the modeller of the various possibilities and challenge their preconceptions of how a method might be applied to a problem system (this is considered at a practical level in section 8.4.8 where the amended toolbox of mixed method designs is presented (Table 19)).

8.4.6 Model development framework 2.0

This section reflects upon the modelling framework and mixed method designs proposed, and how these have been adjusted during and following the research project.

Within this project, mixed methods were considered from the outset; during system exploration, problem exploration, problem selection, conceptual modelling and throughout the model development stages. This has allowed both the modeller and the client to continually consider if, how and why more than one method might be applicable to each problematic situation posed. This in itself encouraged both the modeller and the client to challenge their preconceptions regarding how each issue might be addressed and weigh up the various methods evaluated to be suitable. Through this process several issues were examined in more depth than might have been done, and some issues which seemed simple on the surface were revealed to be complex (such as the capacity of the system: which is subject to significant fluctuation due to staff work patterns, holiday and on-going recruitment).

Following a project, a modeller may reflect on the process and conclude that an alternative method to that used might have been preferable. Modellers are therefore encouraged to reflect upon their decisions during modelling project, and a toolbox of mixed method designs is proposed for this purpose. Mixing methods could encourage a modeller to think about the various modelling options available rather than remain firmly within their usual method(s).

8.4.7 The contribution to the model development process

The theoretical framework presented in chapter 3 of this thesis proposed that the modeller must acknowledge their own preference, education, and other influencing factors when selecting the methodology to address a given problem and system. The developed designs for mixing are presented as a tool to encourage the modeller to think outside of their usual comfort-zone, providing analogies for possible paths through the uncertain terrain of modelling. When scoping the problem and system, thinking about mixing methods alongside multiple single methods encourages a more diverse view by encouraging the modeller to justify and challenge each method proposed and reflect on how it can be used with other methods. Encouraging the modeller, and the client, to challenge their preconceptions surrounding a particular method facilitates new thinking about the problem and the system, and the relevance and potential of the method.

The modelling process embarked upon within this project sought to implement these theoretical contributions and evaluate if they hold any promise of supporting modellers in the future. The cyclical model development process encouraged the modeller to develop insight throughout, and reflect on what methods are chosen and how they are used on several occasions. This project illustrates that it is not possible to concretely select a single modelling design from the outset, but maintaining a flexible methodology offers the opportunity to escape the method trap and engage in mixed method modelling.

Throughout the modelling project it was considered whether the framework should be changed to reflect the more 'unstructured' nature of reality. In this project all stages were not cycled through precisely but more in a two steps forward one step back motion to keep pushing forward. The toolbox of mixed method designs was felt to approximately lie at the heart of the process providing structure to refer to and reflect upon throughout in a light, semi-structured manner (not always taking place at fixed points). However, the explicit utilisation of this toolbox was not as frequent as was foreseen, but took place in a more formalised in depth manner around the cycling between problem structuring, conceptualisation and development of the simulation outline. The examination of past examples enabled the researcher to consider what the potential benefits would be of using a specific design of mix, and what price would be necessary to pay – be it cost, time or detail.

The designs were used to enhance thinking in the project and focus on the potential for methods to model aspects of the system. Had these designs not been considered it is likely that the modeller would have sought to use a single method, or not adjust their view of the system as readily throughout the project.

The framework proposed at the start of the project places mixed methods at the centre and was designed to encourage consideration of the designs between every stage of the modelling process. In practice, reconsidering the mixed method design of the project took the form of re-conceptualising the problem and so consideration of the designs should be formally placed within the conceptual modelling stage (illustrated in Figure 89). That is not to say that consideration should only be made in the design and conceptualisation stage: it has a place throughout the coding of models, and during the development of solutions/understanding. This stage is returned to throughout the modelling project and it was at this point that the mixed DES and SD nature of the project was considered explicitly.

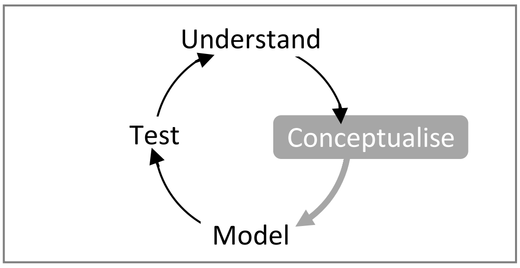


Figure 89: Simple 4 stage model development cycle (adapted from Robinson 2004, fig.4.1)

A mixed method modelling design has been considered at all stages of the system exploration and model development process which encouraged the modeller to remain open to all issues. Structured consideration of mixed method designs took place within the development of the conceptual model and simulation outline and the framework has been updated to reflect this (Figure 90). The phases and stages remain as described in Chapter 5.

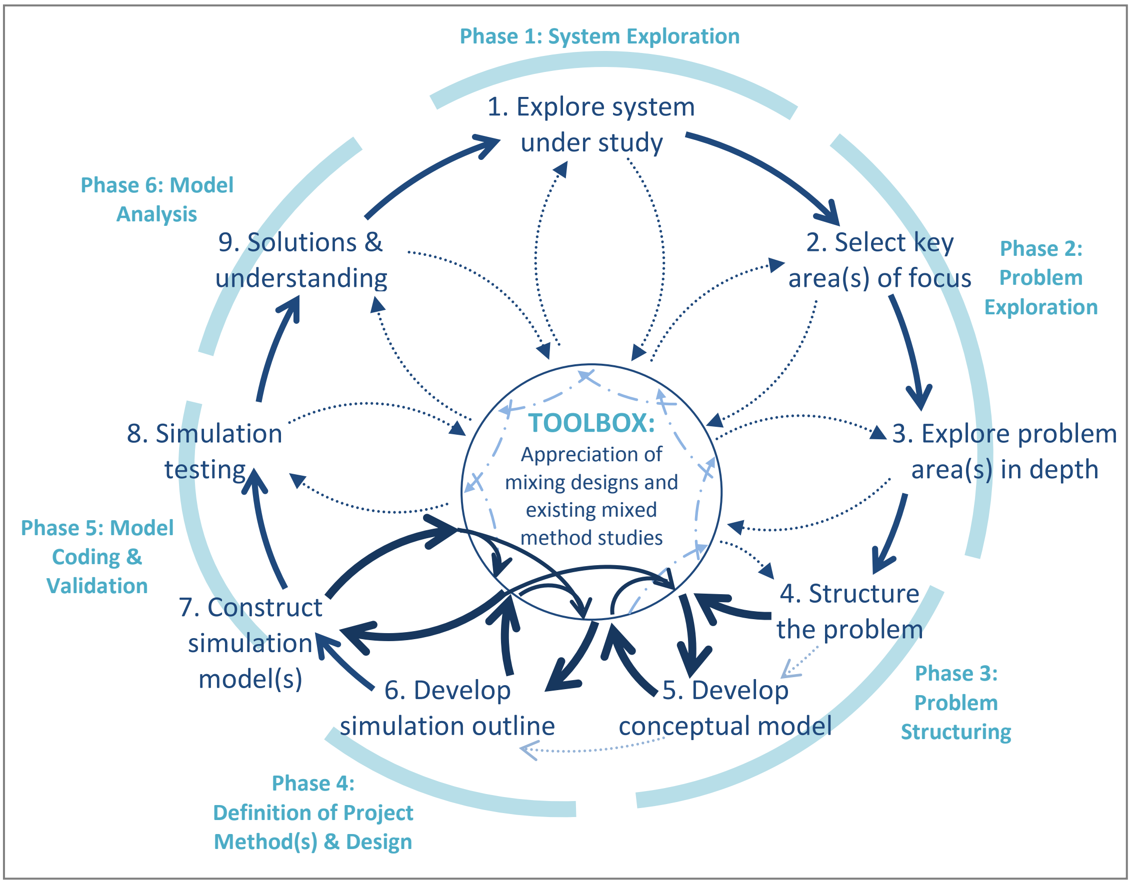


Figure 90: Mixed Methods Model Development Framework 2.0

8.4.8 A toolbox of mixed method designs

8.4.8.1 View of the system

In this project the SD model was always used to take a broad view of the system with the DES capturing a portion of this system view, and altered slightly as the modellers understanding of the problem and system developed. The use of a diagram to represent this helped to highlight these small changes. The main benefit of explicitly stating the system view was to convey the role and scope of each method to the client and stakeholders. However, the system view may be very broad, with little detail included. Therefore two characteristics are proposed: scope and detail.

Figure 27 in *Chapter 5* is extended and shown in Figure 91, where the order in which methods are used is not apparent in situations (a) and (b), and order likely to be important in situations (d) and (e). The overlap in the methods (highlighted in red in the diagram (d)) represents an overlap in the views captured by each method and may reveal potential points of commonality between two methods. This modelling project found that for situation (e) method A contributed insight which helped with the development of the method B model.

However, personal modeller choice will also play a role in the decision, and the level of understanding the modeller has of the parts of the system the methods capture.

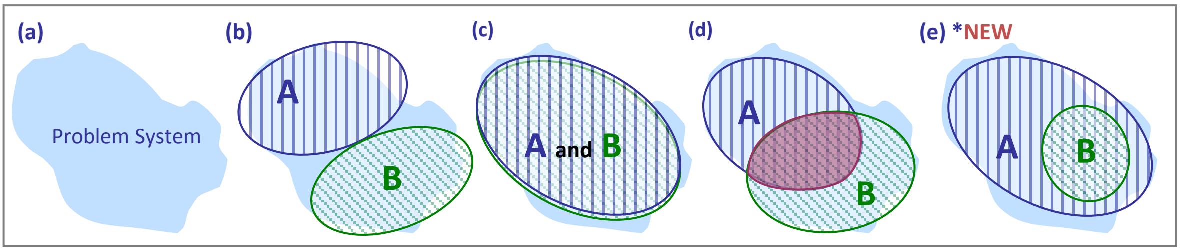


Figure 91: System view 2.0 – How mixed method design of methods A and B may capture the problem system.

8.4.8.2 Method dominance

Dominance was proposed as a concept to convey the order in which methods were used and if they were applied equally or with one method was used substantially more than the other. The dominance of the methods however was not found to be easily represented, and is closely related to the mixed method design and the system view.

8.4.8.3 Mixed method designs

This project has provided the setting for the researcher to examine the applicability and practicality of the theoretical designs to describe, inform and reflect on mixed methods modelling in a complex healthcare problem system. Reflecting on the project leads the researcher to propose an extra layer to consider: the type of interaction between the models. Models may interact softly to pass information and insight, or more formally transfer data. Interaction may be informal or automated to occur at fixed points in time or subject to specific levels being reached/events occurring (such as in hybrid modelling). Therefore, the modeller should state the mixed method design and the amount of interaction between the models.

Table 19 contains the mixed method designs with the updated characteristics. These characteristics include the direction, form, number of and frequency of interactions between the methods. This table is proposed as a tool to support the selection and conceptualisation of a mixed method design, to prompt modellers to consider the design in turn to explore what their models might look like. All designs were applicable when describing example project from the literature (as discussed in *Chapter 5*) and were used to reflect upon throughout the modelling project with the Beatson. For all of these designs, no matter what name a modeller gives them, there are 5 characteristics of a mixed methods project that this researcher proposes should be explored and stated by a modeller:

1. Acknowledgement of the *number of methods* used in a systematic manner in the project. That is that if more than one method has been used but in complete isolation from one another then it is not mixing methods.
2. Acknowledgement of the *number of paradigms*: a modeller may feel they are adopting two methods from the same paradigm or not. This, alongside the modellers own philosophical standpoints, may influence if the methods should be mixed (paradigm incommensurability), and may indicate the acceptability of the mix. As was experienced in this project, using modelling methods from two different paradigms can be a challenge conceptually for the modeller alongside the required technical knowledge of each method.
3. *Overlap of the system view*: Do the models overlap and capture the same parts of the same system, or each represent clearly distinct parts of the system?
4. *Method interaction:* if the models will pass information between each other, the type of information passed (soft informational insight or hard data), the direction information will be passed (from one method to another or between both methods), the number of points of interaction, and the frequency with which it takes place.
5. *Project Output*: This is a characteristic of the mixed method design, and is unlikely to be a key decision making element. However, the number of models produced provides may influence the modeller's decision to adopt a design if moving between designs when significant work has been undertaken in one or two model environments, but is unlikely to be influential when first determining the roles of the methods.

The first characteristic is centred on the modeller's belief that the problem theme within the system can be suitably addressed using a single method, or might have elements which lend themselves to other methods. This is the idea that when thinking about the system, more than one method springs to mind. In the case of a *parallel* design, the whole problem theme may be captured by either method and it is felt that a comparison between the methods might be insightful. Alternatively, in a *sequential* design, one element of the problem theme may need to be better understood prior to addressing the remainder of the problem theme (the issues may be separated into two phases). With an *enrichment* design a primary method is selected but an element, or elements, of the system lend themselves to being modelled by an alternative method. As the number of elements of the problem theme become split between the methods into two or more clusters (models) an *interaction* design might be considered. Finally, an *integration* design may be the only viable solution if these clusters are large in number or completely inseparable.

Table 19: Toolbox of mixed method designs 2.0 – a guide to mixed method designs for modellers

Mixed Method Design	**Isolationism**	**Parallel Design**	**Sequential Design**	**Enrichment Design**	**Interaction Design**	**Integration Design**
Number of possible methods under consideration	1 only	more than 1	1 or more	more than 1	more than 1	more than 1
View of the system	Single view of the system	Two possible representations of the same system	Need to capture different parts/behaviours of the same system	Need to capture different parts/behaviours of the same system	Need to capture different parts/behaviours of the same system	Need to capture different parts/behaviours of the same system
Number of separable roles of each method under consideration	All issues from the problem theme fit within a single method	Single problem theme requiring complementary insight	Single problem theme with issues separable into more than model	Single or multiple role(s)	Single or multiple role(s)	Single role of the methods under consideration – inseparable questions
Interaction likely	-	No	Yes	Yes	Yes	Yes
Direction of interaction	-	-	One direction	One **OR** Both directions	One **OR** Both directions – if only one then sequential design	Both directions
Form of interaction	-	-	Model insight and hard data	Hard data only	Model insight and hard data	Hard data only
Frequency of interaction over time window	-	-	**Once** – single pass of information or data from one model to the next	**Low to High** (Likely to be high)	**Low to High** (Likely to be **low**)	**Low to High** (Likely to be high)
Number of points of interaction	-	-	Single to **m**ultiple	Single to **m**ultiple	Single to **m**ultiple	Single or Multiple (Likely to be multiple)
Triggered or regular interactions	-	-	-	Triggered by the state of the system **AND / OR** Regular, every X timesteps		
Number of models created	1 only	more than 1	more than 1	1 only	more than 1	1 only
Comments	Modeller should remain open to adopting another method as the project progresses	Same system modelled by each method (at least two) for complementary insight	Each method captures different parts of the system or at a different level of detail.	Frequency of interaction and whether it is triggered or regular depends on the master method.	Models developed can operate independently, but work together to contribute to the problem	Methods function together as a single model.

Note: The shading on this table is used to highlight similar characteristics across the mixed method designs

Within the Beatson project the DES was designed to explore the implementation of strategies, whereas the SD was a representation of the considerations when developing such strategies. The models had separable but overlapping roles which led to the final design of softly interacting models. Therefore the number of methods suitable for modelling the problem system may not be the only factor for considering a mixed methods project design. The client or modeller may believe it is preferable to produce a single model or more than one model to answer the questions about the system. If more than one model is to be produced then modellers should consider if the order in which they are developed is important, if one will inform the other, if they will represent the same (or parts of the same) problem theme and if interaction between them is necessary. More than one model may be used when an issue within the problem theme requires more investigation (in detail) or a more general view alongside the issues covered another model.

The left hand side of Table 19 provides a series of characteristics of mixed methods designs which the modeller may use to decide to adopt a mixed method design or to rule out mixing methods or specific mixed method designs for their project. Modellers are encouraged to consider how each possible characteristic may apply to their project. This table may be used in practice during modelling projects as a prompt to ask questions about the problem system they are seeking to provide insight into.

The overview of the mixed method designs presented in Table 19 illustrates the characteristics of the different designs from the model perspective. However, as was discussed in Chapter 5, the problem and system should inform the methodology selection rather than the methodology define the problem system explored. Therefore, contrasting this model perspective with the problem system perspective, the modeller should focus on the system being modelled and the problem in focus. Specifically this related to the view of the problem system that is required and whether the issues may be split into distinguishable groups which, in the modeller’s opinion, may be modelled using DES and SD. Expanding on these characteristics it is possible to provide a list of questions for modellers to ask themselves throughout a modelling project, specifically when moving from a conceptual model to model coding:

Number of Methods:

- Are both DES and SD feasible modelling methods for the problem system?
- Do neither DES nor SD on their own offer the model characteristics you require to model the problem system?

System View:

- What view of the system is required?
- Do DES and SD encourage different perspectives of the system?
- Can a more coherent view of the system be obtained if both DES and SD are used?
- Could each method capture specific and different parts of the system?
- Would a second method (DES or SD) only be required to represent a small part or characteristic of the system?

Separable method roles:

- Can the roles of DES and SD within the project be separated or partitioned according to the issues or questions being posed?
- Would DES and SD each perform different roles within the project?

Method interaction likely:

- Is it foreseeable or has it become apparent that information would need to pass between the methods (such as information about an expected wait in part of the system, a change in the demand on the system, or a delayed response)?

Direction of interaction:

- Will information be passed in one direction only between the methods, from DES to SD only or SD to DES only? If so, the modeller should explore the use of a *sequential* or *enrichment* design.
- Will information pass between the methods in both directions, DES to SD and SD to DES? If so, the modeller should explore *enrichment*, *interaction* and *integration* designs.

Form of interaction:

The information which may be passed between methods can take the form of insight or data to inform or populate the other method (described as *model insight* and *hard data* in the table). Consider:

- An *integration* design produces a single model and therefore the interactions between DES and SD need to be hard data.
- An *interaction* design maintains separate models of DES and SD with defined passing of information. This design enables the modeller to draw insight from one model to inform the other and vice versa and for the interaction of hard data.
- A *sequential* design may transfer model insight, hard data or both from DES to SD (or vice versa), but characteristically involves only a single occurrence of interaction between the methods.

- An *enrichment* design may adopt soft interaction whereby the theoretical perspective of SD is applied within DES (or vice versa). Alternatively, and more commonly, an *enrichment* design may adopt hard data interaction which refers to enriching one method with technical aspects of the other, such as enriching SD with discrete events.

Frequency of interaction:

If information will be passed between the DES and SD elements, how frequently will this occur? For example, if only a single pass of information is envisaged then it may be preferable to maintain separate models, adopting a *sequential* design. If the interactions will occur multiple time then *enrichment*, *interaction* and *integration* designs should be considered.

Number of points of interaction:

The number of likely interaction points may be identified by considering how many elements of the system are common across the methods used. This is not a clearly defining characteristic of the mixed method designs but may be used in conjunction with the frequency of interaction to inform a modeller's decision between an *interaction* and *integration* design. An *interaction* design develops more than one model which may not be preferable if the number of points of interaction and the frequency of interaction are high.

Triggered or regular interactions:

This characteristic in conjunction with the frequency and number of points of interaction should contribute to the modeller's decision to adopt an *interaction* and *integration* design.

Number of models created:

This is the output of the mixed method design and may inform the selection of the design due to modeller and/or client preference.

The decision to use DES or SD is based on a modeller's understanding of the problem and the system, but may be informed by their understanding of the characteristics of each method and examples available. Similarly, characteristics and examples of mixed DES and SD designs are presented to similarly inform a modeller's method selection. These characteristics summarised in Table 19 form a decision tool for modellers to use throughout a project to aid the selection of a mixed DES and SD design. When using this decision tool modeller's are encouraged to reassess their decisions and consider alternative designs throughout the modelling process. These characteristics should be considered throughout a modelling project, and specifically explored by the modeller at the conceptual modelling and model coding stages.

Consideration of these points throughout the modelling project of this thesis helped to steer the modeller to a suitable mixed method design, and confirm why other designs were not suited to the problem system. They are proposed to help modellers explore mixed method designs, and why a design is suited or not to a problem system. This works encourages modellers to not just think of mixing DES and SD, but provides a tool to help explore how the method could be used together in a project. The focus of the tool is DES and SD, but further work may be undertaken to expand it to be applicable to other OR methods.

8.4.9 Validity of the research process

Although this project may not be directly reproducible given the continuously updating regimes for radiotherapy treatment at the Beatson, the process embarked upon is reproducible and generalizable. The application of DES and SD within this project is not the only mixed method design for these two methods. This project may have utilised SD to inform the DES at a different level (such as within a single work centre), or by including different DES characteristics within the SD (such as stochastic elements or entities).This project has only utilised a subset of the proposed mixed method designs, but is used to demonstrate their usefulness in conceptualising and modelling the problem.

8.5 Conclusion

This chapter has reflected on the application of the mixed modelling framework and designs for mixing methods within the project undertaken at the Beatson. Whereas the previous chapter outlined the contribution and outputs of the models, this chapter presented the reflections made throughout the modelling process on the frameworks proposed to support model development and the realised value of mixing methods.

The modelling process was informed by the toolbox of designs for mixing methods throughout. The framework and designs encouraged the modeller to continually reconsider the role of each method within the project and how the models should be used together. This enabled the modeller to produce an auditable trail of the modelling process and enhanced the validation of the project by building confidence in the process and models.

The system and problem exploration process has furthered the researcher's understanding of how OR methods can be applied to all aspects of a project: from hard OR with simulation and data analysis, to an appreciation of soft OR methods for the elicitation of information from the client, and data acquisition. There is no single best approach to mixing methods; no single solution to the challenge of what to do in practice can be offered. However, lessons in the form of support systems to aid model development can be taken from published projects and by reflecting on a being a modeller within a mixed method projects. Adopting a flexible, adaptable model development process supports a modellers evolving understanding of a system and rejects methodolatry[40] (Salt 2008). Numerous methods are often applicable within the same problem system and it is beneficial for the modeller to consider other methods, and therefore consider mixing methods, to challenge their preconceived views of the system and adapt to their emerging understanding.

Although the goals of the researcher and the modeller initially appear to be disparate, the only stage of the project in which they are not completely aligned is in the initial problem selection. At this point the modeller is keen to address the client's core issues, whilst the research goal is to select a problem area important to the client but one that could be explored with mixed methods. However, as is discussed in this chapter, this did not present a problem for several reasons: the number and range of issues raised within the project that lent themselves to a range of modelling methods and the overall applicability of both SD and DES within the system.

The framework and mixed method designs offered the modeller useful concepts to help with the modelling process. The framework encouraged the explicit consideration of mixed methods, which has been found to occur at the conceptual modelling stage of the modelling process. The mixed method designs provided the modeller with a toolbox of options to consider and "trial" throughout the modelling process and enabled the modeller to select a mixed methods design that was most appropriate and fitted with the client's requirements for the project without having to make excessive assumptions about the system.

[40] Methodolatry – the worship of method; to follow blindly and to the letter (without reflection and trial and error)

9 Discussion

This research has explored the potential to mix DES and SD and proposed frameworks to describe and inform mixing these methods. Frameworks, including a toolbox of mixed method designs, intended to incorporate mixing DES and SD methods into the method selection and model development process were developed from analysis of the DES, SD and multimethodology literature. The practicalities of these frameworks have been explored through an action research project within a healthcare organisation which informed adjustments leading to the proposal of framework 2.0.

The following chapter presents a précis of the main conclusions reached through this research. The research agenda is first reiterated, followed by discussion of the theoretical and practical contributions of this research to the research literature. The limitations of the research are presented and finally, other areas of research for further investigation are suggested.

9.1 Research Agenda Recap

This thesis has sought to contribute to the theory and inform the practice of mixed DES and SD modelling. There was uncertainty in the field with regards to if and how these methods can or should be mixed, acknowledgement that modellers of each method need to see past their own preference, and interest in conceptual and practical frameworks to inform mixing DES and SD. It was the aim of this research to explore the potential of mixing DES and SD and the variety of ways which the methods could be mixed; consider if and how the two methods might be used together; examine frameworks to inform how mixing methods can be included in the model development process; then explore and develop these ideas in practice.

The objectives of this research were:

Obj 1. *Obtain a broad understanding of: how DES and SD compare; how modellers choose between them; and the theoretical concerns for mixing OR methods and DES and SD specifically.*

Obj 2. *Gain an in-depth understanding of why and how DES and SD have been mixed, theoretically and practically to inform on issues important to key stakeholders in the past; and what problem situations, particularly healthcare, have been shown to be amenable to mixed DES and SD.*

Obj 3. *Explore the development of frameworks to support mixed method modelling with DES and SD, and how these fit within the modelling selection, design and development process.*

Obj 4. *Reflect upon the value of and challenges faced when embarking upon a mixed DES and SD modelling project within a healthcare organisation, and how insights from a healthcare project could be transferred to other organisations.*

The contribution of this research has been to develop a modelling framework to describe, inform and support the use of mixed methods. This toolbox of mixed DES and SD designs encourages an appreciation of mixing methods and forms a decision tool for consideration prior to, during and following simulation modelling to support the concise description, adoption and implementation of mixed DES and SD modelling. This framework was developed through examination of the literature and the use of a live healthcare action research project.

9.2 Thesis Summary

Chapters 2 and *3* examined the literature in the fields of DES and SD, and multimethodology. *Chapter 2* compared the characteristic features of the methods, the problems they are used to explore and the systems which they are used to represent. *Chapter 3* considers the wider decision process of method selection, explores the value in mixing methods versus the methodological and philosophical standpoint, and examines case examples of mixed DES and SD. These chapters revealed that there is a need for clarity around the language used, the potential value of mixing and a practical framework to incorporate mixed methods into a modelling project.

Chapter 4 presented the research design; detailing the philosophical standpoint of the researcher and how this informs the research methodology. The research objectives were presented which were derived from the research questions developed through the literature review.

Chapter 5 presented the preliminary toolbox of mixed method designs developed from the multimethodology literature and the initial proposal to incorporate an appreciation of mixing methods within the method selection and model development processes. This chapter assessed the appropriateness of the proposed toolbox of designs by applying them to existing published mixed DES and SD case studies.

Chapters 6 – 8 discussed the action research project undertaken to explore and develop the framework and designs within healthcare – an environment rich for both DES and SD modelling. The system and problem exploration process was presented in *chapter 6* and the developed models were described in *chapter 7* from the modeller perspective. The action research project enabled the practicalities of the proposed frameworks to be examined and reflected upon which informed adjustments in the proposed framework and designs (discussed in *chapter 8*).

The following sections highlight key theoretical and practical contributions, limitations and weaknesses, and the opportunities for further research. The sections are structured around the four research objectives of this thesis.

9.3 Key contributions

9.3.1 Objective 1: Comparing DES and SD, choosing between the methods, and theoretical concerns for mixing methods

This work sought to explore what makes a model DES or SD, and what characteristics of the methodology and its representation of the problem system contribute to a modeller's decision to use DES or SD. Examination of the literature emphasised the need for researchers and practitioners to be clear about the methods they select and how these methods have been or will be used within a project.

As discussed in *Chapter 2*, the methods have both some distinguishing and overlapping characteristics. Although defining characteristics and classic applications of the methods exist there are also characteristics not definitively belonging to one method exclusively. The methods have been applied in a variety of ways to create models in practice, and the characteristics of these models contribute to the perceptions of the methods.

When a model displays multiple characteristics from each method it is unclear whether it is DES or SD. This research has presented a range of philosophical, methodological and practical perceptions of DES and SD. Comparing the classic characteristics of DES and SD has provided the modeller with a framework to inform method selection[41], and is designed to help decide when it would be more appropriate to describe a model as mixed methods. Similarly, a problem system can display multiple characteristics and raise questions which

[41] This comparison of characteristics was used to aid selection of an appropriately DES-like and SD-like problem theme for the action research project.

may be addressed by a variety of methods. Characteristics can be mapped to this comparison of DES and SD to aid method selection.

Mixed methods proponents ask why it is necessary to make a binary choice between methods (discussed in *Chapter 3*). In modelling there is often no single solution to the question of which method to use. How a modeller selects methods for a project is influenced by their training, experience and ultimately their personal preference (or hierarchy). As a result a modeller, and their client, may have restricted views of how a method could be applied to a project which in turn potentially limits the benefit the method can provide. As discussed in *Chapter 3*, modellers use their own experience of methods in practice. This research posits that modellers can benefit from being aware of their own preferences for selecting methods and how they are applied. Being open minded to mixing methods, in the same way that it is necessary for modellers to see beyond only the methods they prefer, enables modellers to select the most appropriate methodology for the problem and system.

Whether DES and SD should be mixed has been debated by academics and practitioners. Every modeller has their own individual philosophical and methodological perspective of each method, which informs the potential to mix methods. However, mixing methods remains a popular subject. Barriers to mixing methods can be conceptual rather than philosophical, with modellers interested in mixing DES and SD but uncertain how to conceptualise the problem system to mix methods in practice.

9.3.2 Objective 2: Why mix methods, what problem systems to mix in, and how to mix

9.3.2.1 Why mix methods – the potential value

Methods are mixed in practice to: deal with a complex problem system, support stages of a project, obtain specific benefits from specific methods, and overcome shortfalls of methods (Howick and Ackermann 2011). The rationale for mixed DES and SD projects are similar: the most suitable (or only) way to answer the questions raised, the client requested specific method(s), the system is unique and complex, the desire to do something different, the need to obtain comparative insights, the apparent stages of insight required. These can broadly be split into two groups: personal preferences of the modeller and/or the client and the specifics of the problem system. Mixing methods, with respect to research design, aim to triangulate findings, compare or compare something new (Bryman and Bell 2007). However, *Triangulation* is not frequently discussed as the main purpose or benefit of mixing in the context of mixed DES and SD. For these two methods, a *parallel* mixed methods design is described as comparative rather than confirmatory (such as in Morecroft and Robinson 2008). Rather than cross-check the validity of the results from one method with the other, the value frequently presented in mixed SD and DES projects is the ability to capture something greater and provide additional insight over one of the methods in isolation.

Comparative studies of DES and SD highlight the potential value of mixing methods. Comparison of the methods in this thesis is made using three perspectives: problem, system and methodology. When mixing methods a modeller may see to include methods based on characteristics within these perspectives, but it is not necessary to include them all. For example, a DES model enriched with feedback is only an adjustment in terms of the methodology; the same problem as would have been addressed with an SD model is addressed, and the system view is not adjusted to a broader scope of the system.

Both DES and SD models are presented in the literature in numerous forms: in some cases they may only look like a single method model but the dynamics of interactions may be informed by the principles of another. The software available for modelling DES and SD often enables the user to build these concepts in easily, but this is an adjustment from the original method paradigm. Recognising and stating this would help to clarify how the methods are used and how modellers perceive the methods which may in turn help the field of mixed DES and SD to develop. As discussed in *chapter 2*, there are implications on the development, running and validation of the model[42] should the modeller fail to appreciate the method(s) they are using.

9.3.2.2 What problem systems are amenable to mixing methods

The analysis of mixed case examples enabled the researcher to examine the various problem systems where mixed methods have been used. SD, or DES, plus another OR method are used in projects which may be typically described as appropriate for DES or SD, respectively, or for the other method. Overall the range of contexts where mixed methods are applied follows a similar pattern to those where each method is used in isolation. However, the key characteristic highlighted in all cases is the need for something more, some additional insight that, had a single method been used, would not have been obtained.

[42] Feedback within a DES model may lead to longer warm-up times being required, and random events in SD would imply several runs would be needed.

DES and SD are popular methods when modelling healthcare. Mixed methods lend themselves to any messy, wicked problem. Healthcare systems, due to their complex interrelated nature appear to lend themselves to mixing methods.

The interview and mapping process undertaken at the start of the action research project highlighted the complexity of the system, but also that several methods might be suitable for addressing specific issues (discussed in *Chapter 6*). Appropriate methods were considered for all issues raised and identified in the merged map and three problem themes were identified within the system, both of which being important to the stakeholders and which might have benefited from a mixed use of SD and DES. This has highlighted the rich potential to mix methods within this complex system. The themes of the issues raised are not unique to the Beatson, and mixed SD and DES projects in the literature are undertaken within a variety of systems. For this reason mixed methods are widely applicable but their uptake is dependent on the modeller examining the range of methods suitable to their situation, their propensity to mix methods, and their preference for methods.

The potential to use both DES and SD within the project was identified during the initial system exploration and problem identification stages of the action research project (*Chapter 6*). The problem theme was specifically selected for both its potential DES-like and SD-like issues and its importance to the client. Although at the system and problem exploration stage the researcher-modeller was unsure how the methods would be mixed, it was apparent that both would be able to contribute to the issues raised. On reflection, had both methods not been used the researcher-modeller would not have been able to provide insight into the links between the implementation of new treatment regimes and the impact on staff experience which results in a lagged roll-out, and the net effect of new regimes on patients time to reach treatment. The SD model is able to concisely represent the underlying dynamics of the effect observed in the DES model: of how the implementation of new regimes leads to changes to patient treatment times which are not as initially expected. Therefore the use of mixed methods provided additional insight not foreseen at the start of the project whilst enabling the modeller to examine a suitable strategy and to examine the operational impact of such a strategy (day to day impact).

9.3.2.3 How have and can methods be mixed

Neither DES nor SD should be viewed universally as the best modelling method for every problem system. Each may be applied to a variety of problems along a spectrum of ways and because of this a single design for mixing DES and SD is unlikely to exist. There is likely to be a range of designs for mixing these methods to fulfil the needs of the modelling project, as is evident in the wider multimethodology literature.

This research has collated a set of mixed method designs to describe mixed DES and SD projects (*Chapter 5*). These designs provide a common language and lens through which to read mixed DES and SD projects, and have enabled the researcher to characterise 5 distinct designs of mixed DES and SD. Previously there was overlap between how these projects were described: integrated or hybrid. The designs contribute to clarifying the similarities and differences between the project methodologies. The rationale for mixing methods observed in the DES and SD projects from the literature are in line with those highlighted by Howick and Ackermann (2011) whereby the problem dictated the necessity: to deal with a complex system, to support the stages of a project, to obtain specific benefits or overcome weaknesses of the methods and complement one another[43]. Therefore the mixing of DES and SD occurs for the same reasons as mixing OR methods in general.

The designs are presented to encourage modellers to reflect on the model(s) developed, and aid the transfer of methodology insight. During and following the action research project these designs were utilised and reflected upon to consider their applicability within a real-life project, and potential to inform how the modeller chooses to use both DES and SD. These designs represent various ways to mix the methods, and are proposed as a set of mixed method archetypes for modellers to consider throughout the modelling process.

As was discussed in *Chapter 2*, DES and SD methods may be employed along a spectrum[44] with overlapping characteristics, aims and applications. The comparison of the methods presented at the end of *Chapter 2* illustrates the characteristics along which the methods are stretched. Although the methods are able to be stretched careful consideration is needed regarding the impact these changes have on the robustness and value of the method. At some point in this stretching a model can be referred to as an *Enrichment* mixed method design, whereby a method is adjusted to include characteristics of another. Where this delineation occurs is difficult to define, much like where a river leading to the sea changes from being defined as freshwater to saltwater. This design may be more widely used than would appear

[43] Note that there was some overlap between the papers used by Howick and Ackermann (2011) and those discussed in *Chapters 3* and *5*.

[44] SD spanning from use as micro-worlds to boundary-objects (Zagonal 2002); and DES ranging from simulation as a process for social change to simulation as software engineering (Robinson 2002, 2003) (see *Chapter 2*).

in the literature as most DES and SD software packages provide modellers with such flexibility that they may already be mixing methods in this way without acknowledgement. This research has highlighted this issue and uses this as evidence of support for the use of mixed methods in the fields of DES and SD.

9.3.2.4 Summary

Proponents of either method may have a preference to use their method in isolation, but mixing methods provides the modeller with additional options which may have value over individual methods. The potential value of mixing the methods and how the methods have been mixed in practice was unclear. Difficulty lay in taking lessons from published work due to the inconsistency in language, the range of terms utilised to describe similar mixes, and the lack of standard sample models to draw upon for inspiration and reflection. This research has sought to address this gap; to remove the confusion inherent in applying ambiguous terms (hybrid or mixed) by providing a standard basis for comparison.

The multiple views held on *if* and *how* to mix DES and SD led to the recognition that no single solution to the mixed DES and SD conundrum could be posited. Although several mixed DES and SD projects appear in the literature, it has remained relatively novel. Why modellers decide to mix, and how the mix of methods is undertaken remains unresolved. Cases discussed in the literature emphasise their uniqueness and that a specialist solution (of mixed methods) was required to model the system in order to address the objectives/questions of the project. Structured analysis of these cases enabled the researcher to garner learning points and provide a set of mixed method designs which may be used as archetypes of mixed methods systems, and led to the development of the proposed model development framework for mixed DES and SD modelling.

9.3.3 Objective 3: Propose a framework for mixing and consider how this fits within the modelling selection, design and development process

This section presents the contributions of placing an appreciation of mixing methods within the model development process and toolbox of mixed method designs as a result of the conclusions drawn from this action research study.

9.3.3.1 A mixed DES and SD model development process

This research found that limited guidance existed to assist modellers with mixed DES and SD modelling. Given the range of ways that DES and SD have been used together in projects discussed in the literature there is no single correct way to mix methods. Rather the modeller should be open to the spectrum of uses of DES and SD, and the possibility of mixing methods, to ensure an appropriate project methodology is chosen. A model development framework that included consideration of mixing DES and SD was lacking. Although differences in the model development process of DES and SD exist (as discussed in *Chapter 3*), the frameworks for each method are similarly iterative in nature. It was therefore decided appropriate to adopt a general OR modelling process which explicitly included an appreciation of mixing methods. Placing mixed methods at the heart of this process is designed to encourage the modeller to consider mixing methods during method selection. The toolbox of mixed methods designs discussed in the next section forms a decision tool to aid a modellers selection of a mixed method design for use throughout the modelling process.

Throughout this modelling project the mixed method design altered as the modeller and clients understanding of the system developed. Imposing consideration of mixed methods at an arbitrary point in the model development process may limit the model value. The modelling project was reflected upon to inform the reality of developing mixed methods models. Modellers should appreciate the option of mixing methods throughout, but explicit consideration of and reflection on the mixed method designs is of most use within the conceptualisation and model coding stages. This was seen in practice in the modelling project and the modeller frequently utilised the mixed method designs to reflect on the models being developed and how best to answer the client’s questions.

9.3.3.2 A toolbox of mixed method designs

In addition to this framework a toolbox of mixed method designs has been proposed to encourage modellers to reflect on the various considerations that this researcher believes to be important. Table 19 (in *Chapter 8*, p.230) illustrates the mixed method designs following reflection during and post the project with key questions for modellers to consider throughout their project. These designs were used by the modeller during the Beatson project to determine the project methodology, and may be useful to other modellers when creating a conceptual model to inform them of the key elements of the design. The designs are ranked in the table according to the complexity of the mix, which are discussed next.

The mixed method designs are characterised by the interaction between methods: the type, direction, frequency, and number. When developing mixed method models both data and insight may be transferred between methods (interaction type). The direction of the mix (one way or two) is likely to influence the order in which the methods are used in a project. The frequency of interaction between methods may be at a single point in time (such as in a *Parallel* or *Sequential* design), at fixed points in time (*Interaction* design) or be triggered by the state of the model (*Enrichment*, *Interaction* or *Integration*). The number of points of interaction between methods provides an indication of the complexity of the model(s) and may help the modeller decide between developing one or two models (an *interaction* or an *integration* design). These features denote the functioning of the mixed method design and if they are not considered then the model(s) may not behave as expected. Additionally, these designs highlight the adoption of multiple modelling paradigms which a modeller may wish to justify.

If an SD model is used to generate demand which feeds a DES model of a service process, the demand may in reality respond to the timeliness of the service provided, or be isolated from it. Modellers need to consider the value of developing models that interact in a complex manner. If the impact, significance or amount of passing of data between the two methods is not sufficiently high, then would two separate, *sequentially* developed models be sufficient, would an enhanced model appropriately represent the issue(s), or is it necessary to move past interacting models onto more complex *integrated* modelling? That is not to say that modellers should be put off *integrated* (hybrid) models, but it is advised that they are not undertaken on a whim. Rather, as illustrated in this thesis, it may become apparent through the project that a greater number and frequency of interactions are needed, and that the modeller can step over to a new mixed method design. Therefore the toolbox represents an aid to choosing mixed method designs, with a progression into deeper mixed method designs that a modeller might consider.

Based on the experiences of the modeller in this project, it is recommended that mixing methods is borne in mind when problem structuring and that the mixed method designs are reflected upon throughout the complex process of conceptual modelling and model coding, to ensure that the modeller continually considers the range of methodology options (methods or mixing). With a similar notion to requisite modelling (where a modeller seeks to represent the behaviour of the system without unnecessary detail), the designs could be used to avoid an unnecessarily complex model.

The models were created in a spiral of development, essentially a sequence of SD then DES modelling. As the project resulted in two models (each model iteration built on the previous model) it is worth considering why a simple sequential mixed method design was not undertaken. This was because the view of the system adopted to address the questions surrounding changing of treatment regimes nested one method within the other (DES contained in the SD view). This meant it was necessary to align the two models and transfer insight throughout development. This resulted in insights being obtained in the transitions from one method to the next, and emphasised the points of interaction possible between the models

9.3.3.3 Summary

There is no simple solution to complex modelling. There is software available that enables the development of models using multiple methods but the interactions between the elements of methods must be thought out and coded by the modeller. Careful appreciation of the timing, frequency and purpose of interactions between methods is important to ensure that the model behaves as expected and desired, and provide modellers with characteristic elements of their mixed method design. The experiences of the modeller on this project reveal the importance of reflecting back on the toolbox of mixed method designs between the problem structuring, model conceptualisation and model coding stages of the process. The proposed frameworks are intended to be a first step towards developing best-practice for modellers to ensure a robust, replicable mixed methods model development process is in place. As encouraged by Pidd (2012) undertaking mixed methods modelling needn't be an overly complex process and the proposed frameworks seek to simplify the process as much as possible.

9.3.4 Objective 4: The value of mixing DES and SD, the challenges of healthcare modelling, and the transferability of insights

This section presents the realised value of the mixed DES and SD project and the challenges faced in healthcare. It concludes by reflecting upon the transferability of insights to propose generalised value of each mixed method design.

9.3.4.1 The realised value of mixing DES and SD

Within the Beatson project the methods had clearly defined roles but required some shared information (DES was designed to explore the implementation of strategies, whereas the SD was a representation of how the considerations are made when developing such strategies). The models had separable but closely related roles, and during the project the overlapping view of the system meant that both models had some common elements, and points of interaction between the models were identified, which led to the final design of softly interacting models. Therefore the number of methods suitable for modelling the problem system may not be the only factor for considering a mixed methods project design. The client or modeller may believe it is preferable to produce a single model or more than one model to answer the questions about the system. If more than one model is to be produced then modellers should consider if the order in which they are developed is important, if one will inform the other, if they will represent the same (or parts of the same) problem theme and if interaction between them is necessary. More than one model may be used when an issue within the problem theme requires more investigation (in detail) or a more general view alongside the issues covered by another model.

The project utilised DES and SD in a softly interacting mixed method design. However, prior to model development an extensive system exploration and problem definition process was undertaken with the stakeholders. Therefore, this project has sequentially progressed from a problem structuring method and then onto iterative simulation model development resulting in the softly interacting models. This sub-section discusses the realised benefit of these two key elements of the mixed methods project.

This research finds in support of the already documented potential positive value of using a problem structuring method within a simulation project. Causal mapping of interviews with stakeholders at the Beatson enabled acquisition of a holistic view of the system and its interrelated issues. This enabled the modeller to focus on an important issue whilst demonstrating an appreciation of the wider concerns, leading to buy-in from all stakeholders, even those not involved in decisions relating to the issue in focus (the changing of radiotherapy treatment regimes). Therefore the use of causal mapping within this simulation project gave value by assisting the modelling of the process, revealing the problems to be explored from the multiple stakeholder perspectives and led to the process (not just the models) impacting the stakeholders beliefs about the system.

The realised value of using SD and DES in this project was the ability to capture a systemic view of the system and a process view. Using both of these methods the modeller was able to consider and capture parts of the system that would have been simplified, omitted or not even considered had the two views of the system not been considered throughout the process. By referring to their own experience in each method, and example projects, the modeller was able to challenge their own views of how the system should be modelled and what should be included. Archetypes of system behaviour in SD illustrated the types of issue that could be captured which encouraged the modeller to include them in the model. This meant that aspects of behaviour not always thought about, such as how possible strategies to change treatment regimes might alter in light of the performance of the system, and how performance may be defined in terms of throughput and the research reputation of the centre were explored and captured in the models.

The value of mixing DES and SD by using a *softly interacting* mixed method design was that the modeller has been able to represent the system from two perspectives each with differing foci. More generally, the value of mixing the two methods was found to be the passing of insight between the two views of the system.

9.3.4.2 The challenges of mixing DES and SD in healthcare

A challenge of embarking upon an OR project within any organisation is that stakeholders and the client all have their own preferences for the methods used. As discussed in the research design of this thesis (Chapter 4), all individuals may see the world through differing lenses. Individuals each have their own philosophical views of what constitutes reality, and useful information. Some of the stakeholders involved in the project had distinctly positivist views of the world, looking for quantitative justification of any solutions proposed. Similarly, other stakeholder adopted a more holistic view of the world, recognising the value of insights and shared understanding. This meant that different stakeholders took different value from each of the stages of the model development process, with some interested only in the final numerical outputs; others focused on the inclusive nature of the project and were appreciative of the emerging insights obtained throughout the project. On reflection, the use of the problem structuring process enabled the modeller to engage with the individual views and the two simulation methods enabled representation of the system at two levels of focus.

Healthcare has a history as a setting for simulation and mixed method projects. Healthcare systems are complex and so offer rich settings for research into modelling processes. Although the modeller was required to develop an understanding of this complex system in order to build the models, this was not the largest hurdle of the project. The main challenge was how to conceptualise a mixed method model. This was achieved by iteratively bringing together the two models to identify the points of interaction and highlight the type of information (data or insight) passing between the methods. Healthcare offered a complex setting, but the ability of the modeller to conceptualise the model(s) of the project is not an issue unique to healthcare. Just like using any method (such as SD or DES) it takes practice and guidance to mix methods. Simple example models illustrate the functionality of mixing methods, but may oversimplify the development process by failing to demonstrate the struggle to decide how the model will work. This research has sought to describe a complete project which undertook a repeatable process for others to draw insight from, providing guidance.

In any project, gaining stakeholder buy-in to the project aims, modelling process and the project outcomes can be a challenge. The experiences of this project are no different, but the process embarked upon enabled the modeller to utilise methods that matched across the personalities. All stakeholders were motivated and engaged with the overall purpose of the project: to develop understanding of the system. Additionally, participants are part of an active research centre, and therefore most were engaged with the parallel purpose of the project to undertake research. This meant that the challenges experienced were likely to be similar to other modelling and research projects in other settings.

9.3.4.3 Transferability of generalised value of the mixed method designs

As discussed in the previous section, healthcare offers a rich, complex and interconnected system for modellers to explore, and researchers to adopt as research settings. The insight into mixing methods obtained within this complex system are viewed as transferable to other settings since the methods of interest (DES and SD) have much broader applications than just healthcare. The theory has been developed from the general DES, SD and multimethodology literature rather than situation dependent texts.

This project has provided insight into the challenges and practicalities of mixing DES and SD within a healthcare system. Values obtained by using a softly interacting mixed method design are transferable to other systems using the same mixed method design, and may contribute to the value of other designs. All other mixed method designs were considered throughout the iterative model development with the Beatson. Reflection on this process provides the researcher with insight into the values of each design, based upon experience within a single project:

- ***Isolationism*****:** single, well documented, accepted and supported method
- ***Parallel*****:** the value of two perspectives into the same system view enabling comparison of behaviours.
- ***Sequential*****:** enables progressive emergent insight through the generation of data or insight in one method to pass to the next.
- ***Enrichment*****:** enables the modeller to remain within their preferred method providing a unified view of the problem system but capturing a system characteristic not traditionally captured by that method. The design involves adopting characteristics of another method within a single software environment.
- ***Interaction*****:** enables representation of the problem system from similar or differing perspectives, with differing foci. Characterised by two models which can function both separately and as a single model, offering the benefits of both methods independently with additional insight garnered from the links between the models. Both models can be tested and validated independently prior to linking.
- ***Integration*****:** enables systems previously unable to be modelled to be represented; generating insight where it wouldn't otherwise be achievable. This design is for modelling complex systems that have a variety of behavioural characteristics requiring numerous and frequent bidirectional points of data interaction between the methods.

The general value of mixing SD and DES that can be taken from this project is that mixed methods are used to model system(s), and the problem(s) within them, described in such a manner that they cannot be modelled with a single method. Therefore the systems are more complex in nature, and the modelling is required to capture this complexity. Decisions need to be made with regards to what is modelled (as with a single method modelling project) but also what connections are needed between methods and models. The challenge for the modeller is to identify characteristics of both methods and the mixed method designs within the problem system.

9.3.5 Summary of contributions

This research has examined why, when and how to mix DES and SD to model problem systems. One problem system could be modelled by a variety of methods. Similarly, parts of a problem system could be modelled by a variety of methods. Therefore why must modellers choose one method over the others; mixing methods enables the modeller to select all the methods which suit the problem and system. Utilising a general OR model development process encourages the modeller to explore the system from both DES and SD perspectives. This research provides a toolbox of mixed methods designs for modellers to consider when embarking on the conceptual modelling to model coding stages of a project to encourage frequent reflection on the use of mixed methods.

In a mixed methods project the modeller needs to decide the role of each method within the project and the amount of interaction between the methods as these characteristics inform the mixed method design that may be adopted. Although the value of each mixed method design is based on reflections made on a small number of cases from the literature and the action research project, the designs illustrate the potential of mixing methods and begin to highlight that more complex mixed method designs (with high numbers of interactions) are used for projects where the modeller sees no other suitable solution to address the clients problems.

This thesis has discussed that a project methodology should be informed by the problem and system. However, as a modellers understanding of both develop over the course of a project, their perception of the problem and system is liable to change, which may also require the method to change. Embarking upon a project with a single fixed view of the appropriate project methodology could distort or restrict a modeller’s view of the problem system. Considering mixed method designs alongside isolated methods whilst undertaking a modelling project provides an adaptable and proactive approach to modelling. If OR is a toolkit of methods then it is appropriate to include within it a set of mixed method designs and considerations when mixing methods, to extend the range of modelling options available to OR practitioners.

9.4 Limitations of the research

This section will reflect on the limitations of this research. It will consider the limitation of the research design, and the limited generalizability of the research contributions.

9.4.1 Healthcare & Action Research

The output of action research is *"not intended to be context bound"* (Huxham 2003, p.2): the theoretical development in the form of a framework of mixed method designs to support mixing methods is not intended to be situation specific. As was discussed in the research design (*Chapter 4*) and earlier in this chapter, healthcare offers a rich complex environment to develop the framework and examine the usability of the mixed method designs. Although the concepts of this thesis have only been examined in the context of a healthcare project the theory and models developed are not unique to a healthcare system. The two simulation models are specific to the needs of the organisation but are recognisable as closely aligned with classic applications of DES and SD. The intention of this research was to develop a framework to inform model development, not generalizable healthcare model(s).

The research process was documented from the perspective of the modeller and the researcher, alongside feedback from the client and project stakeholders throughout, and the quality of this research should be assessed on its recoverability rather than replicability (Checkland and Holwell 1998) as no two situations are able to be identical in every aspect.

An action research study would ideally go further, for longer and observe the changes experienced as a result of the project. However, the theory developed relates to the mixing of DES and SD, not to healthcare studies, therefore the change (action) observed is the altered understanding of the system throughout the modelling process. In order to propose the frameworks we have observed 3 cycles of reflection which adds robustness.

9.4.2 Single modelling project

This thesis has discussed a single project. Case study research would prefer more than one case is used. However, this research took the form of an action research study. Care was taken to iterate through the reflective cycles of action research, with three iterations taking place over the three iterative cycles of model development. This reflection enabled the researcher to reconsider the theories being developed in the research (the mixed method designs and model development framework). This research did not seek to evaluate the effectiveness of these theories, but propose useable, actionable theory.

This research applies the proposed frameworks within only a single organisation. The limitations of this are that only a single unit of analysis is presented, and the findings could be project specific. The advantage however of the use of a single research setting was that the modeller/researcher was able to become ingrained within the organisation and ensure a valuable contribution to the system. The length of the intervention provided rich insight into the modelling process of this single project, from conception to solutions and understanding.

9.4.3 Single modeller

This project has been undertaken by a single modeller/researcher. This has a significant impact on the generalizability of the decisions made, such as which methods to apply to the project, but not on the process embarked upon. Whether another modeller would have produced the same models given the same information in the same setting is a question equally applicable to any modelling project. Action research places the individual at the centre of enquiry (McNiff and Whitehead 2006), whereas case study research is focused on the system. The reflections made throughout the project are the modeller's; meaning that a single detailed insight into the process of mixing methods is offered rather than a comprehensive summary of multiple views. A general consensus of views would be interesting but it was not the intention of this research to propose the best or most accepted view of mixing DES and SD: it was the intention of this research to explore frameworks and reflect on their applicability to provide insight from the modeller prior to, during and after the project.

9.4.4 Research outcomes

This research has focused on DES and SD simulation methods. A general model development process from the literature was undertaken with an appreciation of mixing methods and therefore this incorporation of mixing methods into the model conceptualisation to model coding stages is likely to be transferable and useful to the broader OR community. The toolbox of mixed method designs presented began as a collation of designs from the multimethodology literature and remains relevant within this field in general. The specific characteristics of each mixed method design (described in Table 19) may be transferable to the OR simulation field, and the wider modelling community but the appropriateness of the characteristics of the mixed method designs would need to be re-evaluated.

This research has proposed a set of mixed method designs, but only a subset was implemented (*Sequential* and *Interaction*). The applicability of all designs has been illustrated in *Chapter 5*, but further lessons may emerge if a similar project to this was undertaken that resulted in their use. Using these theories in practice will help to further develop their applicability and usefulness.

9.5 Further research

Throughout this research several areas of further research were revealed relating to the DES and SD mixed method field, the wider field of mixing OR methods, and the area of modeller choice. This section will outline 6 areas for further research.

9.5.1 Decision processes for selecting methods

Why choose any method? A method may be chosen because we have to, or we want to. A modeller can select a method because it is the most suited or only option. Alternatively they may choose a method because they want to use it: out of preference for the method, to demonstrate their ability or the feasibility of the model, because they have the opportunity to choose, or for novelty (learning). Expanding on the value of mixed methods would help to pick apart why modellers feel that a mixed methods model design is their only option; or whether there are elements of wanting to select a method.

A modeller's personal perception of methods influences their decision to utilise methods (discussed in *Chapter 3*). However, it remains unclear how modellers select methods: what are the decision-processes involved and key factors in this process? Given the discussion around how to classify OR methods into methods, methodologies, philosophies, would a taxonomy of methods aid this selection process? Questions to explore include: are methods selected based on the perceived value such as social engagement, dynamic, visual; are they considered as a hierarchy of methodologies (the tier above methods – such as simulation in general); which characteristics of the methods form part of this decision process; and, if modellers seek out problems that fit with their suited method(s), what informs this problem selection? This could contribute to the definition of OR methods and how to use them in practice. Additionally, the answers to these questions could impact the decision to mix methods and would provide insight into the requirements of mixed methods over single methods.

9.5.2 Perceptions of mixing methods

It remains unclear how modellers decide to undertake mixed methods, how they talk about mixing methods, and how they decide which mixed methods design is appropriate and preferable? It is proposed that further research could continue to look at published modelling projects which involve a mix of DES and SD to examine further how those undertaking the project explain the methodology. Additionally, speaking to modellers rather than relying on published work would help to unpick the similarities and differences between the value of mixed DES and SD projects.

Similarly, there is scope to examine the literature more widely, and speak to OR modellers in general. Speaking to simulation modellers to capture insights from those that: mix methods, don’t mix methods, or don’t identify that they mix methods, would enable the researcher to explore what mixed method designs are used in practice, and the motivation, rationale and acceptance of mixing methods. Equally, this could be extended to all mixed OR methods projects (not just simulation) to explore how the methodology is explained and justified by the modeller(s), and accepted by the client(s). This would enable the exploration of barriers to mixed method modelling in general.

9.5.3 Value of mixing methods

This research sought to contribute to understanding of the process of mixing methods, and comment on the value. However, the overall value of mixing methods, remains little understood. We know it can be useful, we know it can be the only way to address the problem system but where is the value of mixing occurring? Research is needed into pulling apart the value of mixing methods, and answering the question of whether mixing actually provides more than the value of each method on their own. Analysing existing models to evaluate the value of each method used would fail to capture the value of the process and so observation of and discussion with modellers is needed.

9.5.4 A toolbox for mixing methods

This research has revealed the characteristics of the various mixed method designs and suggested the value of mixing within this project. In undertaking other mixed methods projects it will be possible to explore the applicability of other designs and shed light on the value of these designs. Specifically, views may be gathered into the value of each mixed method design within mixed DES and SD projects, and the applicability of the designs to other methods. These values may then be used alongside the characteristics of the mixed method designs to inform selection.

This research has undertaken modelling with an appreciation of mixing methods on a single project. Further modelling of other issues within the Beatson system or other problem systems (in and out of healthcare) would further illustrate the practicalities of considering mixing methods throughout a modelling process. This would enable the value of mixing DES and SD to be explored on a range of issues by modellers reflecting on their use throughout a modelling project. Observing other modellers using the toolbox of mixed method designs as a decision tool would enable exploration of whether it encourages the undertaking of mixed methods and if it is readily useable by others.

9.5.5 Wider application of the framework and mixed method designs

An extension of this research could explore what other OR methods could be used together according to this framework, and if this framework and designs are equally applicable to a wider set of OR methods. Since the framework and designs were devised from the OR mixed methods literature, not only mixed DES and SD, it is likely that they are applicable, but there may be more designs used with other methods.

9.6 Thesis Summary

This research has presented a review of the literature and developed a framework and toolbox of mixed method designs and mixed method characteristics to describe and inform the undertaking of mixed methods projects. The value observed in the action research project were that the mixed methods framework was open to capturing a broad range of issues, the project challenged stakeholders' beliefs about behaviour of the system, enabled exploration of the value of changing to more complex treatment regimes, and identified process restrictions and limitations to changes in treatment regimes within the Beatson. The research contributions have been to develop a framework of mixed method designs to contribute to the description and adoption of mixing methods, the creation of models depicting the dynamics of a radiotherapy treatment process with the Beatson West of Scotland Cancer Centre, and the proposal of a mixed methods toolbox to aid the mixed methods design selection. The impact of this research has been to change the understanding of stakeholders within the Beatson using this novel framework for mixing methods, and to present this research to practitioners and academics at OR meetings to encourage the adoption of this approach to modelling.

10 Appendix

10.1 Use of PSMs with SD and DES

Table 20 summarises some papers examined that describe the use of SD or DES with a problem structuring method (PSM). These additional methods include Soft Systems Methodology (SSM), Cognitive Mapping, Cause Mapping, Strategic Choice Approach (SCA) and the general 'softening' of the modelling approach. This table demonstrates that both SD and DES have been used in studies with 'softer' complementary methods to facilitate model development, and provide transparency to and involvement in the model building process.

Table 20: Sample of mixed methods papers discussing SD or DES with PSMs

Method	**Complementary Method(s)**	**Author**
DES	Cognitive Mapping	Sachdeva, Williams & Quigley (2007)
	SSM	Gunal & Pidd (2005), Kotiadis & Mingers (2006)
	Soft methods	Robinson (2001)
	Group Support	den Hengst, de Vreede & Maghnouji (2007)
SD	Cognitive Mapping	Ackermann, Eden & Williams (1997)
	Cause Mapping	Howick, Eden, Ackermann & Williams (2008)
	SSM	Coyle & Alexander (1997), Lane & Oliva (1998), Paucar-Caceres & Rodriguez-Ulloa (2007), Vos & Akkermans (1996)
	SCA & SSM	Lehaney, Clarke & Paul (1994, 1999)

10.2 Supporting Information for System Exploration

The ‘shaping’ stage of the SCA process discussed in section is shown in Figure 92. The process embarked upon at the Beatson is similar to this ‘shaping’ stage, which involves listing decision areas, sorting decision areas by categories and levels, refining the expression of decision area, building a decision graph, highlight areas of more significance, superimposing organisational boundaries, selecting problem foci.

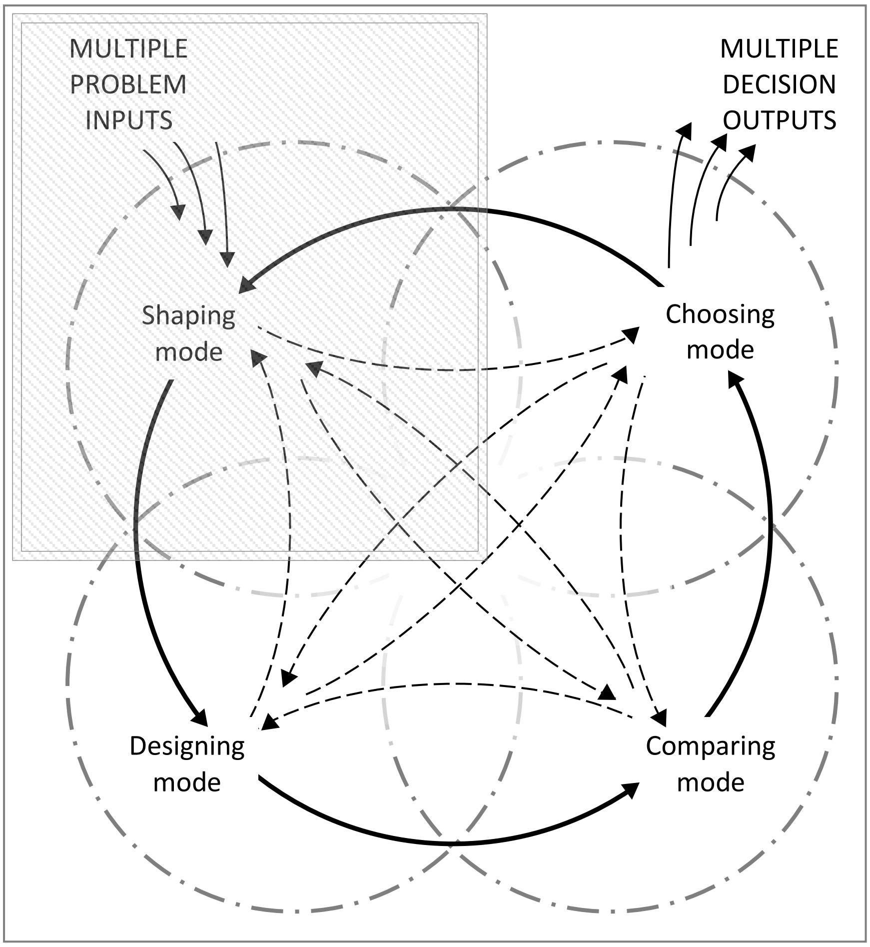


Figure 92: A process of strategic choice (Friend and Hickling 1997, Figure 8 p. 20)

10.3 Stakeholder Mapping Information

As discussed in the main text of this thesis the physical layout of the system was considered when stakeholder mapping, and the centrality of stakeholders to the radiotherapy process highlighted the suitability of their involvement.

Figure 93 illustrates that the core group to be involved in a change project should consider political, not just technical representatives; and external as well as internal system stakeholders. Applying these ideas to the Beatson emphasises the need to include technical personal within the radiotherapy centre (such as physics staff) and consultants (doctors), and front line staff alongside management. This is because those responsible for steering the outcomes of a project are not always those most engaged, accountable or tasked to work on the project.

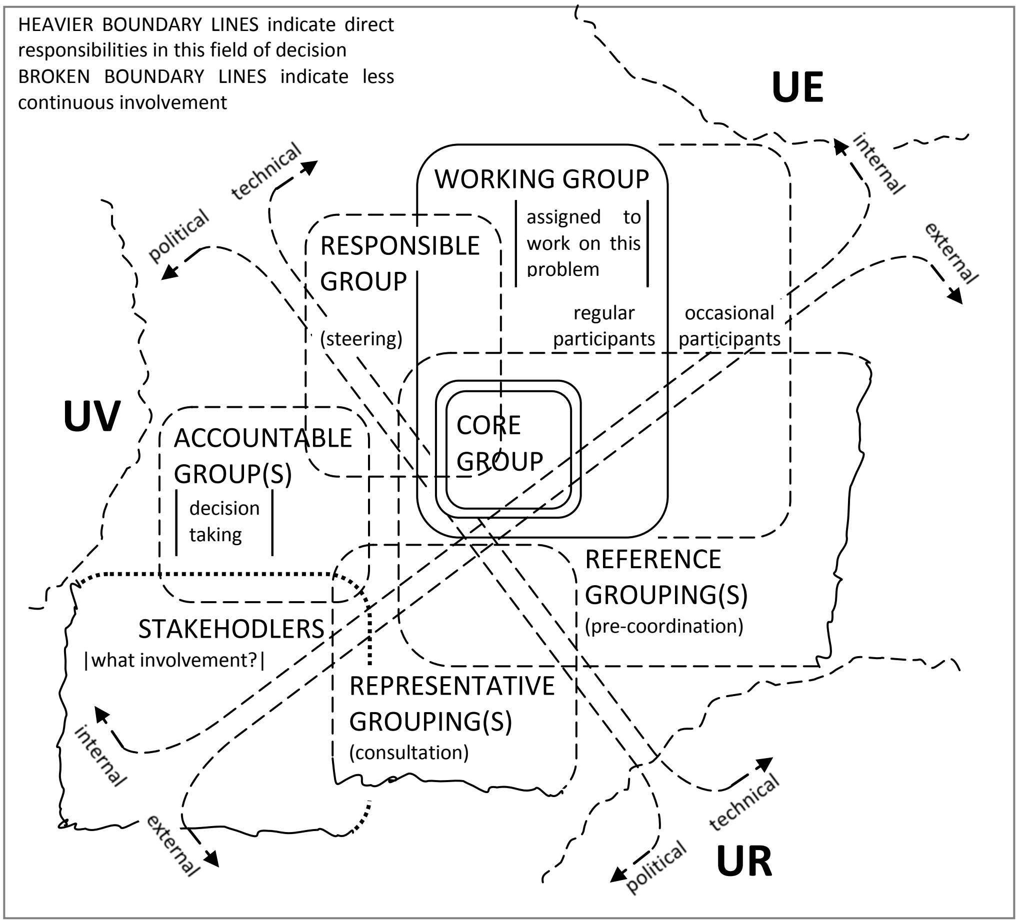


Figure 93: Organisational responsibilities in strategic choice (Friend and Hickling 1997, p.223-224)

Additionally, categories of stakeholders put forward by Friend & Hickling (1997, p.317) were used to assess the stakeholders actively involved in the project (described in Table 21). This enabled the modeller to consider the expected views and group alliances stakeholders might adopt, and explore possible strategies to engage those invited to participate in the project. This helped the researcher to pitch the project to each stakeholder in a manner that emphasised the projects potential benefit to their role in the system, and aided buy-in to the action research project.

Table 21: The broad categories of the stakeholders

Group	Position	Coalitions/Fractions	Engagement Strategy
Consultants	To maintain flexibility and preferable work hours.	Band together with physicists about technology, treatment modality etc.	Emphasise that the project is about understanding the system and is patient focused to ensure equitable treatment for all and high access.
Managers	To ensure the 'company' view is presented, and that efficiencies are explored.	May present a 'gold standard given a level of efficiency / cost effectiveness is achieved' view (gold subject to time constraints) over the pure 'gold standard' of care put forward by clinicians (gold).	Emphasise the potential to see areas for improvement, to understand the knock-on impact of managerial decisions and to justify procurement etc. Approach managers through the initial contact at the Beatson who are also managerial level. Use formal documentation to explicitly set out the goals of group/individual sessions
Physicists	To encourage sufficient time is available to physics and emphasise the intense workload pressure they are under.	Focus on gold standard, driving the profession forwards with research and development, with safety their priority.	Emphasise the benefit of mapping a system to provide clarity brought by documenting the process and how this can improve safety assurance. Discuss how it is possible to model their split time (research versus clinical)

10.4 Interview Plan

Purpose of the research:

The research is focused on modelling and combining two modelling methods (DES and SD). The intention is to develop framework(s) for the use of SD and DES with the modelling purpose to develop understanding of a system.

Overall purpose of the project:

To explore the issues facing the Beatson Oncology Centre Radiotherapy Departments currently and in the future

Purpose of the interview:

- To explore the problem situation
- To gain an understanding of the issues they are currently facing and what they see in their future
- To see how they understand the system they work within, and if there are points they feel need exploration

Starter Question:

What do you see are the issues and challenges for the delivery of radiotherapy in the west of Scotland currently and in the future?

Overview of Format: refer to Table 22 for detail

Section 1: General Issues [circa 20 minutes]

Section 2: Defining the system under study [circa 20 minutes]

Section 3: In-depth exploration of issues with the expected primary focus being on waiting times, capacity & complexity [Up to 40 minutes]

Table 22: Breakdown of the interview questions

1. What are the current issues within the department?	Explore the current status – at both **operational** and **strategic** level. Acknowledge that more likely to get the former from front-line staff, and the latter from managers.
1.1 What makes you view these areas as problematical? - would you like to understand them more?	Determine their interpretation of an issue: - Parts they don't understand but want to? - What they feel is not working well? etc.
1.2 What are you interested in understanding better? - Physical process, structures, informational flows or counterintuitive behaviour of data?	Leading to dynamics and variables they would like to understand – Is their interest **operational** or **strategic**?
1.3 Are there aspects of the system that you are particularly interested in gaining insight into? - How would you want to track these?	What do they see as important to measure – both quantitatively and qualitatively?
1.4 What analytical work do you know about currently going on in the Beatson? By analytical work we mean support work to understand what you do and how it could be improved	To gain insight into their view of this type of work – positive or negative feelings towards it
1.5 What might we learn from other departments: - Who would you aspire to be like? - Who do you see doing things well? - What aspirations do you have for the department and what are these based on?	Do they see other departments working well? This may then need to be modelled differently from the Beatson. This is more likely to be at the **operational** level, although **strategy** may be commented on.
2. What are the current issues that impact upon the department? And, what do you see are the future external forces impacting on the system?	Explore external factors to the current status. **Boundary** setting – where do they see the issues reaching to?
3. Opportunity to further explore the three core areas	Explore the current status – at both **operational** and **strategic** level. Acknowledge that more likely to get the former from front-line staff and the latter from managers.

10.5 Research Ethics

On completion of the University ethics form and agreement to adhere to the University code of practice, confirmation of ethical approval was received on September 2009.

With regards to NHS ethical review, a letter received from the West of Scotland Research Ethics Service (WoSRES) outlines that the project with the NHS may be deemed a service evaluation and "*does not need ethical review under the terms of the Governance Arrangements for Research Ethics Committees (REC) in the UK*". The advice is based on the following.

- The project is an opinion survey seeking the views of NHS staff on service delivery.
- Recruitment is invitational and the transcripts from face to face interviews will be irreversibly anonymized so that the respondent's identity is fully protected.
- It is not possible to identify the individual from any direct quotation used in the reporting of your project"

It is noted that should the nature of the project change and "starts to generate new knowledge and thereby inadvertently becoming research" then it would be necessary to immediately undertake REC review. This research seeks to generate new knowledge, but not on the NHS or the particular service studied, but on the application of modelling tools.

Additionally, clinical access to the Beatson was granted (see document below).

25 SEP 2009

WoSRES

West of Scotland Research Ethics Service

NHS
Greater Glasgow and Clyde

West of Scotland Research Ethics Service
Ground Floor – The Tennent Institute
Western Infirmary
38 Church Street
Glasgow G11 6NT

Jennifer Morgan
c/o Anne Muir
Business Development Manager (Science Faculty)
Research & Innovation
University of Strathclyde
50 George Street
Glasgow
G1 1QE

Date	21 Sep. 09
Your Ref	
Our Ref	WoS ASD 94
Direct line	0141 211 2126
Fax	0141 211 1847
E-mail	Judith.Godden@ggc.scot.nhs.uk

Dear Ms Morgan

Full title of project: Exploring frameworks for combining System Dynamics and Discrete Event Simulation.

You have sought advice from the West of Scotland Research Ethics Service Office on the above project. This has been considered by the Scientific Officer and Committee Administrator and you are advised that it does not need ethical review under the terms of the Governance Arrangements for Research Ethics Committees (REC) in the UK. The advice is based on the following.

- *The project is an opinion survey seeking the views of NHS staff on service delivery.*
- *Recruitment is invitational and the transcripts from face to face interviews will be irreversibly anonymised so that the respondent's identity is fully protected.*
- *It is not possible to identify the individual from any direct quotation used in the reporting of your project.*

If during the course of your project the nature of the study changes and starts to generate new knowledge and thereby inadvertently becoming research then the changing nature of the study would necessitate REC review at that point, before any further work was undertaken. A REC opinion would be required for the new use of the data collected.

It is recommended that potential participants be provided with an Information Sheet in which the following statement is included.

> Note that this project has not been reviewed by the NHS REC based on advice received by the West of Scotland Research Ethics Service.

Note that this advice is issued on behalf of the West of Scotland Research Ethics Service Office and does **not** constitute a favourable opinion from a REC. It is intended to satisfy journal editors and conference organisers and others who may require evidence of consideration of the need for ethical review prior to publication or presentation of your results.

However, if you, your sponsor/funder or any NHS organisation feels that the project should be managed as research and/or that ethical review by a NHS REC is essential, please write setting out your reasons and we will be pleased to consider further.

Where NHS organisations have clarified that a project is not to be managed as research, the Research Governance Framework states that it should not be presented as research within the NHS. This letter has been copied to NHS Greater Glasgow & Clyde R&D Department for their information.

Kind regards

Dr Judith Godden
WoSRES Scientific Officer/Manager

Acute Services Division

Diagnostics Directorate

Diagnostic & Oral Health Directorates
HR Department
Ground Floor, Management Building
Western Infirmary
Dumbarton Road
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G11 6NT

Tel:. 0141 211 2715
Fax:. 0141 211 2965
Email: Nicola.McLaughlin@ggc.scot.nhs.uk

NHS
Greater Glasgow and Clyde

7th December 2009

Private & Confidential
Ms Jennifer Morgan
3/2 100 Elderslie St
Glasgow
G3 7AR

Dear Ms Morgan

Letter of Clinical Access

1. I am instructed by Greater Glasgow and Clyde Health Board, to issue you with a letter of clinical access within the Department of Radiotherapy Physics at the Beatson West of Scotland Cancer Centre from July 2009 until June 2011, being the date of termination of this agreement.

2. Your normal base will be the Beatson West of Scotland Cancer Centre.

3. As this appointment is unpaid, the normal terms and conditions of service for NHS staff so far as governing remuneration and reimbursement of expenses, do not apply. You will however be required to adhere to all other Health Board policies and procedures.

4. (i) The Health Board's insurance indemnity will cover you personally against injury or accident whilst you are on this site.

   (ii) It may, however be in your interest to subscribe to a defence body in order to ensure you are covered for any work that does not fall within the scope of the indemnity scheme.

5. During the course of your attachment you may be privy to confidential information relating to patients, staff and hospital business. Confidentiality of this information must be respected.

6. For the duration of your appointment you will be subject to the Health and Safety Policy, and rules and regulations operating within the Health Board. A copy of the current policy has been attached.

7. Providing you agree to accept this Clinical Access on terms outlined above, I should be grateful if you would sign both copies of this letter returning one to my office, retaining the other for your own information.

I hope that you will enjoy the activities associated with your Clinical Access.

Yours sincerely

Nicola mclaughlin

Nicola McLaughlin
Human Resources Assistant

Delivering better health

www.nhsggc.org.uk

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10.6 Individual Interview Maps

These interview maps have a large number of concepts and are not easily readable printed on paper smaller than A3 size. The intention of the figures below is to illustrate the number of concepts generated at each of the interviews and the links the modeller was able to make at this early stage in the system exploration process. Further detail in the maps can be viewed in images by referring to the PDF of this thesis.

Interviews took between 50 and 120 minutes per participant, with participants varying in the number of links they made between concepts. All participants were eager to discuss a range of themes, providing a broad overview of the system, the participants' aspirations for the system and their perceptions of issues.

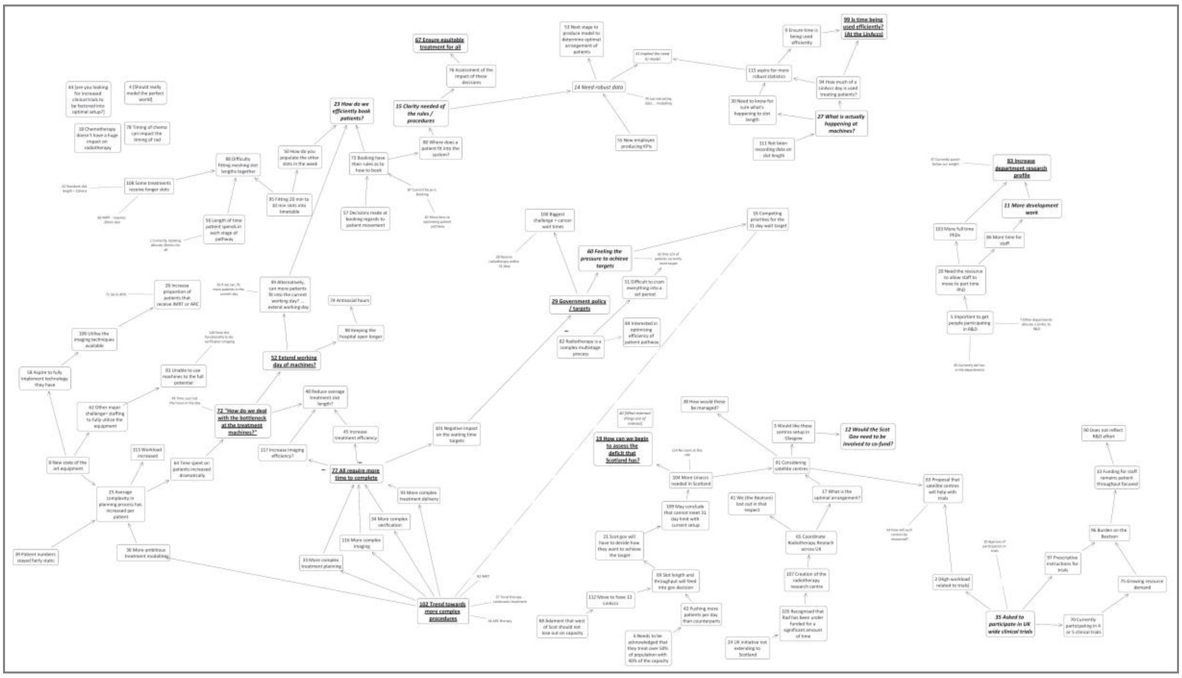


Figure 94: Interview A – clustered concept map

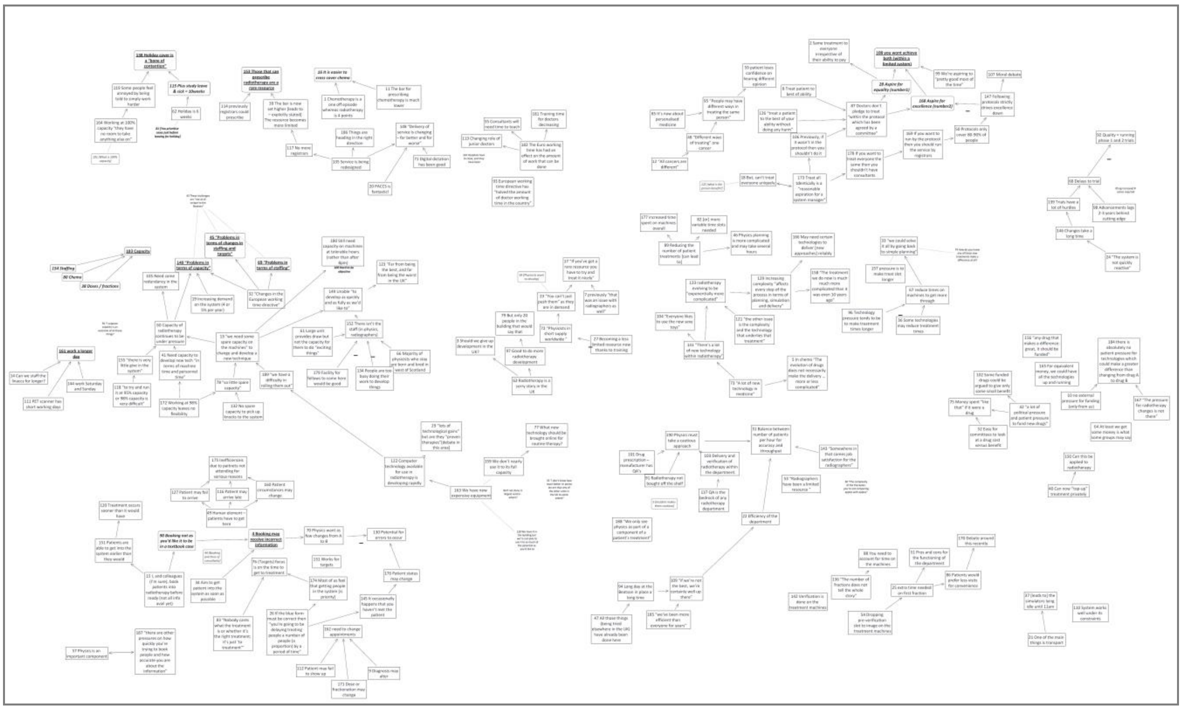


Figure 95: Interview B – clustered concept map

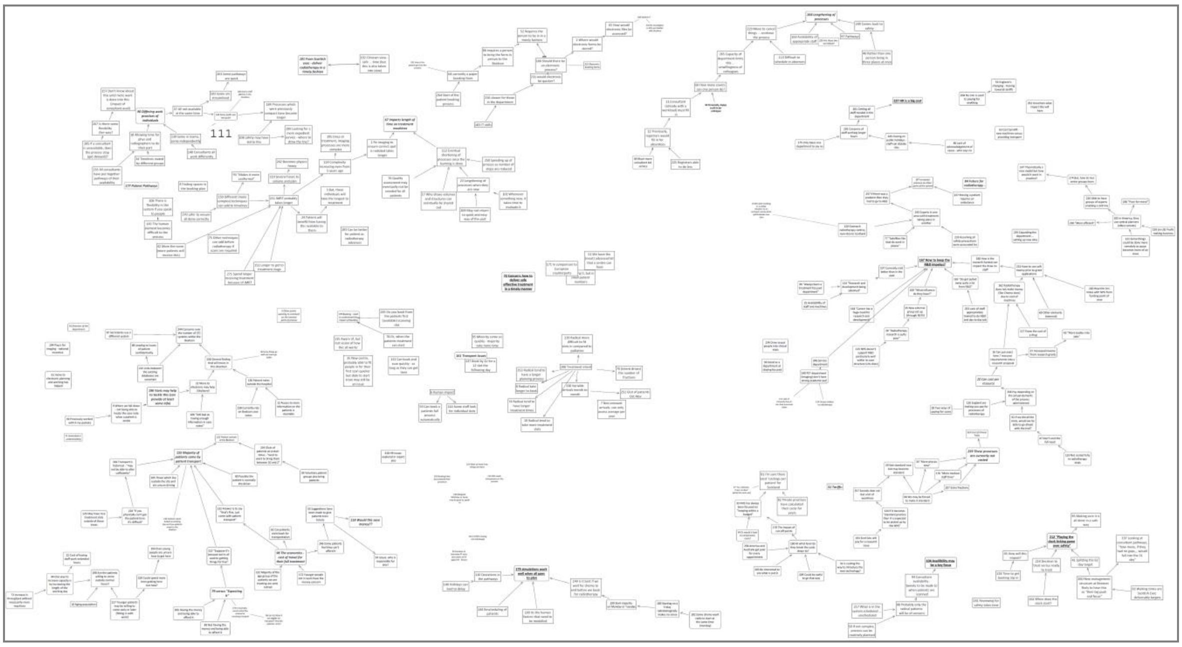


Figure 96: Interview C – clustered concept map

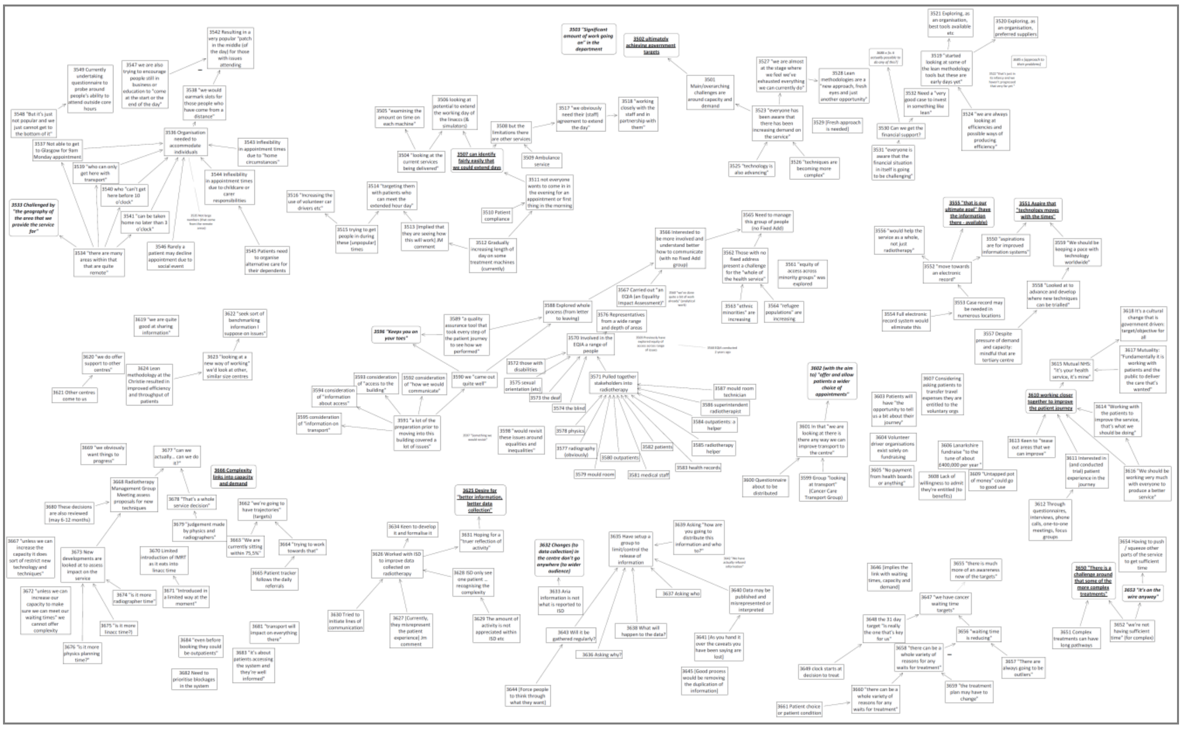


Figure 97: Interview D – clustered concept map

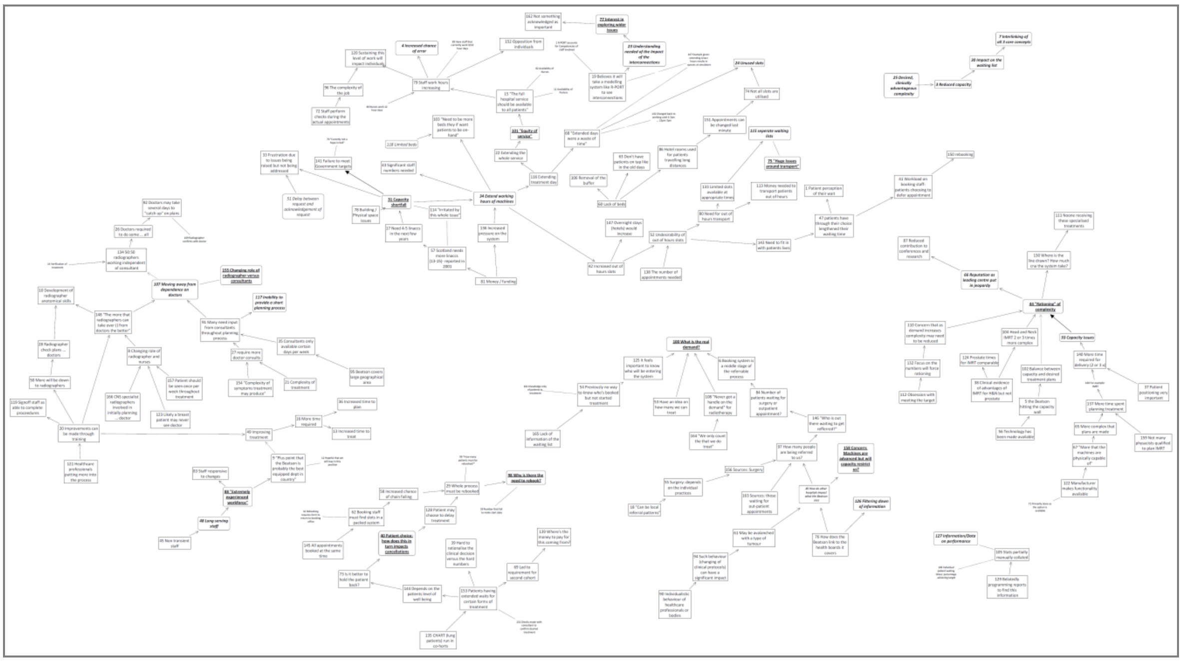


Figure 98: Interview E – clustered concept map

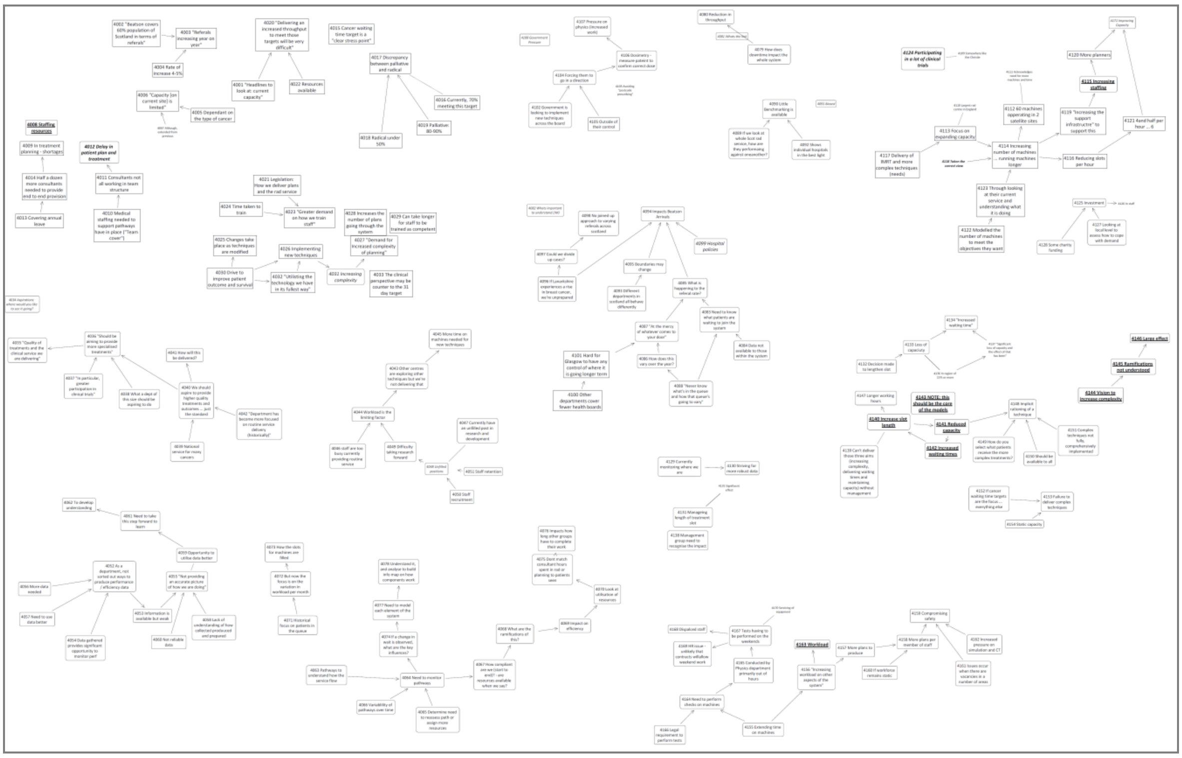


Figure 99: Interview F – clustered concept map

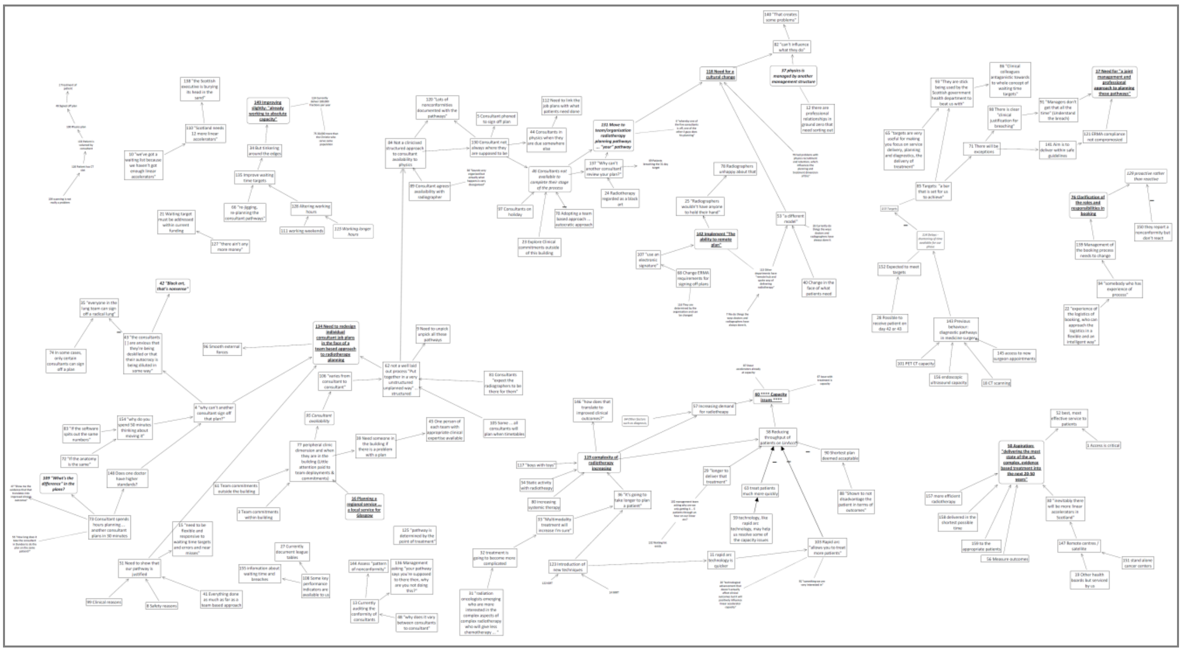


Figure 100: Interview G – clustered concept map

10.7 Cluster Analysis

Using the "CLUSTER" analysis tool within Decision Explorer© clusters with more than 10 concepts were identified, and manually examined to identify problem themes that might be used for the project resulting in 25 clusters (ordered by topic):

Cluster7: Booking and rebooking – how, when and why?

Cluster8: Staffing concerns, morale and the impact of targets and KPIs.
Cluster35: The changing roles of members of staff within the centre and what this means for the day to day and the long term running.
Cluster36: Research reputation and the impact it has on staff retention.
Cluster14: Aspiring for excellence and therefore how to measure excellence.

Cluster9: The desire to provide a regional service and questions raised as to how much they are fulfilling this *(strategic issue)*
Cluster39: Consideration of satellite centres – where to place them, how to serve them with staff *(vehicle-routing type issue).*

Concept3168 (from ***Cluster39***): The knock-on pressure that poor service in one part of the hospital system can have on other parts, such as aftercare, A&E etc.
Cluster85: Effectiveness of patient pathways? (relates to ***Cluster106*** – the need to monitor pathways and determine appropriateness)

Cluster79: Staff concerns about capacity – how to address these concerns and generate useful ideas to move forward?
Cluster94: Bottlenecks in the system – do we need fresh eyes on the system to explore where we can improve?
Cluster61: What is 100% capacity – how many patients is too many?
Holiday procedures – how to manage cover?
Cluster77: Practicalities of extending the working hours – are staff and patients willing? (relates to transport issue)

Cluster81: Need to determine cost of treatment. In real terms, what do the elements of treatment cost as this can be used to accurately apply for funds?

Cluster63: We need to encourage patient pressure to improve RT – drugs are supported but RT capacity does not get the same public support.
Cluster60: The benefit of treating all patients uniquely – evidence of a clinical benefit? *(clinical issue)*

Cluster109: Participation in clinical trials to contribute towards the evidence based research into RT… and what this means on the capacity of the system.
Cluster4: Complexity of new treatment regimes and the impact this has on the systems performance (ties with Cluster36)

Cluster110: Increasing slot length on machines – is this necessary, why is it happening, what could/should be done about it?

Cluster90: Concerns about patients with no fixed address falling through the cracks of the system.

Cluster64: Electronic Health Records (EHR) and electronic booking forms – are they the answer and if so how will they work? (EHR to improve the background info staff have on patients)

Cluster50: System audit reveal points at which errors/delays may occur

Cluster37: Striving for better data collection to allow evidence based changes to be made and support a call for more capacity.

Cluster104: Benchmarking with other RT departments to learn best practice – relates to data issues (cluster 37): how data is collected, prepared and analysed impacts its usefulness.

Cluster70: Transport – how to manage this situation. Are there measures to be introduced to alleviate this constraint?

10.8 Map Themes

Table 23: Defining projects based on themes from the merged map

Theme	Project	Stakeholder and Practical Considerations
Booking Patients	Booking / Scheduling Processes: Eliciting the processes versus conducting data analysis of compliance to pathway	Requires buy-in from booking staff and the manager
	Increasing Machine Slot Length: Is it necessary and why?	Data analysis but the ability to change the process is an issue
Staffing Levels and Availability	Recruitment, Retention and Reputation	Requires buy-in from policy makers and budget holders
	Changing Roles of Radiographers	A hospital or government policy issue
Providing a Regional Service	Definition and Achievement: definition of a regional service and how the centre is meeting this	Strategic issue: requires management and Scottish government involvement
	Consideration of satellite centres: How many and where?	Government and Hospital level
RT Improvement	Clinical Trials Participation: Room in the system for participation?	Clinicians to assess impact
Patient Experience	How do we assess experience and follow-up on patient treatment?	Management (Issue: NHS ethics)
Data Keeping	Electronic Records	Government Issue
	Risk of Error: Assessment and system audit	(currently have audits undertaken)
Benchmarking	Data Collection Best Practices: What data is needed for fair comparison with other centres?	Data Analysts and other RT centres
	Identify suitable comparators: Learn best practice	Management (RT meetings & conferences facilitate this)
Patient Pathways	What is the impact of the pathways?	Booking staff
Capacity and Work Hours	Impact and practicalities of changing work hours	Large number of stakeholders required, top management essential
Cost of Treatment	How much does it actually cost? … Develop improved estimates for funding applications	Hospital management involvement for data collection.
Patient Transport	Survey staff and patients for preferable options	Councils and government would be required for this
Upstream Impact	What are the wider implications of the centres performance?	Policy makers required (Conceptual project)

10.9 Feedback to Participants and Second Interviews

Following the first round of interviews, having created a merged map of the concerns and aspirations of the participants, the researcher provided feedback to those involved to highlight the outputs for the project to date (the map and the problem themes) and to encourage their participation in a follow-up meeting. A document (shown overleaf) was sent to all participants to inform them of the progress made, thank them for their contribution and seek their engagement in a follow-up group session.

A follow-up group session was intended to provide the modeller with the opportunity to:

- discuss the initial findings from the merged map, which had resulted from the interview stage, with the participants;
- gain feedback on the responses given and enable clarification of the intricacies of the complex system;
- present sample DES and SD models to encourage buy-in to the project and the modelling methods by highlighting their applicability to the system and the outputs possible;
- provide some tangible outputs and provoke discussion around the requirements and requests for the direction of the project.

However, after numerous attempts to again find suitable dates, it became apparent that a group session was not well supported by participants. In place of a group session a second round of interviews took place with the same participants with the same aims as the group session: to obtain feedback on the merged map and problems themes, and to show participants two sample models of DES and SD. The follow-up sessions confirmed the direction of the project which was supported by the participants to the modeller and provided useful feedback on the modelling process to date. The merged map provided the focus of the discussion throughout and participants were well engaged with it and the problem themes it illustrated. This set of follow-up interviews provided the modeller with focus for the modelling project and resulted in enhanced engagement from some of the interview participants.

Feedback to staff following interviews

Introduction

The interviews conducted form part of a wider research project undertaken with the Radiotherapy Physics department to learn about how an organisation can use a variety of tools to better understand a system. The research is focused on exploring ways in which the structured combination of two different modelling techniques can be used to inform understanding of a system, and provide vital information to those within the process.

Overall, the work is concerned with exploring how processes can be modelled, how data can be used to generate models and the efficiency of a system. It seeks to further support research being conducted into capacity modelling, radiotherapy planning and scheduling, and work flow structures.

Interviews

The initial phase of the project was focused on gathering and amalgamating the opinions of a cross section of staff. These findings and views could then be used to determine the direction of the modelling project, and allow for contrasts to be drawn between the understandings gained through modelling approaches and the beliefs held.

The intention of the interviews was to provide an opportunity to raise issues, encourage engagement and explore ways to move forward. Through these interviews, it has been possible to gain an understanding of how the Beatson works and how it does so within a wider context, to appreciate factors which impact upon it, consider its strengths and limitations, and articulate the centres aspirations. Individual maps have been generated following the interviews, which have been combined to provide an overall representation of the system.

Core Points Raised

Three core areas were posed for discussion to include, but not be limited to. These were:
- Waiting Times: how delays and targets impact your work
- Capacity: patients, Number of of treatments, machines etc. and how these dictate how the system works
- Complexity: impact of advances in technology increasing the complexity of treatment

During the interviews, all participants had a wealth of information to share on these points, with emphasis shifting depending on the interviewee. Overall, the interdependency of the system was discussed; how the three themes were in fact fairly central to the issues and concerns experienced within the centre, and how they influence one another. Following the development of a combined map of the system, areas of key focus from the interviews were highlighted.

Key aspirations identified were to provide equality and excellence: providing the most state of the art, clinically advantageous complex, and evidence based treatment over the next years. All staff are focused on providing a quality service to patients but have several factors which may pull them in different directions and constrict them.

Waiting Times were one of the central concerns raised within the discussions as the pressure to achieve the targets set by government is felt in all areas. All participants have an acute awareness of the squeeze these targets place on the system, and a frustration that they are unable to do more. The focus on the targets can mean that patients may receive a longer treatment path as the system is focused on meeting the target. Ultimately the waiting times experienced by patients are influenced by the overall capacity of the system and the ability to provide an efficient process through which a patient travels (all the way from the initial receipt of the booking form, to the final dose of treatment). The aspiration is to provide quality care, but this must be done in a timely fashion.

Capacity is being restricted from several sides: physical capacity of the site meaning that alternative ways to increase capacity need to be considered, staffing, resources and time pressures (European directive limiting work hours). One strategy discussed is to extend the working day, but this comes with many issues needing to be resolved, with several knock-on effects. If the working day is to be extended, then consideration must be given to the restrictions on the working hours of staff (to enable a complete service available to all).

Staff availability and the workload placed on staff were discussed to be impacted by the drive to keep in line with the most current techniques. The department is required to keep in line with the standardisation of more complex treatments, meaning that overall staff availability changes in nature. Further to this, as the workload on staff increases there is the potential to compromise safety in order to squeeze the system.

The overall appeal of the department influences the centres ability to retain staff and attract new recruits. Issues such as the morale of staff; the reputation of the department, of which safety, friendliness and research are several aspects; and the overall workload placed on them has been discussed.

Booking is viewed as having a significant impact on the utilised capacity of the system and the time for patients to receive treatment. Currently, there is little understanding across staff as to how the booking process is conducted and how efficient it is. There is interest in the impact booking has on the wider system, clarification of the rules implemented during the booking stages, the impact of patient non-compliance on the booking process, and how the need to re-book patients into the system causes longer patient pathways.

The many interacting issues within the system are discussed above, but there are also wider issues which affect the overall functioning of the system, such as:

- Cultural changed needed to encourage participation in new ventures such as technology or different modes of working
- Staff divides: Clinical staff vs. management impacted by the (perceived) management view of the complexity of the work undertaken

Follow-up Session(s)

Following the interviews and the development of a map of the system, the next proposed stage of the project is a group session or individual follow-up sessions which aim to further explore and amalgamate the opinions, understanding and expertise of a cross section of staff. The intention is to pinpoint areas that participants feel would benefit from further exploration using modelling techniques. To discuss what internal and external aspects impact on the system and, through taster simulation models, explore sample patient pathways and demonstrate the potential for the work conducted.

Thanks are extended to all staff who agreed to participate in this phase of the project

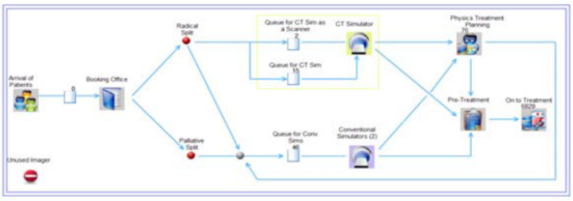
10.10 Sample DES and SD Models

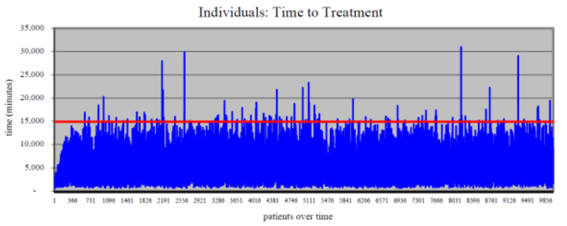
During the follow-up interviews participants were asked to comment on the merged map and the problem themes identified. Additionally, participants were shown basic DES and SD models specific to the Beatson to ascertain if they felt these methods could be useful to the discussed problem themes. These served to demonstrate to the participants the methods the project sought to utilise and the quantitative outputs possible from these methods. The two documents used to illustrate the sample models are shown in Figure 101 and Figure 102.

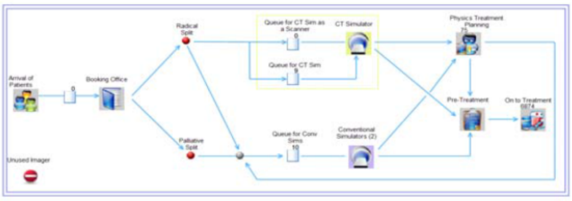
Sample DES Model:

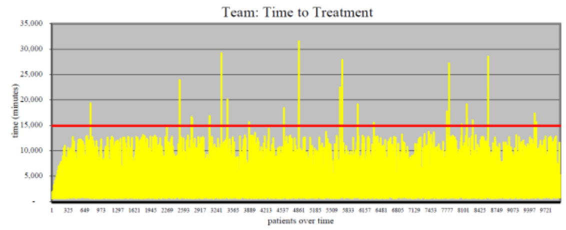
Exploring the Impact of Working in Teams: *Examining how consultants working as individuals versus a team based approach impacts the patient journey through the system. The time to treatment is modelled, representing the time between the patient arriving into the system (arrival of booking form) and the completion of the planning process.*

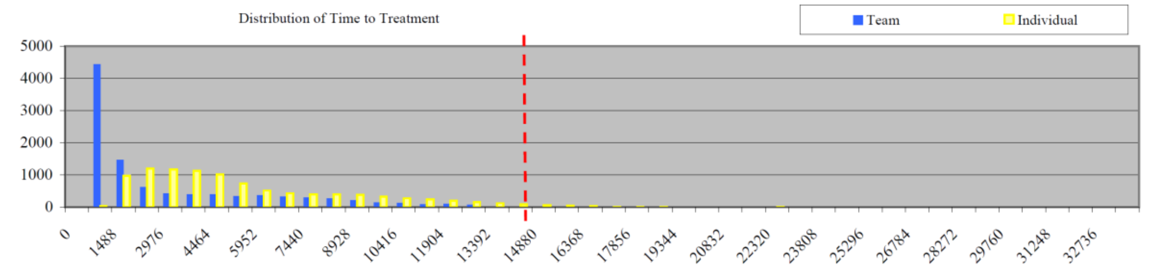
Current: Staff work independently with patients needing to wait until the specific member of staff they have been assigned to becomes available	Proposal: Encourage team working. Staff are able to take on patients originally assigned to a specific person, providing flexibility
Individuals	Teamwork











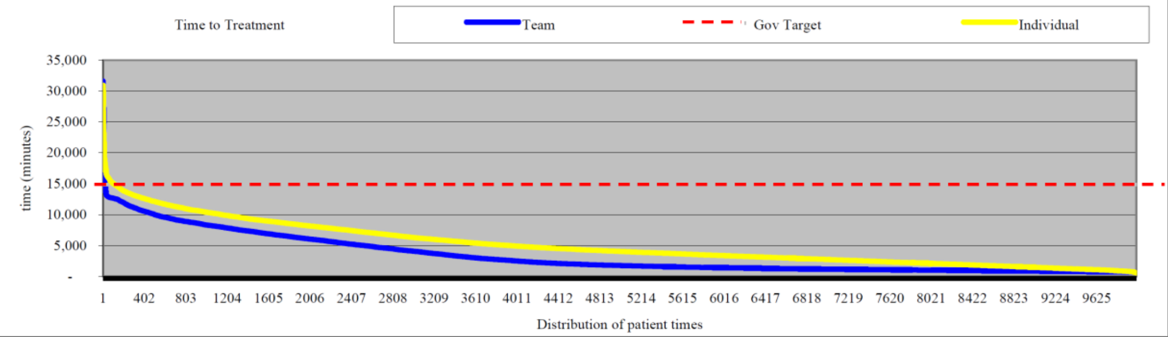


Figure 101: Sample DES model and outputs used in follow-up interviews

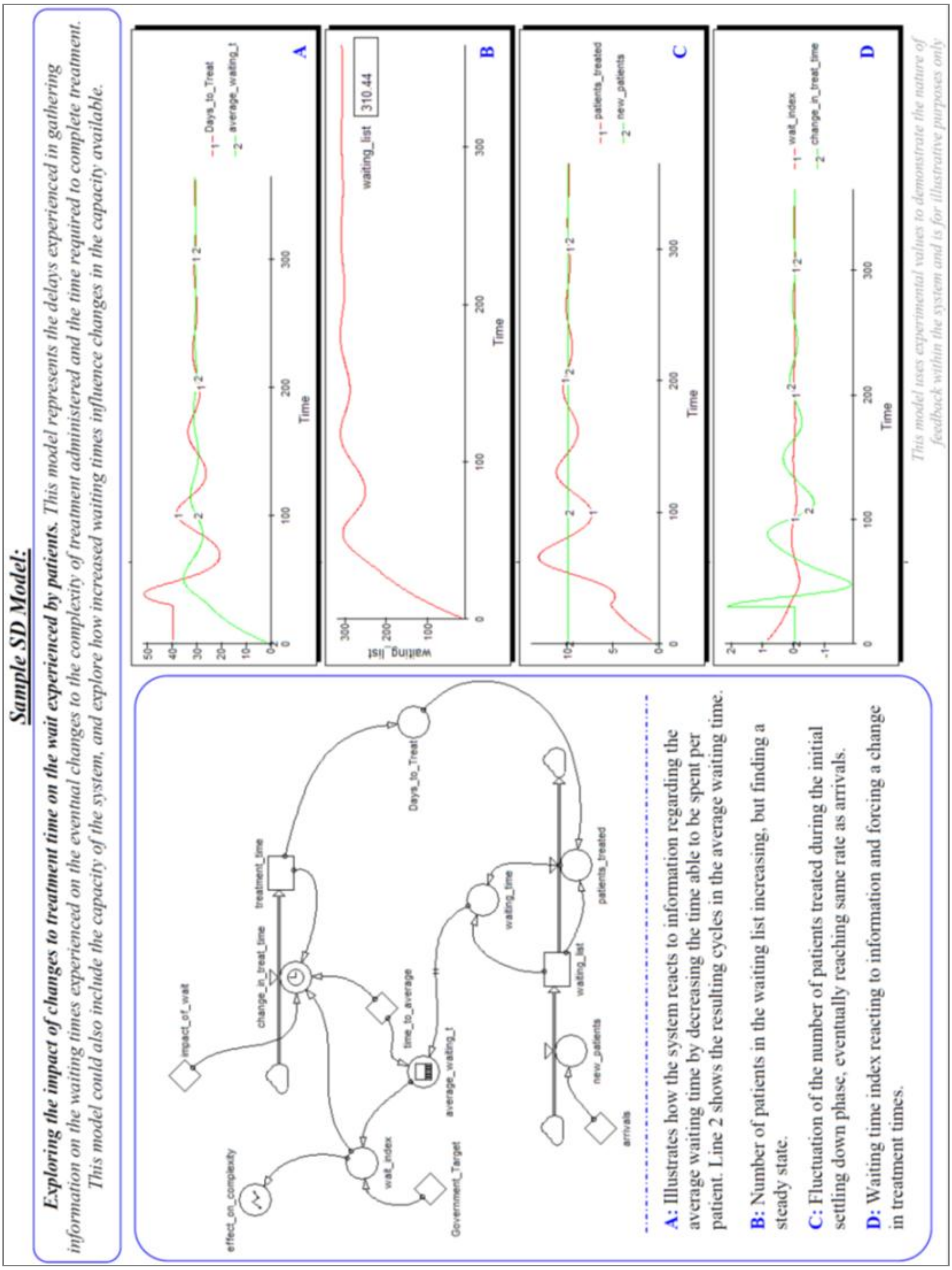


Figure 102: Sample SD model and outputs used in follow-up interviews

10.11 Methods to Apply to the Problem Themes

10.11.1 Identifying methods post first interviews

The first attempt to select appropriate methods for the issues raised in the interviews took place once the modeller had mapped an individual interview. Each statement used to create a concept was examined: if it was a question or an issue then the modeller reflected on what methods had been used to address such an issue before and propose methods which might be applicable. At this point the modeller also noted where more than one method may address the issue (i.e. one method or another; or mixed methods).

The following elements were summarised in the analysis of the individual interview maps:

- *Points of Interest* – statements (quoted or paraphrased) that pose a question or raise an issue ripe for exploration
- *Themes* – emergent during the process of analysing the interviews, once all interviews are brought together these are compared and refined.
- *Methods* – any descriptor of methods that may be used to address the *point of interest*. These are mainly based on personal views but include suggestions of methods from stakeholders.
- *AND / OR* – recorded whether there is an AND or an OR relationship with approaches proposed for one *point of interest*.

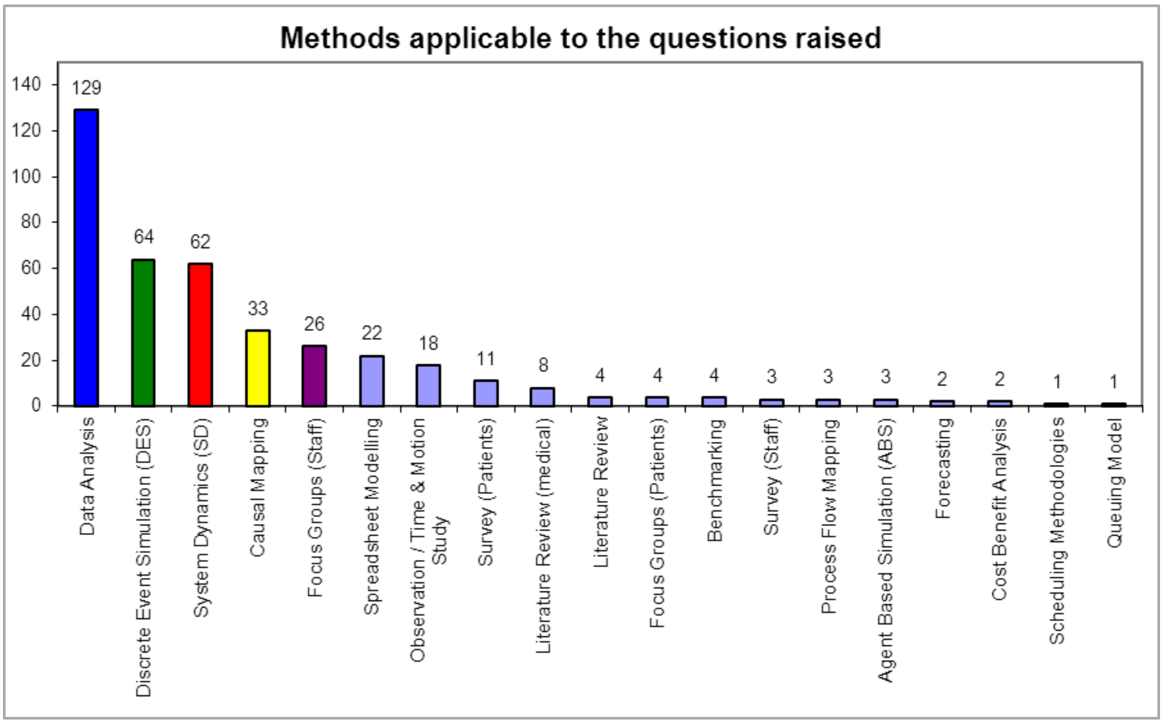


Figure 103: Summary of methods which may be applicable to the Beatson project

Figure 103 shows the methods which were determined to be of use to each of the questions raised during the system exploration (note that more than one method may be assigned to a question). The broad spectrum of methods illustrates the range of issues raised in the interviews. The most frequently assigned method is data analysis, as the general consensus from all participants is the need to provide an evidence base for any system changes which requires the current ‘status’ of the system to be established first. The graph highlights that a large amount of issues were identified where DES and SD could play a role. Previous work at the Beatson has used these methods and members of the Beatson staff are aware of such work, and the interview invite noted that the project aimed to use modelling methods. This reflects the overall purpose of the project: to use simulation methods; and the interviews were conducted and analysed with this in mind.

10.11.2 Considering project methods following second interviews

At the second wave of interviews the modeller discussed the merged map, highlighted the problem themes identified and demonstrated sample models of DES and SD to the participants. Following feedback from the participants on the problem themes the modeller focused on 7 themes, and assigned methods according to the questions posed by interviewees. These questions emphasised required characteristics in a model, and led to the proposal of methods for each project (illustrated in Table 24 and themes highlighted on the merged map in Figure 104).

Table 24: Methods applicable to 7 of the problem themes from the merged map

Problem Theme & description	Method(s)
A: Complexity - Explore with SD the knock on effects and delays experienced as the system tries to cope with changes to radiotherapy techniques. - Work with data to analyse trend for complexity and assess what impact it is currently having on the system performance. - Explore complexities impact on the day to day running of the facility. Explore the impact of variable times to complete plans and how having a series of complex plans can seriously impact performance.	SD Spreadsheet modelling DES
B: Staffing impacting Capacity - Explore the working pressure put on staff: workload per person. - Explore the potential for longer working hours to have a long term impact on staff availability.	Spreadsheet modelling SD
C: Staffing and recruitment - Investigate how the changing roles within the department are changing the setup of the overall system, and changes capacity.	Spreadsheet modelling
D: Booking and transport - Explore what is really going on in booking by conducting a detailed analysis and documenting the process.	Flowcharts
E: Government Pressure Explore how government pressure is impacting the functioning of the system by influencing the way waiting times are handled. This could be done in several ways: - Further mapping of the situation to determine the drivers and what areas it impacts. - Creating a SD model to explore at policy level the impact of government pressure.	Mapping SD
F: Patient Pathways - The move to create patient pathways has stemmed from pressure to meet targets and explore whether they are achievable for all cancer types. Use DES to explore how robust these pathways are with the variability of arrivals experienced in real life. - Alternatively, Conduct data analysis to confirm staff compliance to the pathways. - Are people where they're supposed to be? - Explore and identify the triggers in the system which may cause the pathway to fail or become elongated. (DES and sensitivity analysis)	DES Spreadsheet modelling DES
G: Capacity - Model high level capacity to see the impact of booking, transport and policy level decisions. - Go into detail to model the individual phases of the process incorporating staff and departments.	SD DES

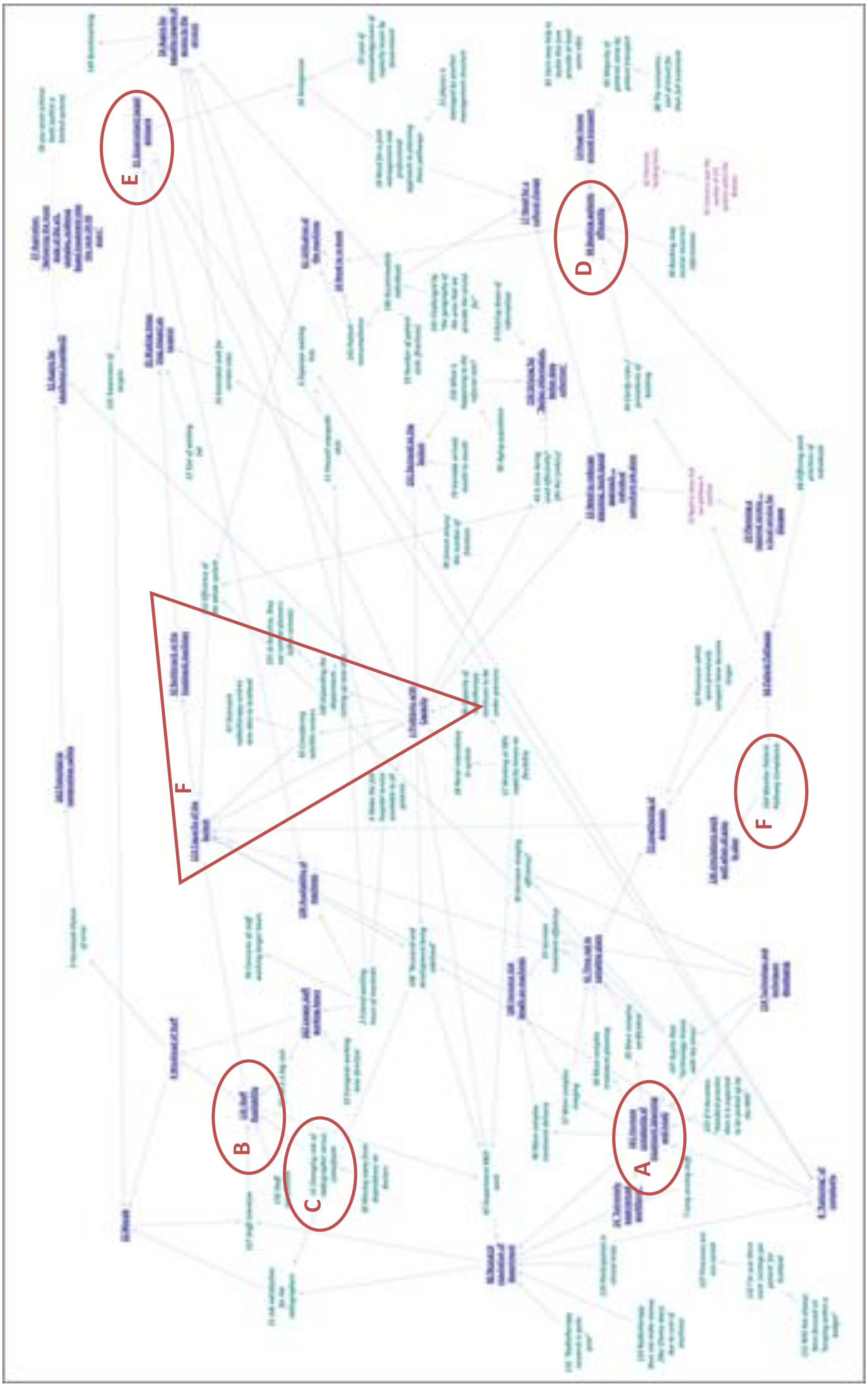
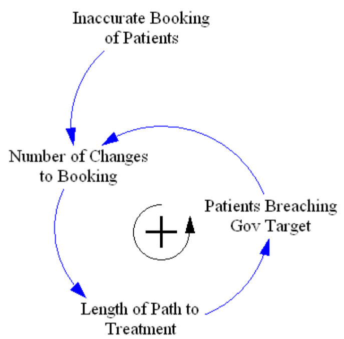
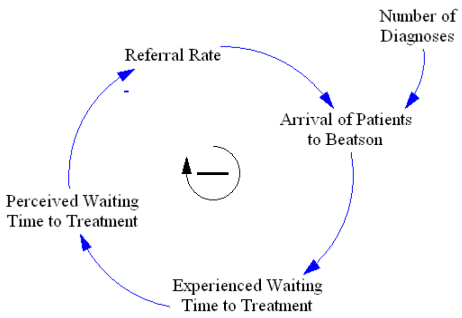
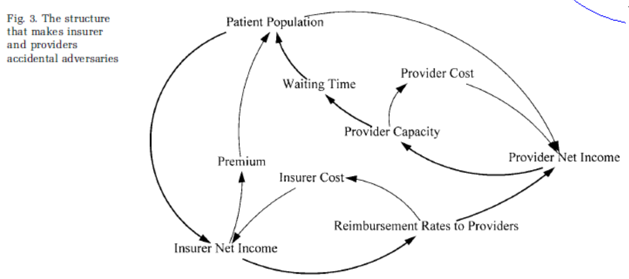


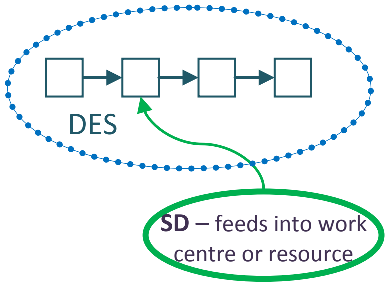
Figure 104: Merged map with problem themes highlighted to explore applicable methods

10.11.3 Discussing projects methods with the client

At this point in the project it is apparent that the use of DES to model the flow of patients through the treatment process would be welcomed, but SD may be used on a range of themes to represent various parts of the system. The table below details the notes made by the modeller, and discussed with the client, to consider how the problem themes identified from the merged map align with SD models of healthcare systems in the literature.

Table 25: Detailed consideration of DES and SD to problem themes

Main themes	Thoughts on modelling – SD and DES focus
Staffing Levels & Availability	- Use SD *aging chains* (such as in Sterman 2000, p.470) to represent the workforce within Physics (long term modelling – years, population rather than individual focus). The SD models staff levels and will be an input into the DES. - Medical workforce planning model (SD: Morecroft 2007, p.317)
Government Targets	- DES to explore how to achieve targets within the radiotherapy treatment process (queues and servers, process flow, individual patients … implies DES)
Booking of Patients	- Mapping and observation of the process to clarify procedures - Simple SD model of the system to illustrate the booking process – focus on how categories of patients are booked into the system (rather than individual uniqueness) 
Patient / Consultant Pathways	- Implement within a DES model to capture the different routes taken by different patients. May also be modelled using SD, allocating resources in this model may be more challenging than in a DES model. - This theme would benefit from data analysis to explore what is done currently and how consistently paths are used.
Demand on the System	- Others use 'Susceptible / Infected / Recovered' models but cancer isn't passed person to person so not applicable. - *Referral rate* – assume national → growth in incidence but referrals respond to perceived length of wait for treatment.   ← Take ideas from the Private Healthcare Model (Hirsch and Immediato 1999, p.323)

Capacity and Bottlenecks	- Cutting corners vs. overtime (as described by Sterman 2000, p. 563-568) to examine the impact of pressure on time per task and demonstrate the importance of setting minimum time standards (burnout and backlog) - Use DES with SD or Agent based simulation characteristics to model Human Behaviour (such as in Brailsford, Sykes and Harper 2006) 
Treatment Complexity	- SD to model technology adoption (Diffusion model Morecroft 2007, p.165) - DES to model the impact of new technology on the flow of patients through the treatment process (as illustrated by the range of projects in the survey by Jun, Jacobson and Swisher 1999)

10.12 DES Model Analysis

The SD model provided insight in every model iteration but the usefulness of the DES was only fully demonstrated at the end of the model development process once the model was confirmed to be convincing by the client (validation). This section details the analysis of the DES model, illustrating the several possible base scenarios of the system (to reflect the resourcing and team working policies), and exploring the impact of increasing the number of patients and changing the patient type through the most complex treatment pathway.

10.12.1 DES Base Scenario

Prior to experimenting with the DES model, a current base scenario needs to be established in order to compare alternative scenarios to search for solutions to the problem (Robinson 2004). Four possible base scenarios for the system are considered, each with varying resource constraints. The current system is represented in these four scenarios with various softening of the resource constraints to reflect: how the system functions on paper (subject to strict consultant timetables), how consultants are likely to work within the system in reality (with relaxed availability), how the system could fully utilise consultant teams, and consultant teams with relaxed availability. In the model, consultants are timetabled to be available at zones of the radiotherapy planning and treatment process at various points throughout the week according to the timetables in the “patient pathways”. However, it is likely there is flexibility around these timetables, along with how consultants with similar speciality are likely to work in teams to ensure patients receive timely care. These four base scenarios are the four levels of constraint the system is or could be subject to.

Base Scenario A: Restricted Consultant Availability

- Consultant availability restricted in line with “patient pathways” and allocated to 3 machine zones: Imaging, Physics, Acuity

Base Scenario B: More Flexible Consultant Availability

- Consultants available at any of the 3 zones if scheduled to be in the hospital

Base Scenario C: Grouped Consultants with Restricted Availability

- Consultants grouped according to Cancer Type allocation (Lung group, Breast group etc.)
- Consultant availability restricted in line with “patient pathways” and allocated to 3 machine zones: Imaging, Physics, Acuity

Base Scenario D: Grouped Consultants with Flexible Availability

- Consultants grouped according to Cancer Type allocation (Lung group, Breast group etc.)
- Consultants available at any of the 3 zones if scheduled to be in the hospital

Results of each of these four scenarios modelled over a year, with a four week warm-up and averaged over 100 runs are presented in Table 26. The base scenario with the most flexibility offers the shortest time to treatment as would be expected. Additionally encouraging consultants to be widely available across all three zones rather than strictly adhering to the patient pathway timetable (B) leads to more completed patient treatments than just having consultants work in groups (C). This indicates the potential impact of the patient pathways timetable on the throughput and performance of the system, and changes to patient pathways should be carefully assessed to ensure they do not excessively restrict the system. However, the best scenario is for consultants to relax their availability and work in teams (D), which ensures timely delivery of treatments and the largest number of patients to complete treatment in the time period.

Table 26: Summary table of base scenarios of DES model (100 runs with four week warm-up)

Scenario	Patients Arriving (per year)	Total Leaving	Completed Patients	Total Sims (#appointments)	Treatments Delivered (#Fractions)	Average Time in System (Days)
A	6,462	5,795	79.90%	8,106.80	91,241.80	29.22
B	″	″	89.95%	8,147.50	106,803.80	28.12
C	″	″	84.20%	8,133.70	96,562.23	28.63
D	″	″	90.30%	8,189.80	106,443.60	26.71

10.12.1.1 Base Scenario A

This impact of consultant availability is seen in scenario A in the form of large queues accruing at acuity (illustrated in Figure 105). This queue in turn masks a problem within physics planning that in the model there are insufficient planning staff able to complete CT Complex[45] plans given the demand on them. Remedial action, in the form of additional acuity capacity from space available on the simulators and a reduction in the time taken for CT Complex plans (or an increase in planners trained at this task), is needed to adjust this scenario so that it is able to achieve a steady state.

10.12.1.2 Base Scenario B

When the consultants are setup to work in teams and distribute their availability around the centre the average time for a patient to reach treatment reduces, but the problem in the CT Complex planning route persists. This issue can be alleviated with the same setup as discussed in Base Scenario A.

[45] CT Complex is the name of one of the 8 patient planning pathways, involving detailed and timely voluming, planning, reviewing and verification.

10.12.1.3 Base Scenario C

This scenario only enables the consultants to work on another team member's patient if at a time that the consultant was timetabled to be available for that zone (one of three: imaging, planning or review). When the consultants are setup to work in teams and distribute their availability around the centre the average time for a patient to reach treatment reduces.

10.12.1.4 Base Scenario D

This scenario is adopted as the base scenario or experimentation as this represents the most optimistic representation of the current system with consultant availability slackened. This may be a closer version of reality due to staff actively 'shuffling' a workload to ensure timely treatment and try to meet the targets. There remains a problem of staffing at CT Complex whereby either the time required per patient needs to reduce, the number of staff increase or a reduction of the number of patients receiving this planning path is made.

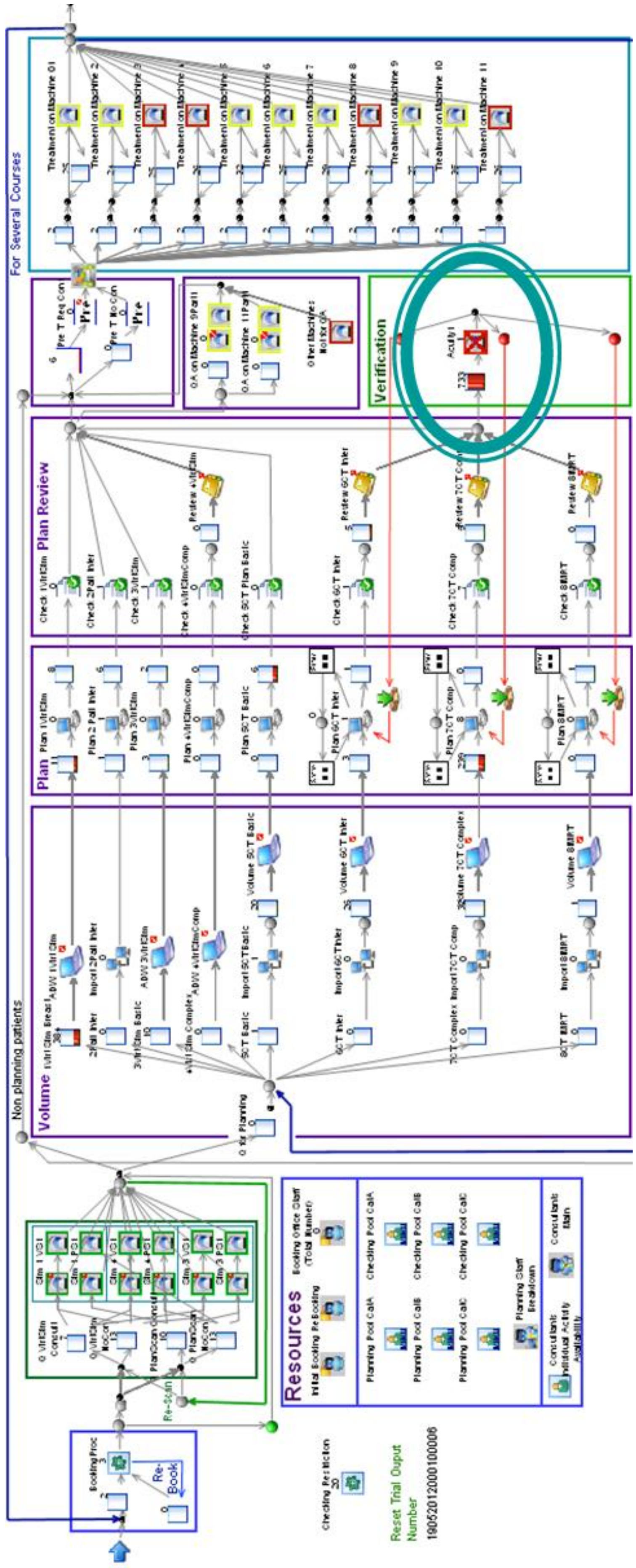


Figure 105: Base scenario A – Restricted Consultant Availability with large queue at Acuity highlighted (image of single run)

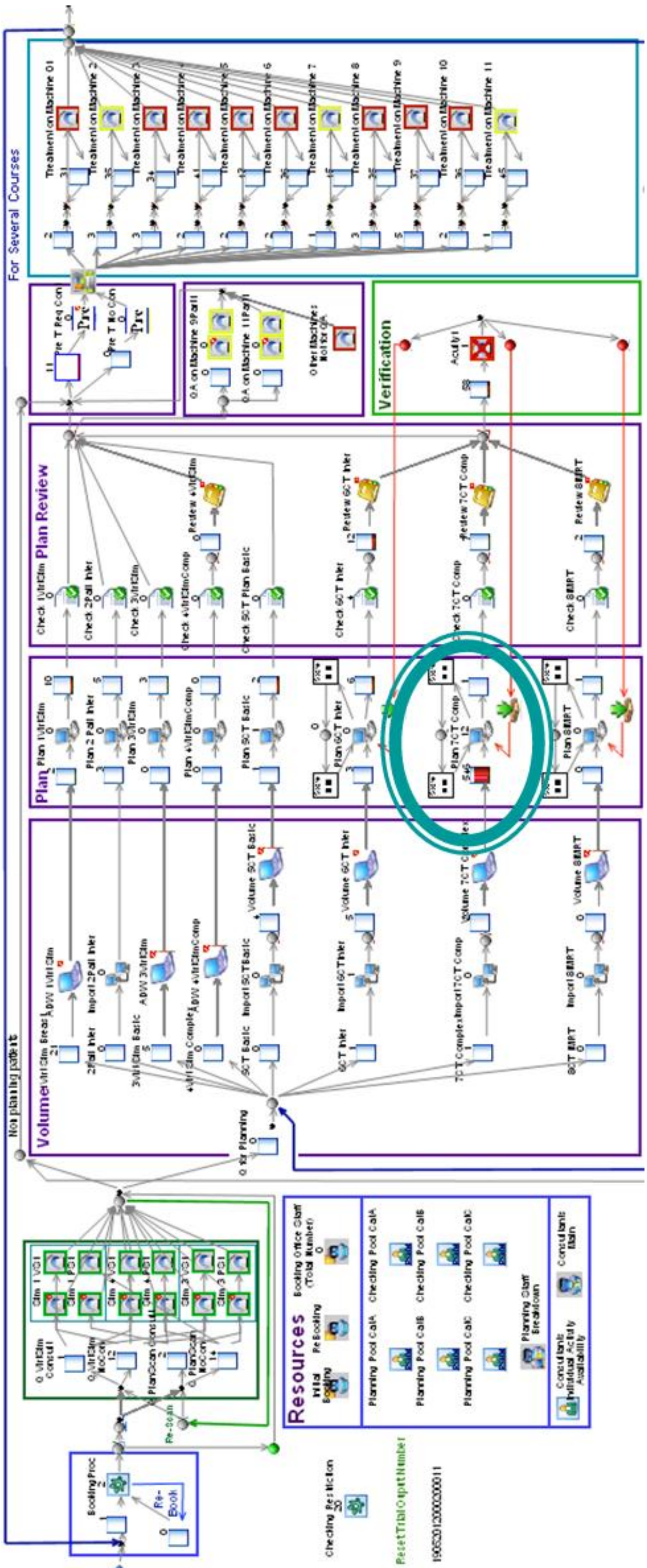


Figure 106: Base scenario B – More Flexible Consultant Availability with large queue at Plan CT Complex highlighted (image of single run)

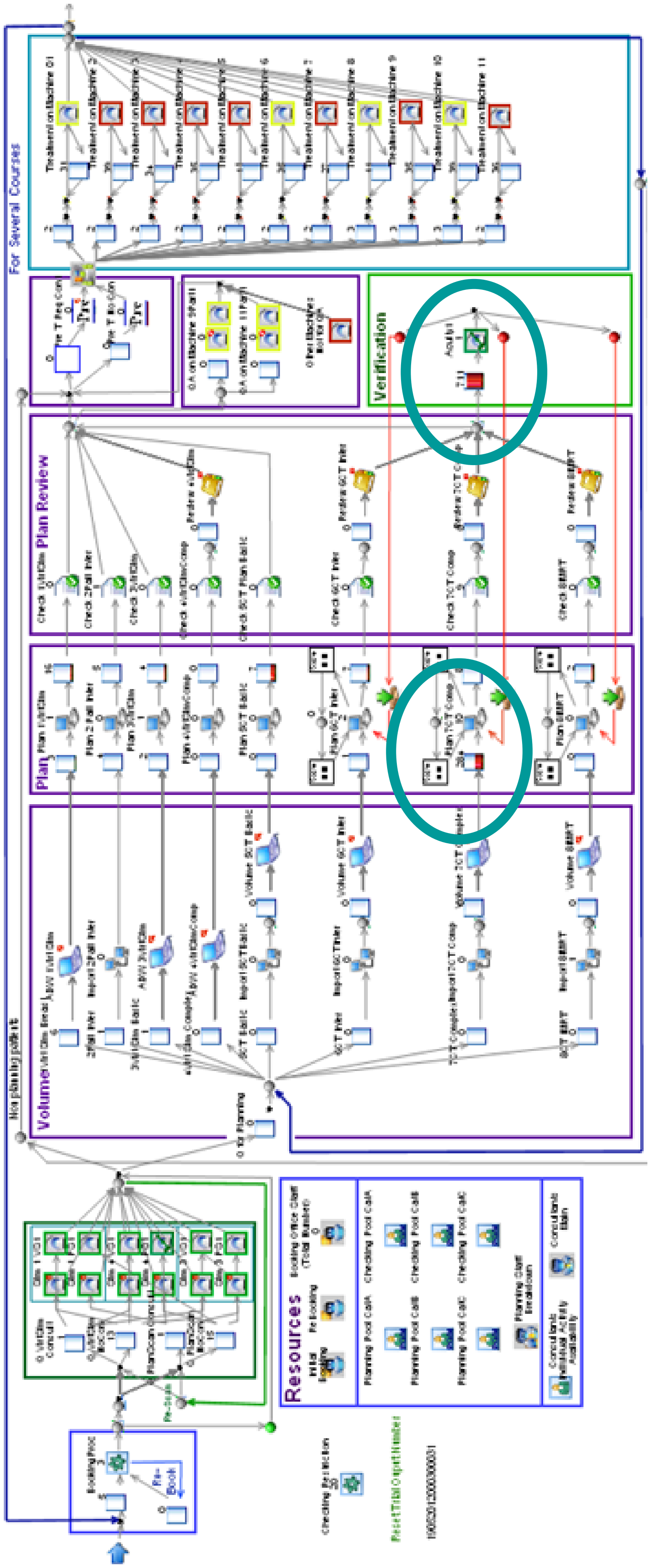


Figure 107: Base scenario C – Grouped Consultants with Restricted Availability with large queues at Plan CT Complex and Acuity highlighted (image of single run)

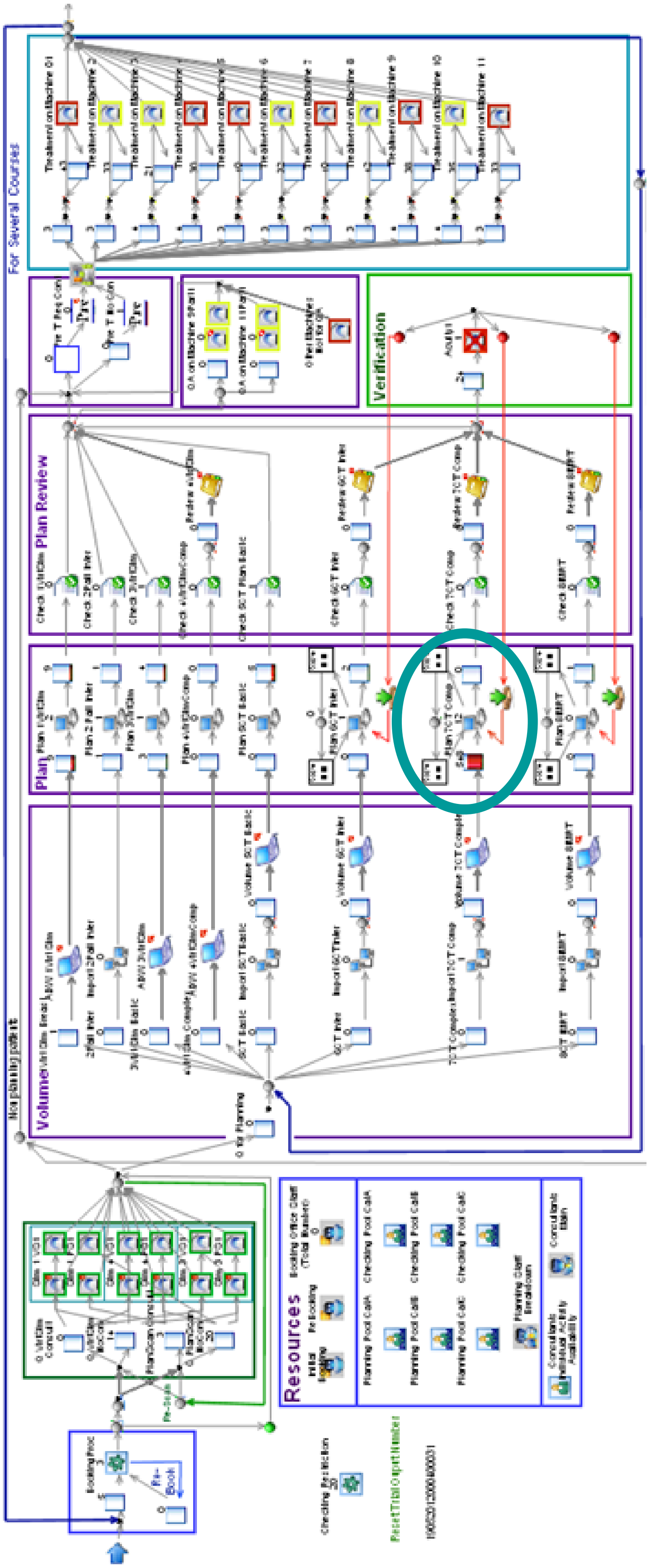


Figure 108: Base scenario D – Grouped Consultants with Flexible Availability with large queue at Plan CT Complex highlighted (image of single run)

The previous section introduced the settings for the base scenarios and illustrated that the setup of the model does not enable these scenarios to achieve a steady state. Base scenario D, which was selected for comparison of alternative system configurations, does achieve a steady state. Therefore it is necessary to adjust the system setup as the current restrictions limit the model so that it is not representing reality. The notation for the adjusted base scenario will be "D0-2" to reflect the two adjustments made to the original setup (base setting D) to ensure a steady state is achieved.

10.12.1.5 Base Scenario D0-2 steady state achieved

Given the planning backlog at CT Complex, queues are also expected at acuity. Given the configuration of consultant availability and qualified planning staff, the restriction placed on the number of plan checks allowed to be performed at any one time places a burden on the system that results in growing queues within physics planning. The planning checking restriction (limiting the maximum number of patients in planning at any one time) is increased from 20 to 40 to allow the staff availability to be the primary throughput restriction. Queues at acuity are managed by using the spare capacity at imaging (adopting one imaging machines unutilised time)

The results from this now stable base scenario are shown in Table 27. These results are based on 100 runs modelling 52 weeks (with 6 weeks warm-up). There exists large variation in the time for a patient to reach their first treatment. This is due to the various pathways embarked on by each cancer type; with CT Complex plans being the timeliest (see Figure 109).

Table 27: Summary of results from Scenario D0.2

Measure	Average
Average number of patients arriving	6,462
Average leaving	6,128
Average completed patients	94.83%
Average total number of imaging sims	8,254.90
Average treatments delivered	106,189.33
IMRT (portion of radical patients)	20.70%
Average Time to Reach First Treatment (Days)	28.52
St. Dev	20.56

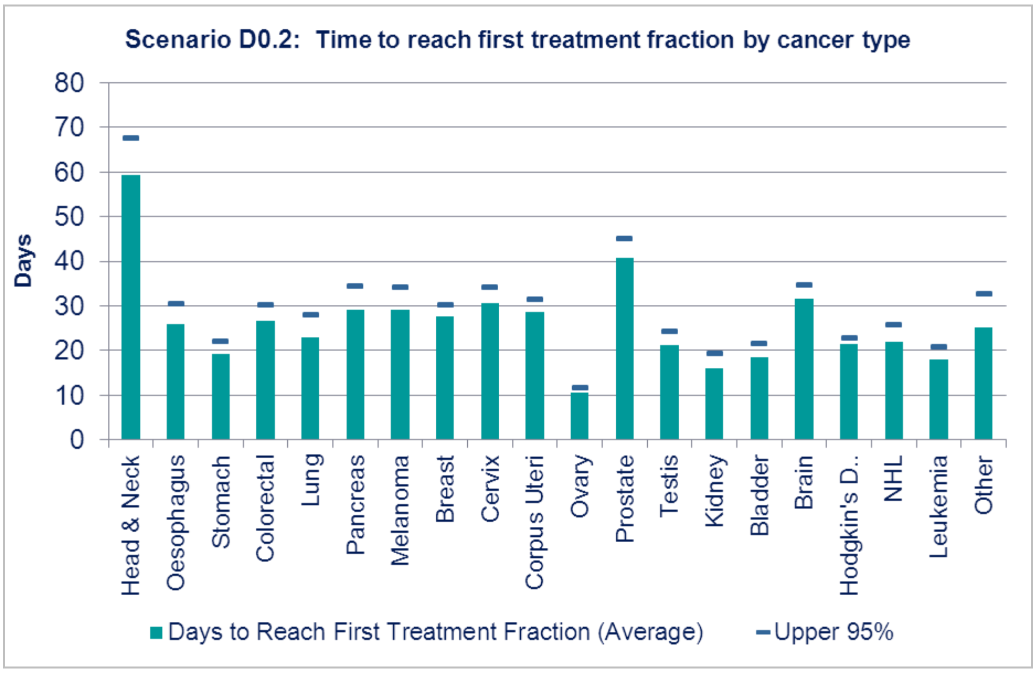


Figure 109: Scenario D0.2 – time to reach first treatment by cancer type

10.12.2 DES Model Experimentation

Scenario D0-2 is used to represent the current Beatson situation and the modeller is able to conduct experiments to establish the impact of new treatment regimes on the time to treat and propose solutions to bottlenecks which occur in the system that satisfy the clients requirements. These experiments consist of a selection of changes proposed to the system (scenarios). They were devised from the interviews with stakeholders and refined during discussions with the client. The six scenarios described in Table 28 depicts a selection of possible future implementation schemes for the Beatson; ranging from what is desirable in the next 6 months, to the ideal scenario of all (radical) patients having access to IMRT, within the constraints of the current machine resources.

Table 28: Scenarios to be explored with DES

#	Name	Description
2	Increase current IMRT activity	Increase Head & Neck (to 25%), Increase Prostate (to 34%), Increase Other (to 30%)
3	Fully implement IMRT where currently used	Increase current IMRT activity on Prostate, Head & Neck, and Brain to 100%
4	Additionally bring in IMRT treatment for “Other”	Increase Other IMRT from 30% to 70%
5	Additionally introduce Breast IMRT	Implement IMRT for 50% of Breast patients
6	Additionally treat all Lung patients using IMRT	Lung 100%, Pancreas and Cervix
7	Implement IMRT across all cancer types (note: Breast and Other have marginal CT Complex treatment plans)	98% of Breast and Other to receive IMRT, 100% of all remaining patients receive IMRT

Criteria for comparison of scenarios are performance measures described as important indicators by the interview participants. For the sake of brevity, only a short summary of a small selection of the experiments conducted on the model are included. Additional experiments took place throughout the project to develop the understanding the modeller and client held of the system.

The solution space of this large DES model is large. Multiple combinations of multiple parameters lead to an unmanageable number of possible scenarios requiring extensive man-hours and/or computer power. A total comparison of scenarios is not possible. Therefore the number of scenarios must be set to a manageable level. Interactive experimentation took place with the client to establish the solution to the growing queues in the first base scenario and led to the verification of the base scenario (D0-2) used in the following experiments.

10.12.2.1 Scenario D2

Increase IMRT activity (Head & Neck [25%], Prostate [34%], Other [30%])

This scenario exhibits increased throughput whilst maintaining the average time to reach first treatment using the same setup as currently in place (base). The model illustrates that it is possible to increase the proportion of patients receiving IMRT without impacting the average time to treatment experienced by all patients. However, the variation in time to reach first treatment across cancer types remains large.

Table 29: Summary of results from Scenario D2 (with D0.2 setup)

Measure	Average
Average number of patients arriving	6,462
Average leaving	6,149
Average completed patients	95.16%
Average total number of imaging sims	8,262.00
Average treatments delivered	117,987.00
IMRT (portion of radical patients)	20.70%
Average Time to Reach First Treatment (Days)	28.64
St. Dev	20.72

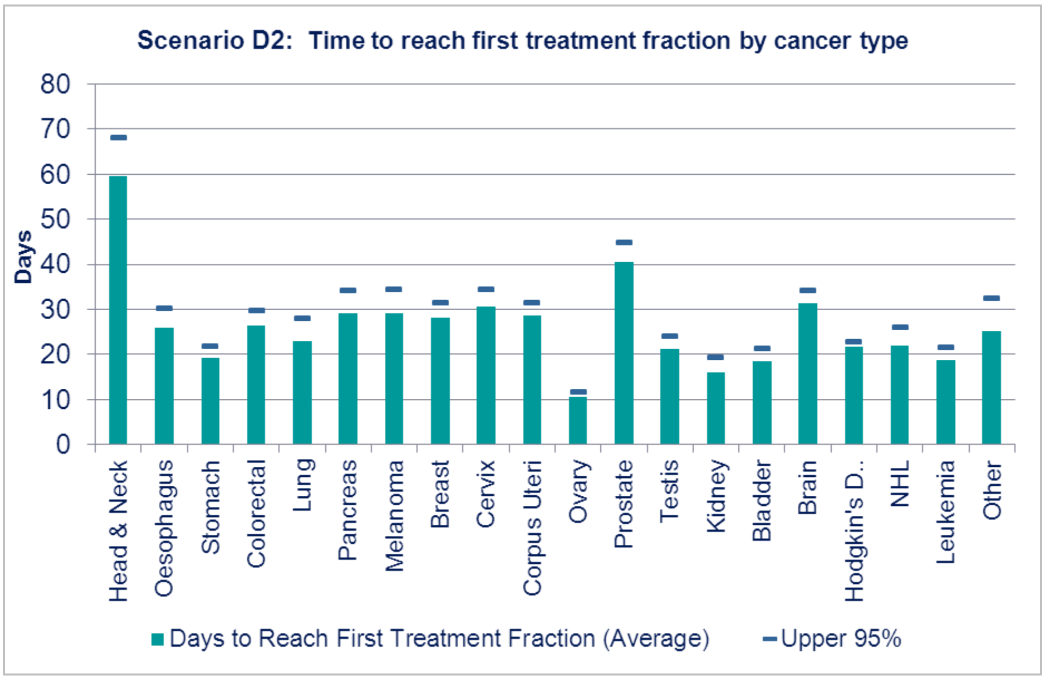


Figure 110: Scenario D2 – time to reach first treatment by cancer type

10.12.2.2 Scenario D3

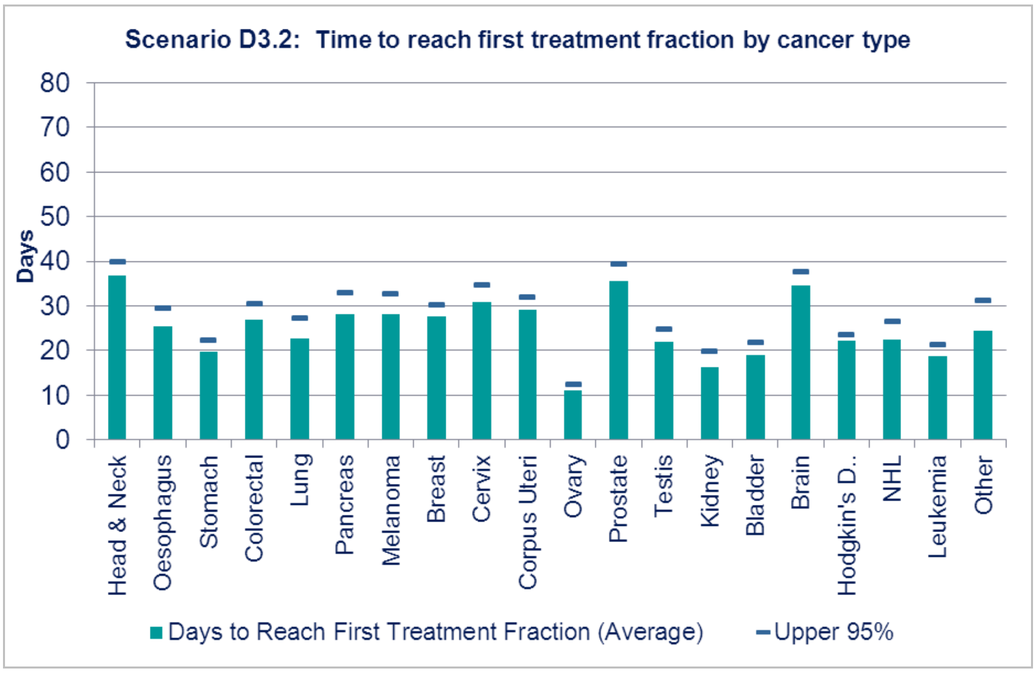
100% IMRT on currently treated cancer types (Prostate, Head & Neck, and Brain)

The base setup of the system is unable to cope with the increased IMRT for Prostate, Head & Neck and Brain patients. An additional IMRT enabled treatment machine is needed (3 IMRT, 8 non-IMRT) and all available time on the imaging machines is adopted for Acuity use.

Table 30: Summary of results from Scenario D3.2 (with additional IMRT)

Measure	Average
Average number of patients arriving	6,462
Average leaving	6,321
Average completed patients	97.83%
Average total number of imaging sims	8,264.00
Average treatments delivered	109,900.00
IMRT (portion of radical patients)	26.80%
Average Time to Reach First Treatment (Days)	26.75
St. Dev	16.31

Figure 111: Scenario D3.2 – time to reach first treatment by cancer type



10.12.2.3 Scenario D4

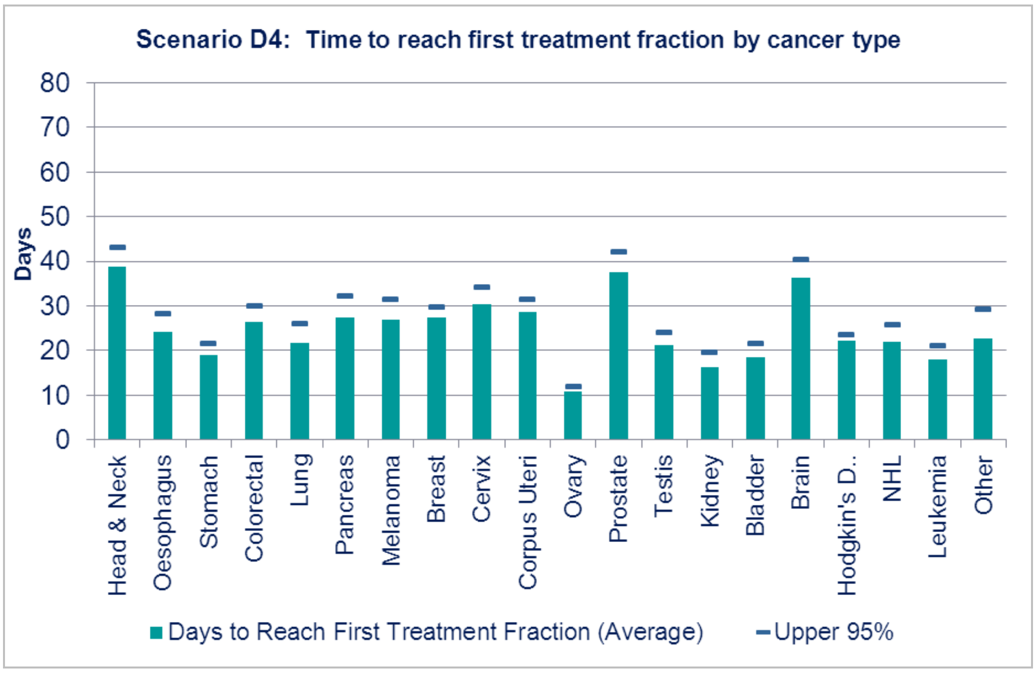
Increase IMRT for "Other" (70% of patients)

No additional change to the system from scenario D3 is required. Increased IMRT is leading to reduced variance in the average time to reach treatment (Table 31), and reduced variance between cancer types (Figure 112).

Table 31: Summary of results from Scenario D4 (with D3.2 setup)

Scenario D4	
Average number of patients arriving	6,462
Average leaving	6,301
Average completed patients	97.57%
Average total number of imaging sims	8,260.00
Average treatments delivered	108,840.00
IMRT (portion of radical patients)	35.40%
Average Time to Reach First Treatment (Days)	26.22
St. Dev	16.59

Figure 112: Scenario D4 – time to reach first treatment by cancer type



10.12.2.4 Scenario D5

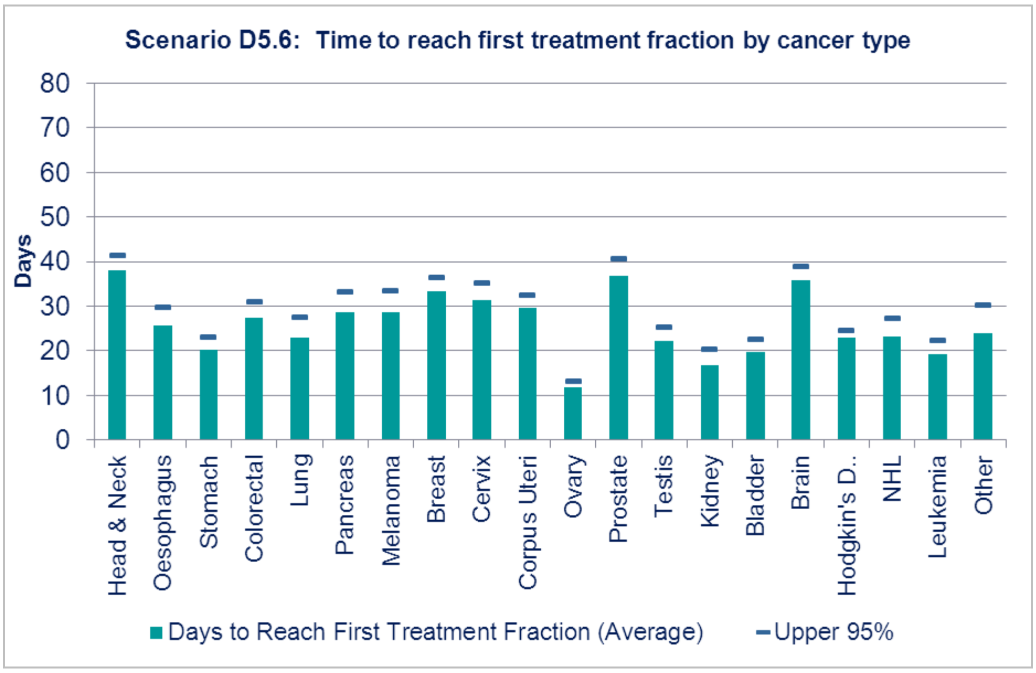
<u>*Introduce Breast IMRT (50% of patients)*</u>

This scenario requires a total of 5 IMRT enabled LinAcc's with a reduced time required at planning or increased planners qualified to complete IMRT plans. The overall result is a reduction in the average time for a patient to reach treatment and reduced variance in time to reach treatment.

Table 32: Summary of results from Scenario D5.6 (5 IMRT treatment machines and more IMRT trained planners)

Measure	Average
Average number of patients arriving	6,462
Average leaving	6,256
Average completed patients	96.74%
Average total number of imaging sims	8,243.00
Average treatments delivered	107,656.00
IMRT (portion of radical patients)	46.70%
Average Time to Reach First Treatment (Days)	28.48
St. Dev	16.66

Figure 113: Scenario D5 – time to reach first treatment by cancer type



10.12.2.5 Scenario D6

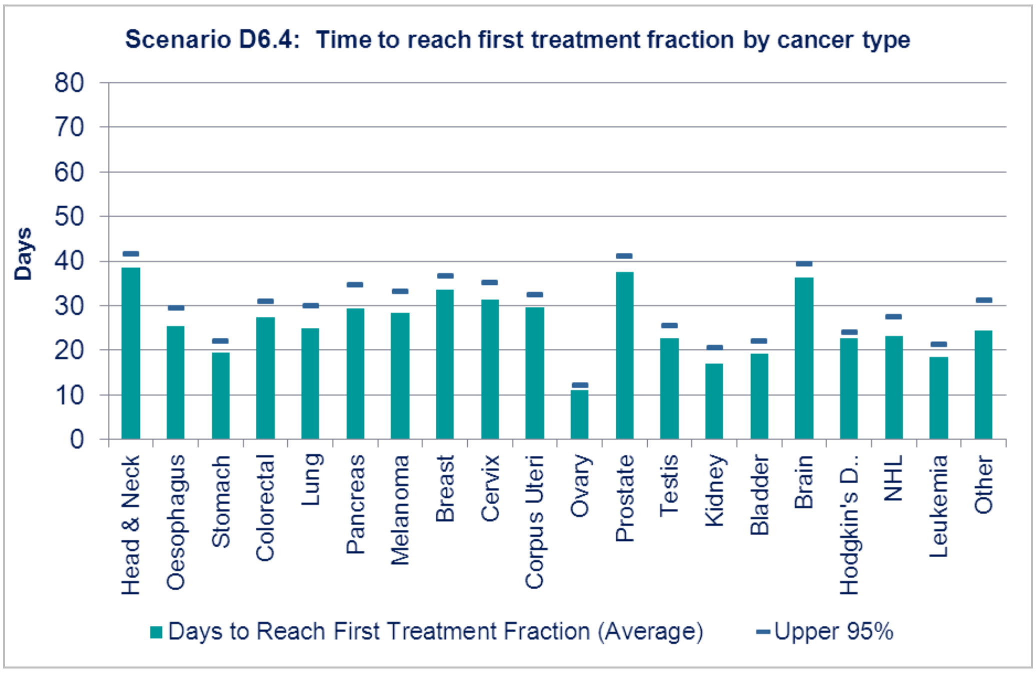
IMRT for all Lung, Pancreas and Cervix patients

Six IMRT enabled LinAccs are required and a reduced time required at planning or increased planners qualified to complete IMRT plans in order for this scenario to be practical within the Beatson. The average time to reach treatment has increased due to the pressure on IMRT resources as a result of the increased proportion receiving this patient pathway. A further IMRT enabled treatment machine and additional reduction in planning time would improve these results.

Table 33: Summary of results from Scenario D6.4
(Reduced IMRT planning time and 6 IMRT machines)

Measure	Average
Average number of patients arriving	6,462
Average leaving	6,229
Average completed patients	96.48%
Average total number of imaging sims	8,235.00
Average treatments delivered	106,410.00
IMRT (portion of radical patients)	55.60%
Average Time to Reach First Treatment (Days)	29.19
St. Dev	17.09

Figure 114: Scenario D6 – time to reach first treatment by cancer type



10.12.2.6 Scenario D7

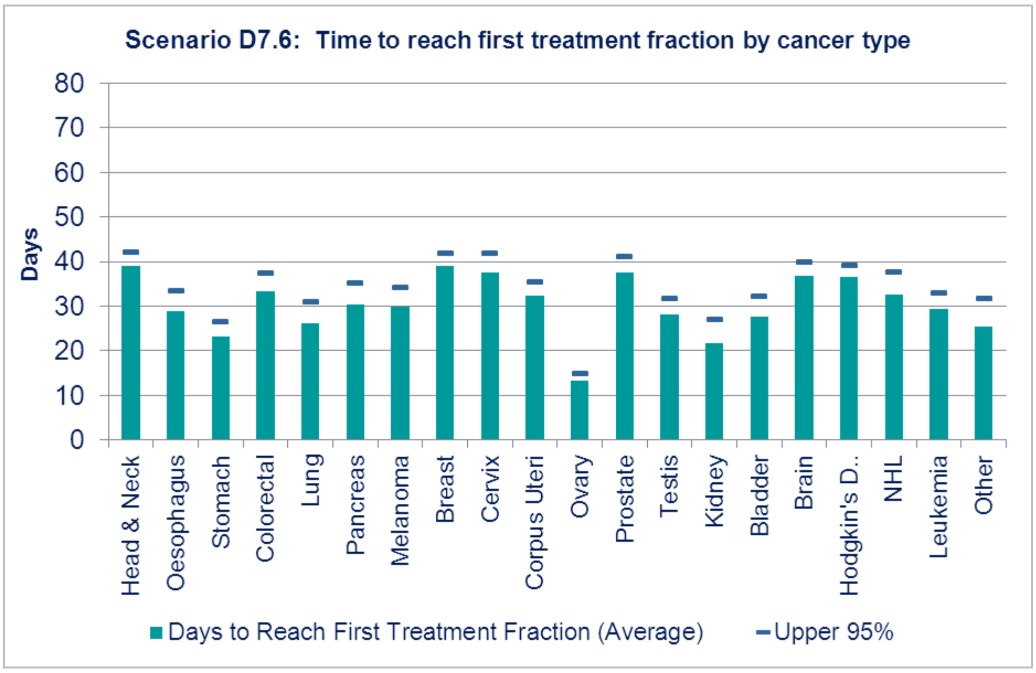
<u>*100% of patients receive IMRT (but 98% of Breast and Other)*</u>

Although this scenario results in an increase in the average time to reach treatment, the variance between patient cancer types reduced leading to more equitable access to treatment. To configure the system to cope with this level of IMRT (almost 100% for all radical patients) it is necessary to have 10 of the 11 LinAccs able to provide this form of therapy, and reduce the time it takes planning to complete IMRT plans. The planning time could form a substantial barrier to the eventual implementation of this scenario and methods to reduce planning times are advised to be investigated.

Table 34: Summary of results from Scenario D7.6 (10 of the 11 LinAccs delivering IMRT)

Measure	Average
Average number of patients arriving	6,462
Average leaving	6,138
Average completed patients	94.93%
Average total number of imaging sims	8,193.00
Average treatments delivered	102,847.00
IMRT (portion of radical patients)	94.50%
Average Time to Reach First Treatment (Days)	32.22
St. Dev	17.02

Figure 115: Scenario D7 – time to reach first treatment by cancer type



10.12.2.7 Summary

Increasing patient access to IMRT requires investment in staff and treatment delivery machines (IMRT enabled LinAccs). The system is able to cope with the first marginal increase in access, but all other scenarios require adjustments to be made to the system. Providing access to IMRT for all radical patients requires the time taken by staff to reduce significantly (through investment in training) or more staff.

All scenarios have been conducted with at most only a minor reduction in average time to complete “Plan 8IMRT”. A larger reduction in the time to complete this stage of treatment would allow a decrease in time to first treatment across all patient groups. However, achieving this reduction would require additional staff and therefor need to take into account the training needs and learning processes explored during the SD modelling.

The sensitivity of the system is due to how close to capacity it is functioning. Any anomalies can cause the system to tip into out of control queue growth. Again, in reality this may be remedied by staff accommodating additional work by working longer hours or by compromising on the roll-out of improved treatment regimes, and each of these has significant disadvantages.

Consultant availability is a heavy constraint on the functioning of the system if the consultant/patient pathways are adhered to strictly when booking patients. Adjusting this scheduled availability, such that a consultant is available to the entire process rather than only one of the three points in the process where they are required, has a positive impact on the performance of the system. Slackening this hard constraint reduces the maximum time to treatment observed in the model which was a by-product of limited consultant availability. This adjusted availability of consultants also means that they do not constrain performance when implementing new treatment regimes.

10.13 Model Validity

The table below details the questions an SD modeller should ask of their model, and which are considered in section 7.5.2. The modeller considered all four through each of the three model development iterations. Focus was drawn however to the first three: with *'Purpose, Suitability, and Boundary; Physical'* and *'Decision-Making Structure'* providing useful points of reflection which led to the models being further developed (the second and third iterations); and *'Robustness and Sensitivity to Alternative Assumptions'* considered whilst testing the models developed at each iteration.

Table 35: Questions model users should ask – but usually don't (Sterman 2000, p.852, Table 21.1)

Purpose, Suitability, and Boundary

- What is the purpose of the model?
- What is the boundary of the model? Are the issues important to the purpose treated endogenously? What important variables and issues are exogenous or excluded? Are important variables excluded because there are no numerical data to quantify them?
- What is the time horizon relevant to the problem? Does the model include the factors that may change significantly over the time horizon as endogenous elements?
- Is the level of aggregation consistent with the purpose?

Physical and Decision-Making Structure

- Does the model conform to basic physical laws such as conservation of matter? Are all equations dimensionally consistent without the use of fudge factors?
- Is the stock and flow structure consistent with the model purpose?
- Does the system represent disequilibrium dynamics or does it assume the system is in or near equilibrium all the time?
- Are appropriate time delays, constraints, and possible bottlenecks taken into account?
- Are people assumed to act rationally and to optimise their performance? Does the model account for cognitive limitations, organisational realities, noneconomic motives, and political factors?
- Are the simulated decisions based on information the real decision makers actually have? Does the model account for delays, distortions, and noise in information flows?

Robustness and Sensitivity to Alternative Assumptions

- Is the model robust in the face of extreme variations in output conditions or policies?
- Are the policy recommendations sensitive to plausible variations in assumptions, including assumptions about parameters, aggregation, and model boundary?

Pragmatics and Politics of Model Use

- Is the model documented? Is the documentation publicly available? Can you run the model on your own computer?
- What types of data were used to develop and test the model (e.g., aggregate statistics collected by third parties, primary data sources, observation and field-based qualitative data, archival materials, interviews)?
- How do the modellers describe the process they used to test and build confidence in their model? Did critics and independent third parties review the model?
- Are the results of the model reproducible? Are the results "add-factored" or otherwise fudged by the modeller?
- How much does it cost to run the model? Does the budget permit adequate sensitivity testing?
- How long does it take to revise and update the model?
- Is the model being operated by its designers or by third parties?
- What are the biases, ideologies and political agendas of the models and clients? How might these biases affect the results, both deliberately and inadvertently?

10.14 Modeller Reflection: During 2nd Modelling Iteration

This section discusses the modeller's utilisation of the mixed method designs to reconsider how to model the problem system which was discussed in section 8.3.6. It outlines how the mixed method design wasn't the only applicable design, but was deemed most appropriate to the situation by the modeller after exploring several possible options.

Figure 116 illustrates SD model B in which was used to understand what impact altering treatment time has on the size of the queues and the average time for patients to receive treatment. DES would traditionally be used to capture the effects of changing service times on a queuing system, but at this point in the modelling we explored if it was possible and practical to enrich the SD model with this DES characteristic. It was possible to manage the changes to the SD and DES models easily as they were separate and not at the same level of detail. If the two methods were used in an *integrated* design as a single model then the knock-on impact of including further detail would have to be considered.

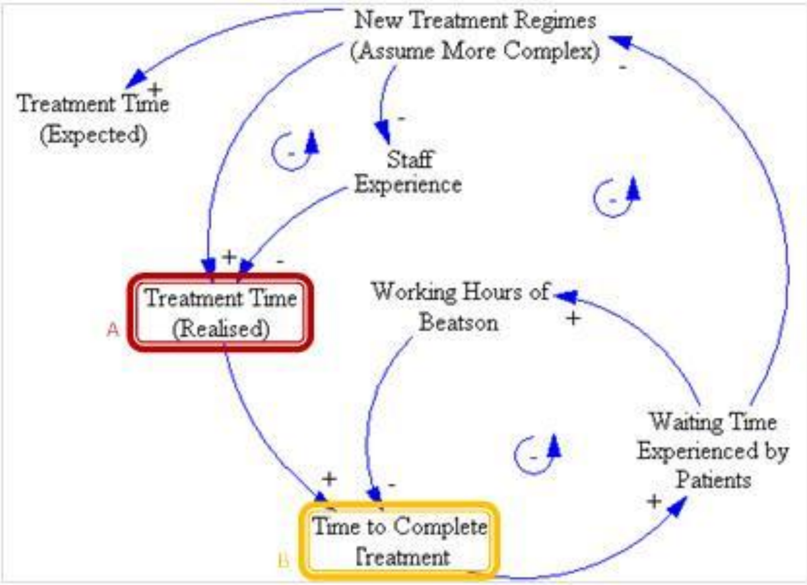


Figure 116: Summarised CLD of the SD model B

The variables *Treatment Time (realised)* [A] and *Time to Complete Treatment [B]* within the model are influencing the queuing and subsequent treatment of patients within the system. To model this aspect of the system it is necessary to consider how SD is traditionally applied to represent queuing systems.

10.14.1 Modelling queues in SD

A classic SD depiction of a queue for a service that is performed at a given rate depending on the staff and work hours available and productivity is shown in Figure 117. This model assumes that the time taken to progress through service is a known variable. However, in the Beatson we know the desired level for this variable (to align with government targets) and we know the time taken to complete tasks (Treatment Time) but we do not know the impact of these on the departure rate.

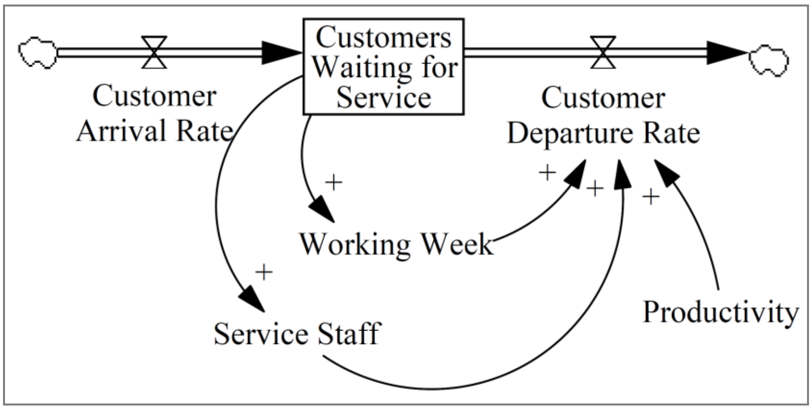


Figure 117: Modelling Queues in SD – Queuing for Service

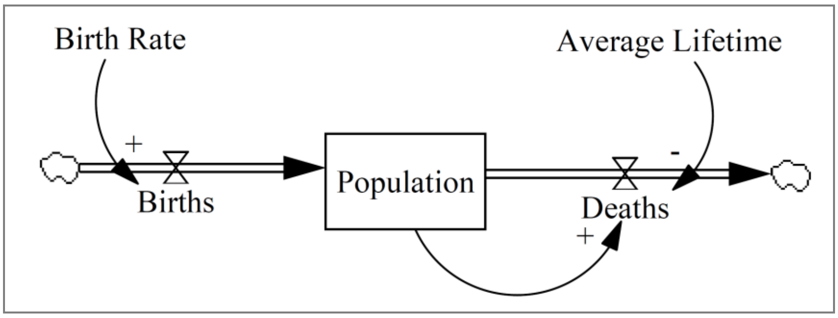


Figure 118: Modelling Queues in SD – Population

An alternative form for modelling a queue in SD (illustrated in Figure 118) uses the average total time in the system (average lifespan) of a population which is appropriate when applied to population models as it can be readily estimated. This structure is relevant and desirable in this context as both average lifetime and birth rate are measures commonly discussed and are easily predictable (from census data for example). Applying the same structure from Figure 118 to the Beatson project, the patient treatment process may be modelling using *Patient Referral Rate* and *Average Time to Complete Treatment* (Figure 119). However, within this project *Average Time to Complete Treatment* is unknown: it is sensitive and subject to change due to changing treatment regimes altering the treatment times, and the relationship between the two variables is unclear.

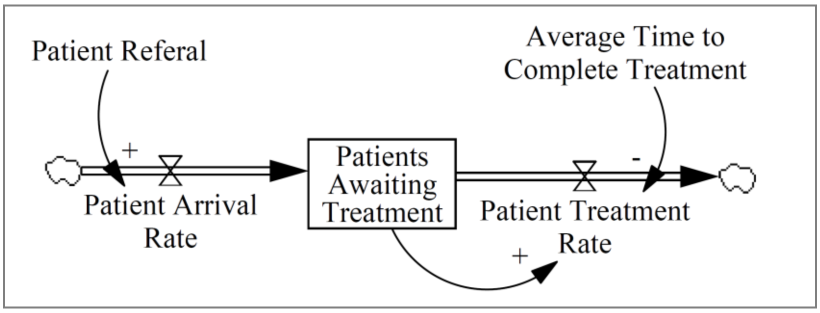


Figure 119: Stock and Flow Diagram of a Patient Treatment Process

10.14.2 Simple estimation of time in system using queuing theory

Queuing theory tells us that the relationship between the two variables is not simply linear; it needs to be modelled carefully to ensure realistic behaviour is generated. Estimating the *Time to Complete Treatment [B]* using queuing theory:

Known: $1/\mu$ = Service Time = *Treatment Time [A]*

λ = Arrival Rate

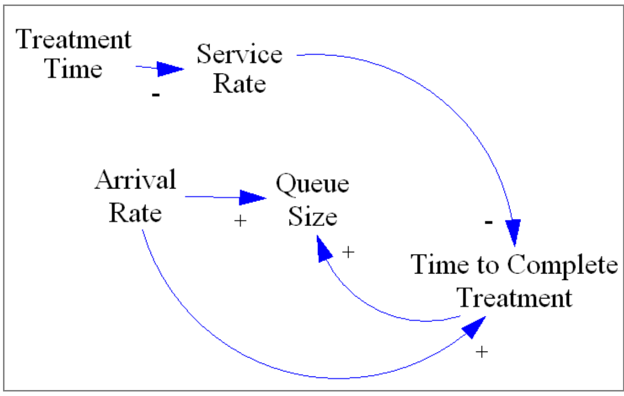
Unknown: E(S) = Mean expected time in system = Av. *Time to Complete Treatment [B]*

Considering the simplest form, with random arrivals and a single server with lognormal service distribution (M|M|1 in Kendall's notation) it is possible to estimate the expected time in the system given an arrival rate and service time (Equation 1).

$$E(S) = \frac{1/\mu}{\left(1-\frac{\lambda}{\mu}\right)}, \; E(S) \rightarrow \infty \text{ as } \frac{\lambda}{\mu} \rightarrow 1$$

Equation 1: Expected time in the system

Within the SD model it is possible to implement this equation and observe exponential queue growth based on an M|M|1 queue. The relationship between service rate and time to complete is estimated using E(S), and as the utilisation of the system increases then the queue grows exponentially.



$$Time\ to\ Complete\ Treatment = \frac{1/ServiceRate}{\left(1 - \left(ArrivalRate/ServiceRate\right)\right)} = \frac{TreatmentTime}{\left(1 - \left(ArrivalRate \times TreatmentTime\right)\right)}$$

Figure 120: Causal Loop of a Simple Queue at the Beatson

10.14.3 Enriching SD

Alternatively, the philosophy of SD could be embraced and the queue modelled as a feedback system. Traditionally, exponential growth within a SD model would indicate that there exists an underlying positive feedback loop (Sterman 2000), as shown in Figure 121, which results in exponential growth. To locate this loop within the Beatson system it is necessary to disaggregate[46] the model to reveal the mechanics behind this behaviour.

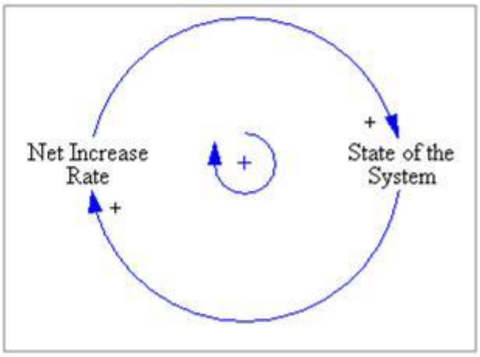


Figure 121: Exponential Growth Feedback Loop

Figure 121 is modified to include the percentage of time a server is not available (to an arriving patient) and the use of resources (Figure 122). This structure clarifies and supports the behaviour described in queuing theory (and that observed within DES models). However, to capture exponential growth in queue size through a feedback loop values that are not easily captured in the Beatson would have been required. These values were not easily estimated; therefore queuing theory was reconsidered, as recommended by Sterman (2000).

[46] Disaggregation of variables is discussed by Sterman (2000, p.215)

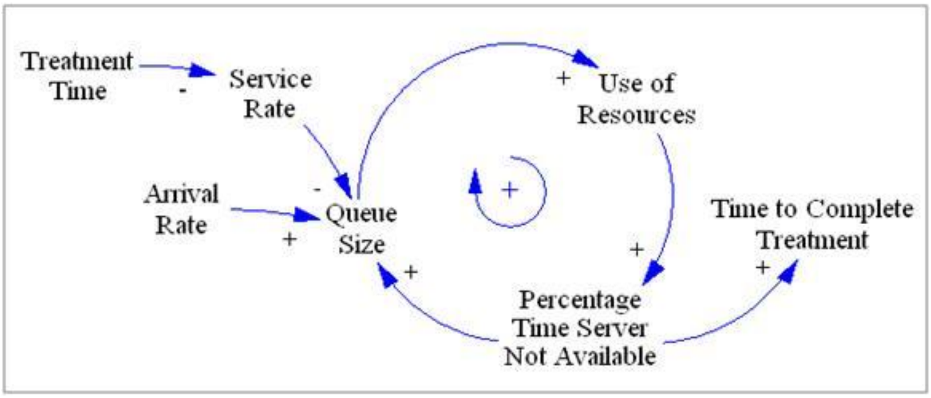


Figure 122: Causal Loop Diagram of the Feedback within a Queuing System

10.14.4 Estimating queue size in SD using queuing theory

In reality, the system within the Beatson consisted of multiple queues for multiple machines through which patients may take multiple routes. A M|M|1 queue does not reflect the stages of treatment in practice and so expanding this to five queues in tandem provided a more accurate representation of the system. In Kendall's notation:

$M|M|C_B \rightarrow \ldots|M\ |C_S \rightarrow \ldots|M\ |C_P \rightarrow \ldots|M\ |C_T$

Where C_B = number of Booking Servers (Booking Staff)

C_S = number of Scanning Servers (Scanners)

C_P = number of Planning Servers (Planning Staff)

C_Q = number of Acuity Servers (QA Machines)

C_T = number of Treatment Servers (Treatment Machines)

Therefore, $E(S) = E(S_B)+E(S_S)+E(S_P)+E(S_Q)+E(S_T)$

To calculate the expected time in the system, when considering queues in tandem, it was necessary to determine the arrival distributions into each subsequent queue which is the departure distribution for the previous queue. For a single M|M|C queue the departing distribution is equal to the arrival distribution of the system (Bunday 1996). This solution holds for a system in a steady state[47] with $\rho<1$. As ρ becomes close to 1, the arrival distributions alter and begin to mimic the behaviour of service at the server they are exiting. Therefore it is possible to implement these concepts within the SD model, but as the system utilisation (p) tends to 1 then the system will not be in a steady state and the expected time in the system becomes unknown (Table 36).

[47] Queueing theory results hold for a steady state system. For this to exist in an M|M|C queue: $\lambda<c\mu$ i.e. $\rho<1$ where $\rho = \lambda / c\mu$ is the utilisation of the system. In the case of a system with n queues in tandem it is necessary for $\lambda<c_n\mu_n$ to hold for all n stages i.e. $\rho_n<1$ for all n.

Table 36: Expected time in the system for queues in tandem

1^{st} stage in tandem queue	For ρ_n<1 Arrival Rate = λ Service Rate = μ_1	$E(S_1) = \frac{1/\mu_1}{(1-(\lambda/\mu_1))}$
	If ρ_n=1 Arrival Rate = λ Service Rate = μ_1 =λ Equation no longer holds	$E(S_1) = \frac{1/\mu_1}{(1-(\lambda/\mu_1))} = \frac{1/\lambda}{(1-(\lambda/\lambda))} = \frac{1/\lambda}{0}$
	Similarly, if ρ_n>1 the equation no longer holds due to E(S) becoming negative => exponential queue growth	
n^{th} stage in tandem queue	If ρ_{n-1}<1, Arrival Rate: λ Service Rate: μ_n	$E(S_n) = \frac{1/\mu_n}{(1-(\lambda/\mu_n))}$
	If ρ_{n-1}>=1, Arrival Rate = μ_{n-1} (service rate of previous stage) Service Rate: μ_n	$ESn=1\mu n(1-(\mu n-1\mu n))$

10.14.5 Summary

When applying these ideas to the Beatson project, it was noted earlier that DES modelling and data analysis revealed the system to be working very close to capacity and so the behaviour of patients arriving into each stage of the queuing system may change behaviour as a result. This altering behaviour meant that it was not efficient or insightful to develop the equations of the relationship between μ and E(S) any further. Rather, implementing further complex conditional equations within the SD model may turn a transparent model opaque and behaviour may not be understood or bought into by the client and project stakeholders.

10.15 Modeller Reflections: During 3rd Modelling Iteration

Figure 123 illustrates the relationship between the SD model and the proposed DES model. The green/blue section of the diagram represents the SD model in its current form (with bold blue curved arrows denoting the feedback). The SD model B uses a queueing theory relationship to represent the Beatson treatment process, but this can be replaced with a DES model as shown in the purple portion of the diagram. The impact of changing one or more of the service times at any of the servers within the Beatson process can be evaluated and fed back into the SD model to more realistically reflect the situation.

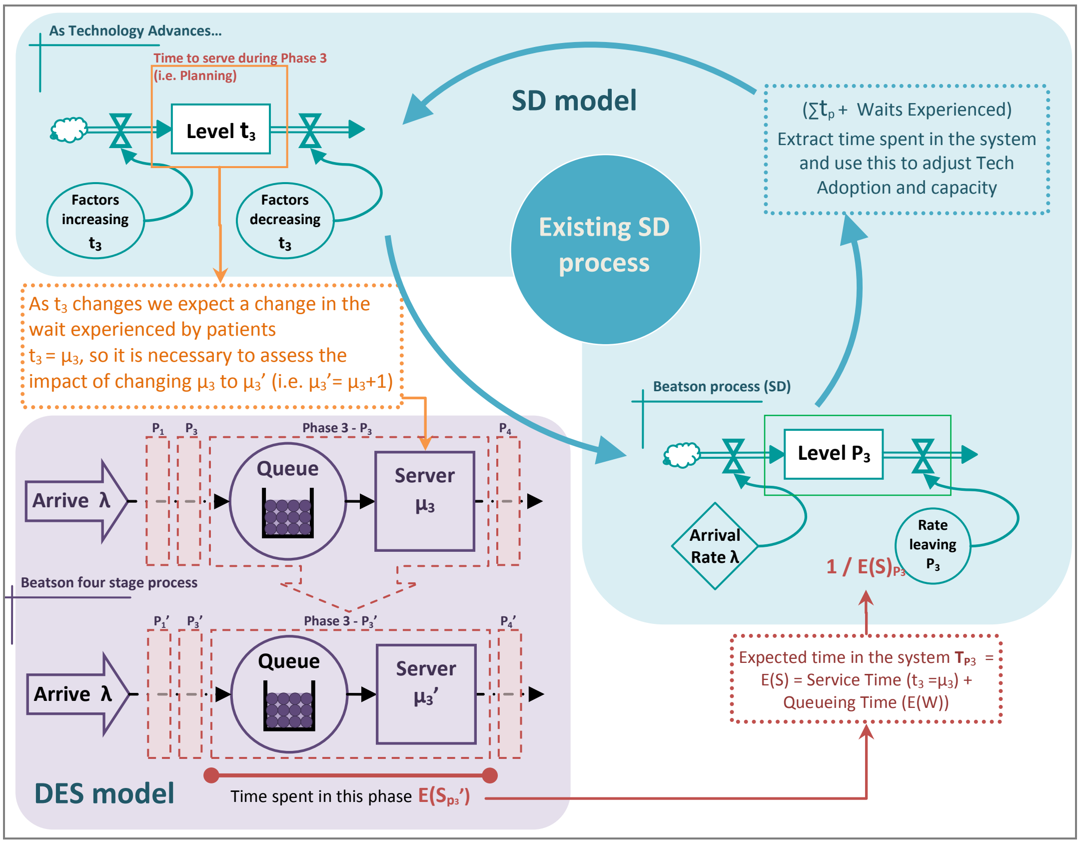


Figure 123: Potential for a DES to add value to a SD model in the Beatson

These principals of interaction between the models may be generalised as illustrated in Figure 124. In this generalised case, the models interact such that:

- the DES model provides the expected total time in the system (or part of the system),
- this information is passed to the SD to inform a rate within the model,
- this rate influences a variable linked to the DES model, such as the resource level or arrival rate,
- the SD model provides the expected change in the level or rate to populate the associated variable in the DES model.

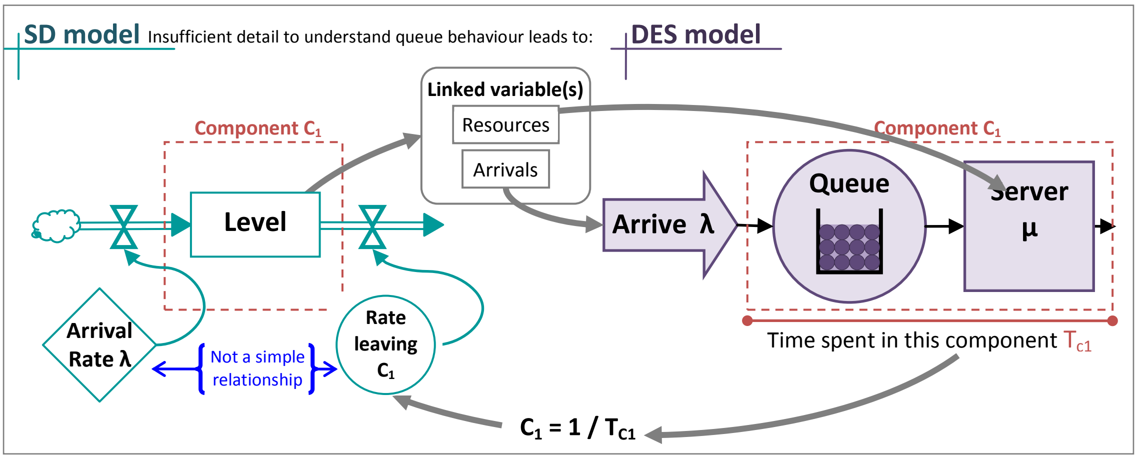


Figure 124: Generalised interaction of SD and DES queue modelling

When considering combining the two methods it is important to consider time units (*timestep*) and the time over which the models run (*timeframe*). The SD model may model a system at a 'per day' *timestep* and for one year (*timeframe*); whereas the DES then may model the intricacies of each day represented in terms of minutes and seconds (the minimum *timestep* between events) over the course of a month (*timeframe*). But, in order to combine the methods we may wish to align the *timeframes*; for example, the DES would represent a day or several days (with multiple runs conducted to provide a range of possible outcomes). The DES is then able to add insight to the SD at a per day level (this is the DES over its *timeframe* informing the SD at each *timestep*). This may be done according to several mixed method designs, all of which pass information between the two models:

Soft *interaction* – Transfer of insight; run the DES to develop understanding of system relationships, and then represent them in the SD model to generate possible futures.

Data *interaction* – A more formal combination of the methods where one method creates scenarios for the next and data is transferred between them. Run the SD model over one DES *timeframe* to give a scenario which can feed into the DES; then, following the DES insight, update the SD policies.

Automated data *interaction* – Use the SD to feed a scenario into a DES, run an appropriate number of trials within the DES (over the *timeframe*) to then feed the results into the SD at each *timestep*.

Integration – Both methods feed data to each other throughout the timeframe of the single model. For the Beatson this design would require extensive data relating to all possible treatment complexity scenarios, and may need a different *timeframe*.

These concepts are discussed in more detail in section 8.3.8 and reflected upon to inform the frameworks proposed in this thesis.

Glossary

2DRT:-	2 Dimensional Radiotherapy
3DCRT:-	3 Dimensional Conformal Radiotherapy: a modified form of EBRT designed to be more accurate and deliver higher radiation doses, most often used in Prostate cancer.
Adjuvant therapy:-	Treatment given after the primary treatment to increase the chances of a cure. Adjuvant therapy may include chemotherapy, radiation therapy, hormone therapy, or biological therapy.
Cauterization:-	The act of coagulating blood and destroying tissue with a hot iron or caustic agent or by freezing. The act of searing some morbid part by the application of a cautery or caustic.
Collapsed Map:-	Map representing key links between clusters, hiding detail that may confuse the overall message.
Combined Map:-	Initial merging of the individual maps.
CSV:-	Comma Separated Variable – a variable holding a list of items, whereby each item is separated from the next by a comma.
DES:-	Discrete Event Simulation
EBRT:-	Electron Beam Radiotherapy
Forward Planned:-	Radiotherapy planning where the physicist decides the number of, angles and shaping of the radiation beams, then calculates the units per beam to provide the prescribed dose of radiation. Used in simple cases, involving trial and error to achieve prescribed dose whilst sparing organs.
Hard coded:-	Variables not dynamically changing. Hard coded features are built into the hardware or software in such a way that it cannot be modified.
HRQOL:-	Health Related Quality of Life: measure discussed in clinical trials and research
IGRT:-	Image Guided Radiotherapy
IMRT:-	Intensity Modulated Radiotherapy: may be inverse (Breast) or forward planned (all others)
Inter-arrival time:-	The time between successive arrivals (in this case, the arrival of patients)
Inverse Planned:-	Automated planning: physicists outlines the organs in a scan, sets the importance factors then runs an optimisation algorithm to minimise the dose to organs whilst providing the required dose.
Linear Accelerator:-	A machine that creates high-energy radiation to treat cancers, using electricity to form a stream of fast-moving subatomic particles. Also called mega-voltage (MeV) or a LinAcc.
Merged Map:-	Final merged map used to represent the range of views, issues and concepts put forward by the 7 interviewees.
Methods:-	General term used to denote any OR tool, method, or methodology; such as DES or SD.
MS:-	Management Science

OR:-	Operational Research
Palliative Therapy:-	Care to relieve and prevent suffering.
Patient Pathways:-	Flow diagrams detailing the various routes a particular consultant's patient may take through the planning and treatment stages. Each consultant has a set of patient pathways which denotes their availability at each stage.
Radical Therapy:-	Treatment intended to cure.
Rapid Arc :-	Rapid Arc delivers a highly precise treatment much faster than other technologies. Treatments that once took 15-30 minutes can sometimes be accomplished in as little as a single rotation of the machine around the patient, that is, in about 2 minutes. It is a new form of IG/IM RT
Respiratory Gating:-	Planned in four dimensions (4-D) to factor in time, enabling the physicist to design a plan around a time window where the tumour moves the least. Then, dose is only given during this window of the breathing cycle. This can mean that the treatment takes longer (per fraction) but reduces impact on healthy tissue.

References

The beatson west of scotland cancer centre [Online]. Available: www.beatson.scot.nhs.uk/ [Accessed 14/03/2011].

Ackermann, F. 1989. Incrementalism and Opportunism in Group Decision Support System Design. *Management Science Working Paper No. 4.* Glasgow, UK: University of Strathclyde.

Ackermann, F. & Eden, C. 2005. Using Causal Mapping with Group Support Systems to Elicit an Understanding of Failure in Complex Projects: Some Implications for Organisational Research. *Group Decision and Negotiation,* 14, 355-376.

Ackermann, F., Eden, C. & Brown, I. 2005. *The Practice of Making Strategy: A Step-by-step Guide*, London, Sage Publications.

Ackermann, F., Eden, C. & Williams, T. 1997. Modelling for litigation: mixing qualitative and quantitative approaches. *Interfaces,* 27 (2). 48-65.

Ackermann, F., Eden, C. & Williams, T. 2003. Structuring a delay and disruption claim: An application of cause-mapping and system dynamics. *European Journal of Operational Research,* 148, 192-204.

Ackermann, F., Tait, A., Eden, C. & Williams, T. 1994. COPE -ing with System Dynamics - a story about Soft and Hard OR. *Management Science Working Paper No. 14.* Glasgow, UK: University of Strathclyde.

Ackoff, R. L. 1973. Science in the Systems Age. *Operations research,* 21 (3). 661-671.

Alvanchi, A., Lee, S. & AbouRizk, S. 2011. Modeling Framework and Architecture of Hybrid System Dynamics and Discrete Event Simulation for Construction. *Computer-Aided Civil and Infrastructure Engineering Journal,* 26 (2). 77-91.

An, L. & Jeng, J.-J. 2005. On Developing System Dynamics Model for Business Process Simulation. *In:* Kuhl, M. E., Steiger, N. M., Armstrong, F. B. & Joines, J. A., (eds.) Proceedings of the 37th Winter Simulation Conference, Florida.

Andersen, D. F., Bryson, J. M., Richardson, G. P., Ackermann, F., Eden, C. & Finn, C. B. 2006. Integrating Modes of Systems Thinking into Strategic Planning Education and Practice: The Thinking Person's Institute Approach. *Journal of Public Affairs Education,* 12 (3). 265-293.

Ashton, R., Hague, L., Brandreth, M., Worthington, D. & Cropper, S. 2005. A Simulation-based Study of an NHS Walk-in Centre. *Journal of the Operational Research Society,* 56 (2).

Bank, J. & Carson, J. S. 1984. *Discrete-Event System Simulation,* Englewood Cliffs, Prentice Hall International.

Banks, J., Carson, J. S., Nelson, B. L. & Nicol, D. M. 1996. *Discrete Event System Simulation*.

Bargal, D. 2006. Personal and intellectual influences leading to Lewin's paradigm of action research. *Action Research,* 4 (4). 367-388.

Barton, P. I. 2000. Modeling, Simulation and Sensitivity Analysis of Hybrid Systems. *In:* Proceedings of the IEEE International Symposium on Computer-Aided Control System Design, 25-27 September 2000 Anchorage, Alaska, USA.

Bayer, S., Brailsford, S. C. & Bolt, T. 2009. Examining the role of simulation models in health planning. *In:* Proceedings of the 27th International Conference of the System Dynamics Society.

Bennett, P. & Worthington, D. 1998. An example of a good but partially successful OR engagement: improving outpatient clinic operations. *Interfaces,* 28 (5). 56-69.

Bennett, P. G. 1985. On Linking Approaches to Decision Aiding: Issues and Prospects. *Journal of the Operational Research Society,* 36 (7). 659-669.

Bider, I. 2005. Choosing Approach to Business Process Modeling - Practical Perspective. *Inconcept*, (34). 16.
Bird, A. 2008. *Thomas Kuhn* [Online]. Available: http://plato.stanford.edu/cgi-bin/encyclopedia/archinfo.cgi [Accessed 14/11/2008].
Borshchev, A. & Filippov, A. 2004. From System Dynamics and Discrete Event to Practical Agent Based Modeling: Reasons, Techniques, Tools. *Proceedings of the 22nd International Conference of the System Dynamics Society.* Oxford, England.
Borshchev, A., Karpov, Y. & Kharitonov, V. 2002. Distributed simulation of hybrid systems with AnyLogic and HLA. *Future Generation Computer Systems,* 18, 829-839.
Brailsford, S. C. 2002. *Using System Dynamics: A Convert's View* [Online]. Available: http://www.orsoc.org.uk/region/study/sdplus/SALLY.pdf [Accessed 15/12/2008].
Brailsford, S. C. 2008. System Dynamics: What's in it for Heathcare Simulation Modellers. *In:* Mason, S. J., Hill, R. R., Monch, L., Rose, O., Jefferson, T. & Fowler, J. W., (eds.) Proceedings of the 40th Winter Simulation Conference, Miami, US.
Brailsford, S. C., Churilov, L. & Liew, S.-K. 2003. Treating ailing emergency departments with simulation: An integrated perspective. *In:* Anderson, J. & Katz, E. (eds.) *Proceedings of Western Multiconference on Health Sciences.*
Brailsford, S. C., Desai, S. M. & Viana, J. 2010. Towards the Holy Grail: Combining System Dynamics and Discrete-Event Simulation in Healthcare. *In:* Johansson, B., Jain, S., Montoya-Torres, J., Hugan, J. & Yucesan, E. (eds.) *Proceedings of the 42nd Winter Simulation Conference.* Ieee.
Brailsford, S. C. & Hilton, N. 2001. A Comparison of Discrete Event Simulation and System Dynamics for Modelling Healthcare Systems. *In:* Riley, J., (ed.) Proceedings of ORAHS, Glasgow Caledonian University. 18-39.
Brailsford, S. C., Lattimer, V. A., Taranas, P. & Turnbull, J. C. 2004. Emergency and On-Demand Health Care: Modelling a Large Complex System. *Journal of the Operational Research Society,* 55 (1).
Brailsford, S. C., Sykes, J. & Harper, P. R. 2006. Incorporating Human Behaviour in Healthcare Simulation Models. *In:* Perrone, L. F., Wieland, F. P., Liu, J., Lawson, B. G., Nicol, D. M. & Fujimoto, R. M., (eds.) Proceedings of the 38th Winter Simulation Conference.
Brooks, R. J., Robinson, S. & Lewis, C. 2001. *Simulation and Inventory Control*.
Brooks, R. J. & Tobias, A. M. 1996. Choosing the Best Model: Level of Detail, Complexity and Model Performance. *Mathematical Computer Modelling,* 24 (4). 1-14.
Brown, J., Cooper, C. & Pidd, M. 2006. A taxing problem: The complementary use of hard and soft OR in the public sector. *European Journal of Operational Research*, 172, 666-679.
Bryman, A. & Bell, E. 2007. *Business Research Methods*, New York, Oxford University Press Inc.
Bryson, J. M., Ackermann, F., Eden, C. & Finn, C. B. 2004. *Visible Thinking: Unlocking causal mapping for practical business results*, John Wiley & Sons.
Bunday, B. D. 1996. *An Introduction to Queueing Theory,* Arnold.
Burrell, G. & Morgan, G. 1979. *Sociological paradigms and organisational analysis*, Heinemann Educational Books.
Carter, M. & Blake, J. T. 2004. Using simulation in an acute-care hospital: easier said than done. *In:* Brandeau, M. L., Sainfort, F. & Pierskala, W. P. (eds.) *Operations Research and Health Care: A Handbook of Methods and Applications.* Boston: Kluwer Academic.
Ceglowski, R., Churilov, L. & Wasserthiel, J. 2007. Combining Data Mining and Discrete Event Simulation for a Value-added view of a hospital emergency department. *Journal of the Operational Research Society,* 58 (2). 246-254.

Chahal, K. & Eldabi, T. 2008a. System Dynamics and Discrete Event Simulation: a Meta-Comparison. *In:* Proceedings of the 50th Conference of Operational Research Society.

Chahal, K. & Eldabi, T. 2008b. Which is more appropriate: A multiperspective comparison between System Dynamics and Discrete Event Simulation. *Proceedings of the European and Mediterranean Conference on Information Systems 2008.* Al Bustan Rotana Hotel, Dubai.

Chatha, K. A. & Weston, R. H. 2006. Combined discrete event simulation and systems thinking-based framework for management decision support. *Journal of Engineering Manufacture,* 220 (B). 1969-1981.

Checkland, P. & Holwell, S. 1998. Action Research: Its Nature and Validity. *Systemic Practice and Action Research,* 11 (1).

Chick, S. E. 2006. Six ways to improve a simulation analysis. *Journal of Simulation,* 1 (1). 21-28.

Coelli, F. C., Ferreira, R. B., Almeida, R. M. V. R. & Pereira, W. C. A. 2007. Computer simulation and discrete-event models in the analysis of a mammography clinic patient flow. *Computer Methods and Programs in Biomedicine,* 87 (3). 201-207.

Coghlan, D. & Brannick, T. 2010 *Doing Action Research in Your Own Organization*, Sage Publications.

Comas, M., Castells, X., Hoffmeister, L., Román, R., Cots, F., Mar, J., Gutiérrez-Moreno, S. & Espallargues, M. 2008. Discrete-event simulation applied to analysis of waiting lists: evaluation of a prioritization system for cataract surgery. *Value Health,* 11 (7). 1203-1213.

Cooper, K., Brailsford, S. C. & Davies, R. 2007. Choice of modelling technique for evaluating healthcare interventions. *Journal of the Operational Research Society*, 58 (2). 168-176.

Corbett, C. J., Overmeer, W. J. A. M. & Van Wassenhove, L. N. 1995. Strands of practice in OR (The Practitioner's Dilemma). *European Journal of Operational Research,* 87 (3).

Cowan, J. 2006. *On becoming an innovative university teacher,* Buckingham, UK, Open University Press.

Coyle, R. G. 1977. *Management System Dynamics*, London, John Wiley & Sons.

Coyle, R. G. 1983. The technical elements of the system dynamics approach. *European Journal of Operational Research,* 14, 359-370.

Coyle, R. G. 1985. Representing Discrete Events in System Dynamics Models: A theoretical Application to Modelling Coal Production. *Journal of the Operational Research Society,* 36 (4). 307-318.

Coyle, R. G. 1986. Comment on 'System dynamics and operational research: An appraisal'. *European Journal of Operational Research,* 23, 403-406.

Coyle, R. G. & Alexander, M. D. W. 1997. Two approaches to qualitative modelling of a nation's drugs trade. *System Dynamics Review,* 13 (3). 205-222.

Crotty, M. 1998. *The Foundations of Social Research*, Sage Publications.

Curtis, N. J., Dortmans, P. J. & Ciuk, J. 2006. 'Doing the right problem' versus 'doing the problem right': problem structuring within a Land Force environment. *Journal of the Operational Research Society,* 57 (11).

Davies, J. P., Eisenhardt, K. M. & Bingham, C. B. 2007. Developing theory through simulation methods. *Academy of Management Review,* 32 (2). 480-499.

Davies, R., Roderick, P. & Raftery, J. 2003. The evaluation of disease prevention and treatment using simulation models. *European Journal of Operational Research*, 150 (1). 53-66.

De Vreede, G.-J. & Ackermann, F. 2005. Introduction to the Special Issue: International Perspectives in Group Decision & Negotiation Research. *Group Decision and Negotiation*, 14, 265-266.

den Hengst, M., de Vreede, G.-J. & Maghnouji, R. 2007. Using soft OR principles for collaborative simulation: a case study in the Dutch airline industry. *Journal of the Operational Research Society,* 58 (5).

Dick, B., Passfield, R. & Wildman, P. 2000. *A beginner's guide to action research* [Online]. Available: http://www.scu.edu.au/schools/gcm/ar/arp/guide.html [Accessed 25/03/2008].

Dierks, M. M., Dulac, N., Leveson, N. G. & Stringfellow, M. V. 2008. System Dynamics Approach to Model Risk in Complex Healthcare Settings: Time Constraints, Production Pressures and Compliance with Safety Controls. *In:* Proceedings of the 26th International Conference of the System Dynamics Society.

Doebelin, E. O. 1998. *System Dynamics: Modeling, Analysis, Simulation, Design,* New York, Marcel Dekker Inc.

Donzelli, P. & Iazeolla, G. 2001. A Hybrid Software Process Simulation Model. *Software Process: Improvement and Practice*.

Easterby-Smith, M., Thorpe, R. & Lowe, A. 1991. *Management Research: An Introduction,* London, Sage Publications.

Eden, C. 1990. Part III: Mixing Methods - Introduction. *In:* Eden, C. & Radford, K. J. (eds.) *Tackling strategic problems: the role of group decision support.* London: Sage.

Eden, C. & Ackermann, F. 1998. *Making Strategy: The Journey of Strategic Management,* London, Sage Publications.

Eden, C. & Ackermann, F. 2006. Viewpoint: Where next for problem structuring methods. *Journal of the Operational Research Society,* 57, 766-768.

Eden, C., Ackermann, F., Bryson, J. M., Richardson, G. P., Andersen, D. F. & Finn, C. B. 2008. Integrating Modes of Policy Analysis and Strategic Management Practice: Requisite Elements and Dilemmas. *Journal of the Operational Research Society,* 1-12.

Eden, C. & Sims, D. 1979. On the nature of Problems in Consulting Practice. *Omega,* 7 (2). 119-127.

Eisenhardt, K. M. 1989. Building Theories from Case Study Research. *Academy of Management Review,* 14 (4).

Eldabi, T., Paul, R. J. & Young, T. 2007. Simulation modelling in healthcare: reviewing legacies and investigating futures. *Journal of the Operational Research Society,* 58 (2). 262-270.

Fahrland, D. A. 1970. Combined discrete event continuous systems simulation. *Simulation,* 14, 61-72.

Fioroni, M. M., Franzese, L. A. G., Zanin, C. E., Furia, J., Perfetti, L. d. T., Leoranrdo, D. & da Silva, N. L. 2007. Simulation of Continuous Behaviour Using Discrete Tools: Ore Conveyor Transport. *In:* Henderson, S. G., Biller, B., Hsieh, M.-H., shortle, J., Tew, J. D. & Barton, R. R., (eds.) Proceedings of the 39th Winter Simulation Conference : 40 years! The best is yet to come.

Flood, R. L. 1999. *Rethinking The Fifth Discipline: Learning within the unknowable*, Routledge.

Flood, R. L. & Jackson, M. C. 1991. *Creative Problem Solving: Total Systems Intervention,* Department of Management Systems and Sciences, University of Hull, UK

Forrester, J. W. 1958. Industrial Dynamics: a major breakthrough for decision makers. *Harvard Business Review,* 36 (4). 37-66.

Forrester, J. W. 1961. *Industrial Dynamics,* Cambridge, Mass (Portland, Oragon), MIT Press (Productivity Press).

Forrester, J. W. 1968a. Industrial Dynamics—After the First Decade. *Management Science,* 14 (7). 398-415.

Forrester, J. W. 1968b. *Principals of Systems,* Cambridge, Mass., Wright-Allen Press.

Forrester, J. W. 1992. From the Ranch to System Dynamics: An Autobiography. *In:* Bedeian, A. G. (ed.) *Management Laureates: A Collection of Autobiographical Essays.* JAI Press.

Forrester, J. W., Mass, N. J. & Ryan, C. J. 1976. The Systen Dynamics National Model: Understanding Socio-Economic Behavior and Policy Alternatives. *Technological Forecasting and Social Change,* 9, 51-68.

Forrester, J. W. & Senge, P. M. 1980. Tests for building confidence in system dynamics models. *TIMS Studies in the Management Sciences,* 14, 209-228.

Friend, J. & Hickling, A. 1997. *Planning under pressure: the strategic choice approach,* Oxford, Boston, Butterworth-Heinemann.

Ghauri, P. & Gronhaug, K. 2005. *Research Methods in Business Studies: A Practical Guide,* Pearson Education Limited.

Gibson, I. W. 2007. An Approach to Hospital Planning and Design Using Discrete Event Simulation. *In:* Henderson, S. G., Biller, B., Hsieh, M.-H., Shortle, J., Tew, J. D. & Barton, R. R., (eds.) Proceedings of the 39th Winter Simulation Conference : 40 years! The best is yet to come. 1501-1508.

Girot, A. 2001. Reflective skills. *In:* Maslin-Prothero, S. (ed.) *Baillere's study skills for nurses.* London: Baillaire Tindall in associationwith the RCN.

Greasley, A. 2004. *Simulation Modelling for Business,* Ashgate Publishing.

Greasley, A. 2005. Using system dynamics in a discrete-event simulation study of a manufacturing plant. *International Journal of Operations & Production Management,* 25 (6). 534-548.

Greenberger, M., Crenson, M. A. & Crissey, B. L. 1976. *Models in the policy process : public decision making in the computer era,* New York, Russell Sage Foundation.

Greenwood, D. J. & Levin, M. 1998. *Introduction to Action Research: Social Research for Social Change,* Thousand Oaks, California, Sage Publications.

Gunal, M. M. & Pidd, M. 2005. Simulation modelling for performance measurement in healthcare. *In:* Kuhl, M. E., Steiger, N. M., Armstrong, F. B. & Joines, J. A., (eds.) Proceedings of the 37th Winter Simulation Conference.

Han, S., Pena-Mora, F., Lee, S. & Park, M. 2006. A Hybrid Simulation Model for Integrated Strategic-Operational Management. *Proceedings of the Joint International Conference on Computing and Decision Making in Civil and Building Engineering.* Montreal, Canada.

Harper, P. R., Phillips, S. & Gallagher, J. E. 2005. Geographical Simulation Modelling for the Regional Planning of Oral and Maxillofacial Surgery across London. *Journal of the Operational Research Society,* 56 (2).

Harper, P. R. & Pitt, M. A. 2004. On the challenges of healthcare modelling and a proposed project life cycle for successful implementation. *Journal of the Operational Research Society,* 55, 657-661.

Hart, C. 1998. *Doing a literature review : releasing the social science research imagination* London Sage Publications.

Harwood, S. A. 2011. Mixing methodologies and paradigmatic commensurability. *Journal of the Operational Research Society: Viewpoints,* 62 (4). 806-809.

Helal, M., Rabelo, L., Sepulveda, J. & Jones, A. 2007. A Methodology for Integrating and Synchronizing the System Dynamics and Discrete Event Simulation Paradigms. *Proceedings of the 25th International Conference of the System Dynamics Society and 50th Anniversary Celebration.* Boston.

Hills, P. R. 1971. HOCUS. P. E. Group, Egham, Surrey, England, U.K.

Hirsch, G. B. & Immediato, C. S. 1999. Microworlds and generic structures as

resources for integrating care and
improving health. *System Dynamics Review*, 15 (3).
Hollocks, B. W. 2006. Forty Years of Discrete-Event Simulation - a personal reflection. *Journal of the Operational Research Society,* 57, 1383-1399.
Homer, J. & Oliva, R. 2001. Maps and models in system dynamics: a response to Coyle. *System Dynamics Review*, 17 (4). 347-355.
Homer, J. B. & Hirsch, G. B. 2006. System Dynamics Modeling for Public Health: Background and Opportunities. *American Journal of Public Health,* 96 (3). 452-458.
Howick, S. & Ackermann, F. 2011. Mixing OR methods in practice: Past, present and future directions. *European Journal of Operational Research*.
Howick, S., Ackermann, F. & Anderson, D. 2006. Linking event thinking with structural thinking: methods to improve client value in projects. *System Dynamics Review*, 22 (2). 113-140.
Howick, S. & Eden, C. 2004. On the nature of discontinuities in system dynamics modelling of disrupted projects. *Journal of the Operational Research Society,* 55, 598–605.
Howick, S., Eden, C., Ackermann, F. & Williams, T. 2008. Building Confidence in Models for Multiple Audiences: the Modelling Cascade. *European Journal of Operational Research*, 186, 1068-1083.
Huxham, C. 2003. Action research as a methodology for theory development. *Policy & Politics,* 31 (2). 239-248.
Huxham, C. & Vangen, S. 2001. Research Design Choices for Action Research: Comparative case studies from research on inter-organisational collaboration. *Working Paper Series 98/5.* Glasgow, UK: Strathclyde University Business School.
Ingalls, R. G. 2008. Introduction to Simulation. *In:* Mason, S. J., Hill, R. R., Monch, L., Rose, O., Jefferson, T. & Fowler, J. W., (eds.) Proceedings of the 40th Winter Simulation Conference.
ISIP (Integrated Service Improvement Programme). 2007. *A Practical Guide for the NHS: Stakeholder Engagement* [Online]. Available: www.isip.nhs.uk/practical/PGstakeholder.ppt [Accessed 13/01/2010].
Jackson, M. C. 1999. Towards coherent pluralism in management science. *Journal of the Operational Research Society,* 50.
Jackson, M. C. 2011. The multi-methodology debate: a response to Harwood. *Journal of the Operational Research Society: Viewpoints,* 62 (4). 811-813.
Jackson, M. C. & Keys, P. 1984. Towards a System of Systems Methodologies. *Journal of the Operational Research Society,* 35 (6). 473-486.
Jacob, M., Suchan, C. & Ferstl, O. K. 2010. Modelling of Business Systems Using Hybrid Simulation - a new Approach. *In:* lexander, T., Turpin, M. & Van Deventer, J. P., (eds.) Proceedings of the 18th European Conference on Information Systems, Pretoria, Südafrika.
Jacobson, S., Hall, S. N. & Swisher, J. R. 2006. Discrete-Event Simulation of Health Care Systems. *Patient Flow: Reducing Delay in Healthcare Delivery*.
Johnson, S. & Eberlein, B. 2002. Alternative Modeling Approaches: A Case Study in the Oil & Gas Industry. *In:* Proceedings of the 20th International Conference of the System Dynamics Society, July 28 – August 1 Palermo, Italy.
Jun, J. B., Jacobson, S. H. & Swisher, J. R. 1999. Application of Discrete-Event Simulation in Health Care Clinics: A Survey. *Journal of the Operational Research Society,* 50, 109-123.
Keys, P. 1988. A methodology for methodology choice. *Systems Research,* 5 (1). 65-76.
Keys, P. 1991. Beyond Hard Systems Thinking. *The Systemic Nature of the Operational Research (Contemporary Systems Thinking)* New York: Springer.
Kim, D. H. & Senge, P. M. 1994. Putting systems thinking into practice. *System Dynamics Review,* 10 (2-3). 277-290.

Kljajić, M., Bernik, I. & Škraba, A. 2000. Simulation Approach to Decision Assessment in Enterprises. *Simulation*
[Society for Modelling and Simulation International (SCS)], 75 (4). 199-210.

Kotiadis, K. & Mingers, J. 2006. Combining PSMs with hard OR methods: the philosophical and practical challenges. *Journal of the Operational Research Society,* 57 (7). 856-867.

Kouikoglou, V. S. & Phillis, Y. A. 1990. AN EFFICIENT DISCRETE-EVENT MODEL FOR PRODUCTION NETWORKS OF GENERAL GEOMFPRY. *In:* Proceedings of the 29th Conference on Decision and Control, December 1990 Honolulu, Hawali.

Kouskouras, K. G. & Georgiou, A. C. 2007. A discrete event simulation model in the case of managing a software project. *European Journal of Operational Research,* 181 (1). 374-389.

Kuljis, J., Paul, R. J. & Stergioulas, L. K. 2007. Can health care benefit from modelling and simulation methods in the same way as business and manufacturing. *In:* Henderson, S. G., Biller, B., Hsieh, M.-H., Shortle, J., Tew, J. D. & Barton, R. R., (eds.) Proceedings of the 39th Winter Simulation Conference : 40 years! The best is yet to come. 1449-1453.

Landry, M., Malouin, J. L. & Oral, M. 1983. Model Validation in Operations Research. *European Journal of Operational Research,* 14 (3). 207-220.

Lane, D. C. 1993. A comment on prolegomena to OR modelling of the global environment-development problem. *Journal of the Operational Research Society,* 44 (12).

Lane, D. C. 1999. Social theory and system dynamics practice. *European Journal of Operational Research,* 113, 501-527.

Lane, D. C. 2000. You Just Don't Understand Me: Modes of failure and success in the discourse between system dynamics and discrete event simulation. *LSE OR Working Paper 00.34.* London.

Lane, D. C. & Husemann, E. 2008. System dynamics mapping of acute patient flows. *Journal of the Operational Research Society,* 59 (2). 213-224.

Lane, D. C., Monefeldt, C. & Rosenhead, J. V. 2000. Looking in the wrong place for healthcare improvements: A system dynamics study of an accident and emergency department. *Journal of the Operational Research Society,* 51, 518-531.

Lane, D. C. & Oliva, R. 1998. The greater whole: Towards a synthesis of system dynamics and soft systems methodology. *European Journal of Operational Research,* 107.

Lara, C. & Dickson, K. 2008. Developing simulation models of possible future scenarios for the delivery of acute care in NHS Ayrshire and Arran to inform the decision making process. *In:* Proceedings of the Operational Research Society Simulation Workshop 2008.

Lee, S., Han, S. & Peña-Mora, F. 2007. Hybrid system dynamics and discrete event simulation for construction management. *ASCE International Workshop on Computing in Civil Engineering.* Pittsburgh, PA.

Lee, Y. H., Cho, M. K. & Kim, Y. B. 2002. A Discrete-Continuous Combined Modeling Approach for Supply Chain Simulation. *Simulation,* 8 (5). 321-329.

Lehaney, B., Clarke, S. A. & Paul, R. J. 1999. A case of an intervention in an outpatients department. *Journal of the Operational Research Society*, 50 (9). 887-891.

Lehaney, B., Kogetsidis, H., Platt, A. & Clarke, S. 1998. Windows-based simulation software as an aid to learning. *Journal of European Industrial Training,* 22 (1). 12-17.

Lehaney, B. & Paul, R. J. 1994. The Use of Soft Systems Methodology in the Development of a Simulation of Out-patient Services at Watford General Hospital. *Journal of the Royal Society of Health,* 114 (5). 248-251.

Linstone, H. A. 1978. The Dephi technique. *In:* Fowles, J. (ed.) *Handbook of Futures Research.* London: Greenwood Press.

Lorenz, T. & Jost, A. 2006. Towards an orientation framework in multi-paradigm modeling - Aligning purpose, object and methodology in System Dynamics, Agent-based Modeling and Discrete-Event-Simulation. *Proceedings of the 24th International Conference of the System Dynamics Society*.

Magidson, J. 1992. Systems practice in several communities in Philadelphia. *Systems Practice,* 5 (5). 493-508.

Mak, H.-Y. 1992. *System Dynamics and Discrete Event Simulation Modelling.* PhD, London School of Economics and Political Science. Thesis number DX201735.

Martin, R. & Raffo, D. 2000. A Model of the Software Development Process Using Both Continuous and Discrete Models. *International Journal of Software Process Improvement/Practice.*

Maxwell, J. A. 2005. *Qualitative Research Design: An Interactive Approach,* Thousand Oaks, CA, Sage Publications.

Mazaeda, R., Merino, A., de Prada, C. & Acebes, F. 2012. Hybrid modelling of batch centrifuges as part of a generic object oriented beet Sugar Mill library. *Simulation Modelling Practice and Theory,* 22, 123–145.

McNiff, J. & Whitehead, J. 2006. *All you need to know about Action Research,* Sage Publications.

Meadows, D. H. 1980. The Unavoidable A Priori. *In:* Randers, J. (ed.) *Elements of the System Dynamics Method.* Waltham, MA: Pegasus Communications.

mindtools. 2010. *Mind Mapping* [Online]. Available: http://www.mindtools.com/ [Accessed 14/02/2010].

Mingers, J. 2000. Variety is the spice of life: combining soft and hard OR/MS methods. *International Transactions in Operational Research,* 7 (6). 673-691.

Mingers, J. 2004. Future directions in management science modelling: Critical realism and multimethodology. *In:* Fleetwood, S. & Ackroyd, S. (eds.) *Critical realist applications in organisation and management studies.* Routledge.

Mingers, J. 2006. A critique of statistical modelling in management science from a critical realist perspective: its role within multimethodology. *Journal of the Operational Research Society,* 56 (2). 202-219.

Mingers, J. 2011. Clarification or confusion: response to Harwood. *Journal of the Operational Research Society: Viewpoints,* 62 (4). 809-811.

Mingers, J. & Brocklesby, J. 1997. Multimethodology: Towards a Framework for Mixing Methodologies. *Omega,* 25 (5). 489-509.

Mingers, J., Gill, A., Ackermann, F., Bennett, P., Bentham, J., Brocklesby, J., Eden, C., Flood, R., Jackson, M., Leonard, A., Midgley, G., Ormerod, R., Romm, N., Skyrme, D., Spaul, M., Schwaninger, M., Taket, A., White, L. & Williams, T. 1997. *Multimethodology: The Theory and Practice of Combining Management Science Methodologies,* John Wiley & Sons.

Mitchell, G. 1993. *The Practice of Operational Research,* John Wiley and Sons.

Morecroft, J. D. W. 1982. A Critical Review of Diagraming Tools for Conceptualizing Feedback

System Models. *Dynamica,* 8 (1). 20-29.

Morecroft, J. D. W. 2007. *Strategic Modelling and Business Dynamics: A Feedback Systems Approach,* John Wiley & Sons.

Morecroft, J. D. W. & Robinson, S. 2006. Comparing Discrete-Event Simulation and System Dynamics: Modelling a fishery. *In:* Robinson, S., Taylor, S., Brailsford, S. C. & Garnett, J., (eds.) Proceedings of the Operational Research Society Simulation Workshop 2006, 28/03/2006 - 29/03/2006 Royal Leamington Spa.

Morecroft, J. D. W. & Robinson, S. 2008. Explaining Puzzling Dynamics: Comparing the Use of System Dynamics and Discrete-Event Simulation. *Proceedings of the SD+ Study Group Meeting.* London South Bank University.

Morecroft, J. D. W. & Sterman, J. D. (eds.) 1994. *Modeling for Learning Organizations,* Portland OR: Productivity Press.

Munro, I. & Mingers, J. 2002. The use of multimethodology in practice—results of a survey of practitioners. *Journal of the Operational Research Society,* 53, 369-378.

Nance, R. E. & Sargent, R. G. 2002. Perspectives on the evolution of simulation. *Operations research,* 50 (1). 161-172.

Naseer, A., Eldabi, T. & Young, T. P. 2010. RIGHT: A toolkit for selecting healthcare modelling methods. *Journal of Simulation,* 2, 2-13.

Naturo, J., Kuruganti, P. T., Miller, L., Mullen, S. & Shankar, M. 2007. Integrated Hybrid-Simulation of Electric Power and Communications Systems. *Proceedings of the Power Engineering Society General Meeting.* IEEE.

NHS Scotland 2006. Cancer in Scotland: Radiotherapy Activity Planning for Scotland 2011 - 2015. *In:* Department, S. E. H. (ed.). Report of the Radiotherapy Activity Planning Group.

Ormerod, R. 1995. Putting Soft OR Methods to Work: Information Systems Strategy Development at Sainsbury's. *Journal of the Operational Research Society,* 46 (3).

Ormerod, R. 1998. Putting soft OR methods to work: information systems strategy development at Palabora. *Omega,* 26 (1). 75-98.

Ormerod, R. 1999. Putting soft OR methods to work: the case of the business improvement project at PowerGen. *European Journal of Operational Research,* 118, 1-29.

Ormerod, R. J. 1997. The design of organisational intervention: Choosing the approach. *Omega,* 25 (4). 415-435.

Owen, C., Love, D. & Albores, P. 2008. Selection of Simulation Tools for Improving Supply Chain Performance. *In:* Proceedings of the 50th Conference of Operational Research Society. 199-207.

Oxford English Dictionary (OED) 2012.

Ozgun, O. & Barlas, Y. 2009. Discrete vs. Continuous Simulation: When Does It Matter. *In:* Proceedings of the 27th International Conference of the System Dynamics Society.

Paucar-Caceres, A. & Rodriguez-Ulloa, R. 2007. An application of Soft Systems Dynamics Methodology (SSDM). *Journal of the Operational Research Society,* 58, 701-713.

Pena-Mora, F., S., H., Lee, S. & Park, M. 2008. Strategic-operational construction management: hybrid system dynamics and discrete event approach. *Journal of Construction Engineering and Management, ASCE.*

Phelps, R. A., Parsons, D. J. & Siprelle, A. J. 2002. Non-item based discrete-event simulation tools. *In:* Yucesan, E., Chen, C.-H., Snowdon, J. L. & Charnes, J. M., (eds.) Proceedings of the 34th Winter Simulation Conference.

Pidd, M. 2003. *Tools for Thinking: Modelling in Management Science,* John Wiley & Sons.

Pidd, M. 2004a. *Computer Simulation in Management Science* John Wiley & Sons.

Pidd, M. 2004b. *Systems modelling: theory and practice,* John Wiley & Sons.

Pidd, M. 2012. Mixing other methods with simulation is no big deal. *In:* Laroque, C., Himmelspach, J., Pasupathy, R., Rose, O. & Uhrmacher, A. M. (eds.) *Proceedings of the 44th Winter Simulation Conference*

Platts, K. 1993. A Process Approach to Researching Manufacturing Strategy. *International Journal of Operations & Production Management,* 13 (8). 4-17.

Proctor, S., Lehaney, B., Reeves, C. & Khan, Z. 2007. Modelling Patient Flow in a Radiotherapy Department. *OR Insight,* 20 (3).

Proudlove, N. C., Black, S. & Fletcher, A. 2007. OR and the challenge to improve the NHS: modelling for insight and improvement in in-patient flows. *Journal of the Operational Research Society,* 58 (2). 145-158.

Rabelo, L., Eskandari, H., Shaalan, T. & Helal, M. 2007. Value chain analysis using hybrid simulation and AHP. *International Journal of Production Economics,* 105 (2). 536-547.

Rabelo, L., Helal, M., Son, Y.-J., Jones, A., Min, J. & Deshmukh, A. 2003. A Hybrid Approach to Manufacturing Enterprise Simulation. *In:* Chick, S. E., Sanchez, P. J., Ferrin, D. & Morrice, D. J., (eds.) Proceedings of the 2003 Winter Simulation Conference.

Randers, J. 1980. Guidelines for Model Conceptualization. *In:* Randers, J. (ed.) *Elements of the System Dynamics Method.* Waltham, MA: Pegasus Communications.

Rapoport, R. N. 1970. Three Dilemmas in Action research. *Human Relations,* 23 (6). 499-513.

Rawlings, K. 2000. System Dynamics v Discrete Event Simulation - Is There a Winner? *Proceedings of the ISMOR Conference.* HVR Consulting Services Limited.

Reiner, G. 2005. Customer-oriented improvement and evaluation of supply chain processes supported by simulation models. *International Journal of Production Economics,* 96 (3). 381-395.

Richardson, G. P. & Pugh, A. L. 1981. *Introduction to System Dynamics modelling with DYNAMO.*

Richardson, G. P. & Pugh, A. L. 1989. *Introduction to System Dynamics Modeling,* Waltham, Massachusetts, Pegasus Communication.

Roberts, E. B. (ed.) 1978a. *Managerial Applications of System Dynamics,* Cambridge, Massachusetts: Productivity Press.

Roberts, E. B. 1978b. System Dynamics - An Introduction. *In:* Roberts, E. B. (ed.) *Managerial Applications of System Dynamics.* Cambridge, Massachusetts: Productivity Press.

Roberts, E. B. 2007. Making System Dynamics Useful: A Personal Memoir. *System Dynamics Review.* MIT Sloan Research Paper No. 4649-07. Available at SSRN: http://ssrn.com/abstract=989062

Roberts, N., Anderson, D. F., Deal, R. M. & Garet, M. S. 1983. *Introduction to Computer Simulation: The System Dynamics Approach,* Reading, Massachusetts, Addison-Wesley.

Robinson, S. 1994. *Successful Simulation: A Practical Approach to Simulation Projects,* McGraw-Hill.

Robinson, S. 2001. Soft with a hard centre: a discrete event simulation in facilitation. *Journal of the Operational Research Society,* 52 (8). 905-915.

Robinson, S. 2002a. General concepts of quality for discrete-event simulation. *European Journal of Operational Research,* 138 (1). 103-117.

Robinson, S. 2002b. Modes of simulation practice: approaches to business and military simulation. *Simulation Modelling Practice and Theory,* 10, 513-523.

Robinson, S. 2003. *Simulation – The Practice of Model Development and Use*, John Wiley & Sons.

Robinson, S. 2004. *Simulation - The Practice of Model Development and Use,* John Wiley & Sons.

Robinson, S. 2005. Discrete-event simulation: from the pioneers to the present, what next? *Journal of the Operational Research Society,* 56 (6). 619-629.

Robinson, S. 2007. Editorial: The future's bright the future's...Conceptual modelling for simulation. *Journal of Simulation,* 1 (3). 149-152.

Robinson, S. 2008. Conceptual modelling for simulation Part I: definition and requirements. *Journal of the Operational Research Society,* 59 (3). 278-290.

Robinson, S. 2012. Tutorial: Choosing what to model - conceptual modeling for simulation. *In:* Laroque, C., Himmelspach, J., Pasupathy, R., Rose, O. & Uhrmacher, A. M. (eds.) *Proceedings of the 44th Winter Simulation Conference*

Robinson, S., Alifantis, A., Edwards, J. S., Ladbrook, J. & Waller, T. 2005. Knowledge Based Improvement: Simulation and Artificial Intelligence for Identifying and

Improving Human Decision-Making in an Operations System. *Journal of the Operational Research Society*, 56 (8). 912-921.

Sachdeva, R., Williams, T. & Quigley, J. 2007. Mixing methodologies to enhance the implementation of healthcare operational research. *Journal of the Operational Research Society*, 58 (2). 159-167.

Salt, J. D. 2008. The seven habits of highly defective simulation projects. *Journal of Simulation,* 2, 155-161.

Santos, S., Belton, V. & Howick, S. 2002. Adding value to performance measurement by using system dynamics and multicriteria analysis. *International Journal of Operations & Production Management*, 22 (11). 1246-1272.

Santos, S., Belton, V. & Howick, S. 2008. Enhanced performance measurement using OR: a case study. *Journal of the Operational Research Society*, 59, 762-775.

Sargent, R. G. 2008. Verification and Validation of Simulation Models. *In:* Mason, S. J., Hill, R. R., Monch, L., Rose, O., Jefferson, T. & Fowler, J. W., (eds.) Proceedings of the 40th Winter Simulation Conference.

Sargent, R. G. 2013. Verification and validation of simulation models. *Journal of Simulation,* 7, 12-24.

Saunders, M., Lewis, P. & Thornhill, A. 2003. *Research Methods for Business Students*, Pearson Education Limited.

Saunders, M., Lewis, P. & Thornhill, A. 2007. *Research Methods for Business Students*, Pearson Education Limited.

Schahill, S. L., Harrison, J. & Carswell, P. 2010. What constitutes an effective community pharmacy?—development of a preliminary model of organizational effectiveness through concept mapping with multiple stakeholders. *International Journal for Quality in Health Care*, 22 (4). 324-332.

Schein, E. H. 2010. *Organizational Culture and Leadership,* Wiley & Sons.

Schmidt, M. J. & Gary, M. S. 2002. Combining system dynamics and conjoint analysis for strategic decision making with an automotive high-tech SME. *System Dynamics Review*, 18 (3). 359-379.

Schultz, M. & Hatch, M. J. 1996. Living with Multiple Paradigms: The Case of Paradigm Interplay in Organisational Culture Studies. *Academy of Management Review,* 21 (2). 529-557.

Scottish Government. 2008. *Healthier Scotland: Better Cancer Care, An Action Plan* [Online]. Available: http://www.scotland.gov.uk/Resource/Doc/242498/0067458.pdf [Accessed 01/02/2013].

Shannon, R. E. 1975. *Systems Simulation: The Art and Science,* Englewood Cliffs, New Jersey, Prentice-Hall.

Shanthikumar, J. G. & Sargent, R. G. 1981. A Hybrid Simulation/Analytic Model of a Computerized Manufacturing System. *In:* Proc. 9th IFORS International Conference Operational Research, Hamburg, FRG.

Shanthikumar, J. G. & Sargent, R. G. 1983. A Unifying View of Hybrid Simulation/Analytic Models and Modeling. *Operations research*, 31 (6). 1030-1052.

Sharp, J. A. & Price, D. H. R. 1984. System Dynamics and Operational Research: An Appraisal. *European Journal of Operational Research*, 16 (1). 1-12.

Smith, M. K. 2001. *Kurt Lewin: groups, experiential learning and action research* [Online]. Available: http://www.infed.org/thinkers/et-lewin.htm [Accessed 25/03/2008].

Spicer, D. P. 1998. Linking mental models and cognitive maps as an aid to organisational learning. *Career Development International,* 3 (3). 125 - 132

Sterman, J. D. 2000. *Business Dynamics: Systems Thinking and Modelling for a Complex World*, Jeffrey J. Shelstad.

Stotz, M. & Grobler, A. 2006. Identifying Fruitful Combinations Between System Dynamics and Soft OR. *In:* Operations Research Proceedings. Springer Berlin Heidelberg.

Stringer, E. T. & Genat, W. 2004. *Action Research in Health,* Upper Saddle River, New Jersey, Pearson Education.

Su, Y. & Jin, Z. 2008. Modeling Health Service Centers with Simulation and System Dynamics. *In:* Proceedings of the Tenth International Conference on Computer Modeling and Simulation, UKSIM, 1-3 April 2008. 649-654.

Susman, G. I. 1983. Action Research: A Sociotechnical Systems Perspective. *In:* Morgan, G. (ed.) *Beyond Method: Strategies for Social Research.* Sage Publications.

Sweetser, A. 1999. A Comparison of System Dynamics (SD) and Discrete Event Simulation (DES). *In:* Proceedings of the 17th International Conference of the System Dynamics Society, Wellington, New Zealand.

Swinerd, C. & McNaught, K. R. 2012. Design classes for hybrid simulations involving agent-based and system dynamics models. *Simulation Modelling Practice and Theory,* 25, 118-133.

Tako, A. A. & Robinson, S. 2008. Model building in System Dynamics and Discrete-event Simulation: a quantitative comparison. *In:* Proceedings of the 26th International Conference of the System Dynamics Society, 29/09/2008 Athens, Greece.

Tako, A. A. & Robinson, S. 2009. Comparing discrete-event simulation and system dynamics: users' perceptions. *Journal of the Operational Research Society,* 60, 296-312.

Tako, A. A. & Robinson, S. 2010. Model development in discrete-event simulation and system dynamics: An empirical study of expert modellers. *European Journal of Operational Research*, 207 (2). 784-794.

Taylor, K. & Dangerfield, B. 2005. Modelling the feedback effects of reconfiguring health services. *Journal of the Operational Research Society,* 56 (6). 659-675.

Taylor, K. & Lane, D. C. 1998. simulation applied to health services: opportunities for applying the system dynamics approach. *Journal of Health Services Research and Policy,* 3 (4). 226-232.

Taylor, S. J. E. & Robinson, S. 2006. So where next? A survey of the future for discrete-event simulation. *Journal of Simulation,* 1 (1). 6.

Tustin, A. 1953. *The Mechanism of Economic Systems: an approach to the problem of economic stabilization from the point of view of control-system engineering* Cambridge, MA, Harvard University Press.

Urry, S. A. 1991. *Introduction to Operational Research: the Best of Everything,* Harlow.

Vasilakis, C., Sobolev, B. G., Kuramoto, L. & Levy, A. R. 2007. A simulation study of scheduling clinic appointments in surgical care: individual surgeons versus pooled lists. *Journal of the Operational Research Society,* 58 (2).

Venkateswaran, J. & Son, Y.-J. 2004. Distributed and Hybrid Simulations for Manufacturing Systems and Integrated Enterprise. *In:* Proceedings of the Annual Industrial Engineering Research Conference, 15-19/05/2004 Houston, USA. Department of Systems and Industrial Engineering, The University of Arizona.

venkateswaran, J., Son, Y.-J. & Jones, A. 2004. Hierarchical Production Planning Using a Hybrid System Dynamic-Descrete-Event Simulation Architecture. *In:* Ingalls, R. G., Rossetti, M. D., Smith, J. S. & Peters, B. A., (eds.) Proceedings of the 36th Winter Simulation Conference.

Vennix, J. A. M. 1996. *Group Model Building: Facilitating Team Learning Using System Dynamics*, John Wiley & Sons.

Vennix, J. A. M., Andersen, D. F., Richardson, G. P. & Rohrbaugh, J. 1994. Model Building for Group Decision Support: Issues and Alternatives in Knowledge Elicitation. *In:* Morecroft, D. J. D. W. & Sterman, J. D. (eds.) *Modeling for Learning Organizations.* Portland OR: Productivity Press.

Vos, B. & Akkermans, H. 1996. Capturing the dynamics of facility allocation. *International Journal of Operations & Production Management,* 16 (11). 57.

Vos, L. 2007. Evaluating hospital design from an operations management perspective. *Health care management science,* 10, 357-364.

Weaver, K. & Olson, J. K. 2006. Understanding paradigms used for nursing research. *Journal of Advanced Nursing,* 53 (4). 459-469.

West of Scotland Cancer Network (WoSCAN). Available: www.woscan.scot.nhs.uk [Accessed 26/11/2012].

Williams, T. 2008. *Management Science in Practice*, John Wiley & Sons.

Wolstenholme, E. F. 1980. Modelling discrete events in system dynamics models. *Dynamica,* 6 (1).

Wolstenholme, E. F. 1982. System Dynamics in Perspective. *Journal of the Operational Research Society,* 33, 547-556.

Wolstenholme, E. F. 1990. *System Enquiry – A System Dynamics Approach,* Chichester, John Wiley & Sons.

Wolstenholme, E. F. 1999a. A patient flow perspective of U.K. Health Services: Exploring the case for new "intermediate care" initiatives. *System Dynamics Review,* 15 (3). 253-271.

Wolstenholme, E. F. 1999b. Qualitative *vs* quantitative modelling: the evolving balance. *Journal of the Operational Research Society,* 50 (4). 422-428.

Wolstenholme, E. F. 2003. Towards the Definition and Use of a Core Set of Archetypal Structures in System Dynamics. *System Dynamics Review,* 19 (1). 7-26.

Wolstenholme, E. F. 2004. Using generic system archetypes to support thinking and modelling. *System Dynamics Review,* 20 (4). 341-356.

Yin, R. K. 2003. *Case Study Research: Design and methods,* SAGE Publications.

Zagonel, A. 2002. Model conceptualization in group model building: A review of the literature exploring the tension between representing reality and negotiating a social order. *Proceedings of the 20th International Conference of the System Dynamics Society.* Palermo, Italy.