Development of Capability Maturity Framework for manufacturing research centres

By

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Declaration of authenticity and author's rights

This thesis is the result of the author's original research. It was composed by the author and contains material that was previously submitted for examination, as the first year requirement of the EngD programme, which is equivalent to a MSc degree (in Advanced Manufacturing, dissertation titled 'Development of technology readiness based framework in managing manufacturing improvement within innovation providers') (that is in relation to Chapter 4, Phase 1 interviews).

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Sections of this thesis have been/will be published as a journal paper/conference contribution &/or paper/book chapter and/or presented at academic symposia Therefore content from this thesis appears in the texts outlined below.

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Abstract

Capability development (i.e. capability maturity) processes in research centre environment have not been sufficiently examined in the literature. The literature review suggested that most relevant studies tend to focus either on academic theories that discuss improvement of industrial capabilities, or processes, validated in an industrial environment. Furthermore, literature is unclear on definition, importance and work of research centres (i.e. a clear lack of uniformity). Even though, research centres contribute to technological innovations, they have not received the same level of attention.

That is why it was important to identify challenges relevant to research centres. For example, not having a standard process tailored to research centres' needs in order to evaluate maturity of their internal capabilities. That knowledge gap was captured through three phases of interviews: 1) Exploratory study, 2) Framework development, 3) Framework modifications. Those phases were crucial as they helped to design, developed and validate Capability Maturity Framework, which introduces a standardised process for research centre.

Phase 1) started with exploratory interviews to understand why existing solutions cannot be applied to research centres and also what are research centres requirements (that have not been met so far by existing solutions). The interviews involved ten practitioners from four research centres as well as three participants from two industrial manufacturing companies. Results from Phase 1) fed into Phase 2): Framework development. Interviews with sixteen practitioners from seven research centres in the UK were conducted during Phase 2). Those interviews helped to define structure of Capability Maturity Framework. That led to Phase 3): framework modifications. Phase 3 of interviews was organised to understand what format (of the framework) would be the most user-friendly and what least user-friendly aspects should be avoided. Eighteen practitioners from different teams across a research centre took part in Phase 3).

Once Phases 1-3 were completed, Capability Maturity Framework was evaluated by participants from various research centres, and a few who work in industrial companies but have a close relationship with a research centre. In total 34 participants reviewed the framework. Validation findings provided evidence that the need for such a framework exist and has not been fulfilled yet by any other existing solutions. The framework not only offers new maturity scale for a research centre' capabilities, but also transparency of information across a centre. Results from validation stage showed that there is a need for a solution that captures capability maturity in research centres, and that Capability Maturity Framework could fill that gap. Nonetheless, some findings suggest that Capability Maturity Framework could be further enhanced especially having a more robust process to manage input data. Validation findings also provided insightful foundation for improvements of Capability Maturity Framework, and for new areas of investigation.

The biggest contribution of this study is the Capability Maturity Framework for research centres in the manufacturing sector. This study presents how the framework was developed and how various information sources (i.e. literature findings, interviews) influenced the design of the framework.

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Nomenclature

Abbreviation	Meaning
3D	3 dimensional
ADR	Annual Development Review
AFRC	Advanced Forming Research Centre
AMRC	Advanced Manufacturing Research Centre
BD	Business Development personnel
CM	Challenge related to capability management
CMF	Capability Maturity Framework
CML	Capability Maturity Level
CMM	Capability Maturity Model
CMMI	Capability Maturity Model Integration
COO	Chief Operating Officer
CORE projects	Projects with Core funding from Innovate UK (including the additional allocation for HVM Plus and HVM Reach) – for long term investment in infrastructure, expertise and skills development (HVMC, 2016)
CPI	Centre for Process Innovation
CTO	Chief Technology Officer
D	Dimension
DCT	Dynamic capabilities theory
HR	Human Resources
HVM	High Value Manufacturing
HVMC	High Value Manufacturing Catapult
IE	Industry Engagement personnel
IMRLs	Innovative Manufacturing Readiness Levels
IT	Information Technology
LMC	Lightweighing Manufacturing Centre
Max	Maximum
MCRL	Manufacturing Capability Readiness Levels
Min	Minimum
MRL	Manufacturing Readiness Levels
MS Project	Microsoft Project software
MTC	Manufacturing Technology Centre
NAMRC	Nuclear Advanced Manufacturing Research Centre
NCC	National Composites Centre
NMIS	National Manufacturing Institute for Scotland
OM	Challenge related to operations management
P	Participant
Power BI	Data visualisation software
Q	Question
RBV	Resource based view
RC	Research Centre
RQ	Research Question
RT	Research Theme
S1	Survey 1
S2	Survey 2
SLR	Systematic Literature Review
SM	Challenge related to strategic management
SMEs	Small and medium enterprises
SML	Sub-dimensional Maturity Level
SP	Science parks i.e. research centres
SPL	Strategic Programme Lead
SPSS	Software used for statistical analysis

ST	Sub-theme
TC	Technological Capability
Tech	Technology
TL	Team Lead
TOS	Technical, operational, strategic (responsibilities)
TQM	Total Quality Management
TRL	Technology Readiness Levels
TTO	Technology transfer office i.e. research centre
VoD	Valley of Death
WMG	Warwick Manufacturing Group

Chapter 1: Introduction

1.1 Background and Motivation for research

Manufacturing sector in the UK relies heavily on the research centres helping to develop new technologies in order to overcome the valley of death (VoD). Valley of Death was described as "a position in the technology implementation landscape where a disproportionate level of failure occurs" (Ward, et al., 2017), or as "an inability to advance from a technology's demonstration phase through the commercialisation phase" (Frank, et al., 1996). "The valley of death concept has been essential to the success in the United Kingdom of raising awareness of HVM (High Value Manufacturing) issues, especially in the United Kingdom where it has driven the establishment of the HVM Catapult network" (Ward, et al., 2017). According to (HVM Catapult, 2020) seven centres have a collective asset base (including equipment and buildings) totalling £791m, and 3,130 full time employees. Moreover, "in 2019/20 the HVM Catapult's Centres supported companies across 4,646 projects to harness the power of innovation and strengthen their performance. Those companies ranged from small social enterprises to global giants employing thousands of people both directly and through their UK supply chains" (HVM Catapult, 2020). HVM research and development network created a considerable economic impact: for every £1 that was received from core public funding, £15 of net benefit was generated to the UK economy (Siora, 2015).

HVMC's mission is to address the valley of death. Therefore, HVMC often undertake work that is at middle Technology Readiness Level (TRL), which happen to be problematic for many industrial companies. That challenge was the starting point for this research and created a motivation for development of **capability maturity framework that 1) is created for research centres and 2) will allow research centres to understand how mature their capabilities are and if they can address middle TRL issues (i.e. VoD) that industrial companies struggle with.**

Therefore, the role of research centres in the manufacturing sector has become crucial in the recent years. However, **the literature does not sufficiently address the problem of defining, measuring and evaluating capabilities of research centres**, especially when considering long-term projects. That is why it is important for research centres to have a reliable and structured approach of managing their capabilities and this will help with developing and applying high value technologies. However, currently available solutions (e.g. TRL, MRL, MCRL, IRL, CMM) are customised for work and needs of industry. Table 1.1 below shows description and some main disadvantages of most mentioned industrial approaches.

It is important to highlight that those approaches does not take into consideration research centres' needs. Above solutions were created to answer industrial problems, taking into consideration industrial requirements. However, nowadays many industrial companies relay on research centres' work and abilities to deliver innovative solutions. Therefore, those approaches do not take into consideration how modern research centres work and their unique characteristics. For example, research centres often need to provide solutions to several projects. While industrial companies need only one specific solution for their challenge, research centres need an approach that does not concentrate on only one product/service (and how that product service is delivered to the market). They need to make sure that they have relevant capabilities applicable to several projects.

Table 1.1: Overview and disadvantages of some of the industrial approaches

Approach	Overview	Disadvantages
Technology Readiness Levels (TRL)	• *TRLs are "a type of measurement system used to access the maturity level of a particular technology"* (NASA, 2012) • *"Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the projects progress. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest"* (Mai, 2012)	• *"TRLs are context specific. A technology that is mature in one operating plant cannot be assumed to be as mature in a different one. Even those that appear the same might have significantly different operating conditions (…) It does not imply that the technology "will result in successful development of the system"* (NDA, 2014) • *"Despite this increase in uptake of practice, little research has been formally conducted to understand and describe TRL application"* (Olechowski, et al., 2020)
Manufacturing Readiness Levels (MRL)	• *MRL 1-3: Pre-Concept Development (Innovation Stage)* • *MRL 4: Concept Development* • *MRL 5-6: Technology Development* • *MRL 7-8: Engineering and Manufacturing Development* • *MRL 9-10: Production and Deployment* (Fernandez, 2010)	• *"It describes today's position, without providing close support (…) in how to plan or execute a specific project or lower level task"* (Ward, et al., 2012)
Manufacturing Capability Readiness Levels (MCRL)	• *MCRL 1-4: Conception and assessment of Manufacturing Technology* • *MCRL 5-6: Critical 'pre-production' phase, where expensive full-scale equipment and processes must be used but ahead of product launch, or factory* • *MCRL 7-9: implementation of the process on the shop floor, and also confirms volume production with assured quality* (House of Commons, 2013)	• *In relation to MCRL 4-6: "investment is high, but there is no certainty that (…) the proposed process will be successful"* (House of Commons, 2013) • *"Size of the framework is overwhelming and it is time-consuming"* (Uflewska, et al., 2017)
Innovative Manufacturing Readiness Levels (IMRL)	• *IMRL 1: Understanding materials' properties at micro and nano-scale, technical and manufacturing strategy planning and detailed design* • *IMRL 2: Materials processing capabilities, validation, and component technologies dependencies* • *IMRL3: Adequacy and integration (scale-down challenges), system engineering, prototypes, and overall production preparation* • *IMRL 4: Combined systems tests, verification, inspection and trial production* • *IMRL 5: Overall systems are in operation, quality measurement and initial market audit* (Islam, 2010),	• *Applicable only to micro and nano-manufacturing technologies i.e. not applicable to large/medium technologies/products (due to specific parameters)* (Uflewska, et al., 2017) • *Practicability and applicability of this framework is still in question as it is a conceptual approach* (Uflewska, et al., 2017)
Capability Maturity Models (CMM)	• *"Based on the specific software practices adopted, the CMM classifies the software process into five maturity levels. (…) "Maturity levels were associated with a software product based on the maturity level of the IT firm at the beginning of a product's design."* (Harter, Krishnan, & Slaughter, 2000)	• such tool has to be adjusted to the needs of specific industry and addresses common problems that affect multiple actors • subjectivity of data
Capability Maturity Model Integration (CMMI)	• *"CMMI divides an organization's research and development capabilities into five levels: the initial level, managed level, defined level, quantitative management level and optimization level."* (Huang, et al., 2019) • *The main objective of this model is to assess and improve the processes of organisations within the scope of the development, operation, and maintenance of information systems and software products.* (Patón-Romero, et al., 2019)	• *"Processes that depend on the interaction of individuals can be difficult to quantify. This leads to the evaluation results that vary according to the context in which they are applied"* (Silva, et al., 2019) • *"When it comes to links that require executive staff to judge subjectively or actively contribute their experience and wisdom, the subjective initiative of the individual can influence the effects of process execution; for example, in the QA audit process, review process, testing process, etc., Therefore, it is necessary to consider people-orientation in these processes." (*Huang, et al., 2019)

In other words, industry wants to understand the level of confidence in the readiness of a particular product/service to solve specific challenges, while research centres need to understand strengths and weaknesses in their technological capabilities. That is why the requirements for industry and for research centres differ, and that is why existing approaches do not work.

Additionally, as presented in Table 1.1, the previously described solutions are too complex, time consuming and often include multiple aspects unrelated to research centres' needs or work. The issue with those industrial approaches (from a research centre perspective) is that these approaches aim to get technology ready for a specific application (whether it is a programme, product or planning horizon). However, the job of a research centre is also to put technologies on the shelf for wider usage, and so research centres need to have mature capabilities in order to do so. Industrial solutions were created to address specific need of a company, which is not the same for research centres, i.e. "they (industrial approaches) are not well suited to dealing with the provision of base technology capability which might be needed to serve a number of end-use applications" (Ward et al, 2017).

Furthermore, the aim of this research is not to improve the industrial approaches. Even though industrial approaches could be modify and improved, **they still do not address the needs of research centres, i.e. they are not fit for purpose**. That is why **a new framework developed for research centres and with the involvement of research centres is needed.**

On the other hand, existing **academic theories** (e.g. dynamic capabilities theory (DCT), resource-based view (RBV)) concentrate on market growth and financial impact merely from the industrial perspective. Moreover, some major concerns (related to the fact that **those theories do not consider research centres or even small enterprises, and their complexity and in result- their practicality**) were also identified when reviewing literature e.g. "the differentiation between resources and capabilities has been largely overlooked. The two constructs appear to be used interchangeably by many authors" (Hitt, et al., 2016). Table 1.2 shows further concerns regarding DCT and RBV.

Table 1.2: Concerns regarding academic approaches, i.e. DCT and RBV

DCT	RBV
• "One of the criticisms of the dynamic capabilities concept is that they are difficult to measure empirically" (Easterby-Smith, et al., 2009)	• Resource based view (RBV) does not distinguish between small or large companies, which also creates a disadvantage as there are many different-sized companies who will need different approaches that address their industrial needs. However, that differentiation was not found in the literature.
• Dynamic capabilities theory (DCT) is advocated by many researchers, however, they mostly concentrate on industrial context excluding SMEs (Ferreira, et al., 2020), and research centres	• RBV assumes that resources are unique for each company, i.e. they cannot be replicated anywhere else (Qi, et al., 2020). Therefore, it suggests that each company has different set of skills, capabilities etc. This approach that does not apply to manufacturing research centres as they do share similar capabilities or skillset (HVMC website 2020). Hence, a theory that takes into consideration replication of resources should be considered for research centres.
• "The definition [of dynamic capabilities] provided by (Teece, et al., 1997) was broad enough to provide opportunities for others to refine, reinterpret and expand the concept. (…) This definition, while	• RBV mentions that resources are immobile. However in a HVMC world, there are cross-Catapult projects where transfer of knowledge takes place. Therefore, intangible capabilities as knowledge or experience is

providing a start, left open the questions of what constitutes such abilities, what their attributes are, how they can be recognized, and where they come from" (Easterby-Smith, et al., 2009)	shared between Catapults to achieve a common goal.
• "There is a need to establish clearer linkages about how dynamic capabilities include the utilization of resources and the implementation of new processes" (Easterby-Smith, et al., 2009)	

Neither existing theories nor industrial approaches can address the key gap of capability maturity demonstration in the context of research centres. That is why this research will focus on knowledge gap that impacts work of research centres and explain the importance of those from research centres' perspective.

This study argues that addressing this gap, *lack of structured capability maturity solution for research centres*, is essential as it offers lens for technological capability maturity at research centres. In summary, this research attempts to answer three research questions (RQs):

- RQ1: Is there a need for capability maturity framework applicable to manufacturing research centres?
- RQ2: Could a novel framework fill in the need for capability maturity framework at manufacturing research centres?
- RQ3: Could a novel framework fill in the need for capability maturity framework across various manufacturing research centres?

This EngD thesis presents an empirical study that aims to develop and evaluate a technological capability maturity framework for research centres.

1.2 Aim and objectives

The aim of this EngD is to develop capability maturity framework in the context of manufacturing research centres. The framework was developed in order to provide insight into research centres capabilities and define their maturity. To achieve this aim, the following objectives were defined:

Objective no 1: Identify issues related to readiness solutions based on literature

- Review literature on technology maturity and readiness as well as capability maturity to establish knowledge gap.
- Investigate capability maturity and readiness solutions to identify current issues from research centre perspective, as well as understand how research centres view capabilities and what challenges they need to overcome.

Objective no 2: Develop a capability maturity framework to address research centre needs identified in previous objective

- Develop the capability maturity framework based on the literature and insights from research centres' representatives.
- Evolve the capability maturity framework using data collection to test the mechanism of the new framework

Objective no 3: Evaluate capability maturity framework to assess the extent to which it addresses research centres' capability gaps

Objective no 4: Discuss completed work to identify strengths, weaknesses, and areas for future work.

1.3 Research Contributions

Considering unique characteristics of manufacturing research centres (e.g. combining theoretical knowledge and transforming it into practical applications, delivering projects for variety of industrial companies, etc.), this research delivered five research contributions. Those contributions add value to the conversation in manufacturing management community but also in research centre community, which has become bigger over the last few years.

Research Contribution no 1: The first contribution is recognition of lack of uniformity related to definition and objectives of research centres (Cadorin, et al., 2019). Literature presents various names for research centres, e.g. technology transfer offices (Leischning & Geigenmüller, 2020), (Good, et al., 2019), intermediate research organizations (Spring, et al., 2017) incubators, accelerators, broker services (Fini, et al., 2018).

Research Contribution no 2: While research centres enjoy a flexible approach to innovation, they lack the standardised processes to evolve and grow. They struggle with recognition of their mature and immature capabilities, as well as implementation of formal process that will review what research centres know and do not know. Therefore, the lack of standardised solution that provides information on capability development is important aspect in research regarding research centres. The fact that "there is no generally accepted approach to evaluate the performance of SPs" (Lecluyse, et al., 2019) shows the need for a capability maturity solution developed specifically for research centres.

Research Contribution no 3: Having identified that there is no common/standardised approach for research centres (Research Contribution No 2), another contribution relates to the emerging discussion on research centres and their capability maturity challenges, as well as their biggest challenges (i.e. challenges that affect research centre on a regular basis). Those challenges were explored by identifying how research centres work and overcome those challenges. This study also captured informal processes that research centres use to evaluate how mature there are at specific capabilities. That contribution was captured through series of interviews with research centre representatives.

Research Contribution no 4: Lastly, the fourth contribution was generated by reviewing the literature in order to recognise that the majority of the studies found focused on capability development of industrial companies. Research centres have not received the same level of attention, despite of their important contribution to technological innovations (in manufacturing or other sectors/topics). Hence, it is clear that Capability Maturity Framework (created through this EngD project), and future modifications, included in Chapter 9, will provide a helpful foundation for technology managers, leaders, researchers and policy makers, providing information needed to improve technological capabilities in manufacturing research centres and bridging the valley of death.

Research Contribution no 5: As research centres have not received the same level of academic attention as industrial companies, it is one of the reasons why research centres struggle with monitoring and managing their own internal capabilities. That is why the Capability Maturity Framework was designed, developed and validated, in order to support maturity process of research centres in manufacturing sector. This contribution is perhaps the most important one as it delivers mechanism that can be applied in research centres, because it was created for research centres (instead of being created for industrial company, and tried to fit in a research centres). The process involved understanding how research centres operate and identifying most important aspects of their operations (i.e. dimensions of Capability Maturity Framework).

1.4 Research Method and Analysis

This project followed action research approach as it "emphasises the iterative nature of the process of diagnosing, planning, taking action and evaluating," and "the researchers are often part of this change process itself" (Saunders, et al., 2009).

Existing research on technology capability maturity models fails to explain capability maturity in research centre context. What is more, current literature does not consider capability maturity model development and the challenges faced by research centres. Action research approach was implemented to allow the capability maturity framework to be created, evaluated and improved through series of interviews with research centres. Action research assumes that social phenomena are constantly changing, i.e. they are not static. In addition, "the following two beliefs are normally associated with action research designs:

1. The best way of learning about an organisation or social system is through attempting to change it, and this therefore should be an objective of the action researcher.
2. The people most likely to be affected by, or involved in implementing, these changes should as far as possible become involved in the research process itself.

Figure 1.1 below shows all major research activities that lead to the Capability Maturity Framework development as well as validation.

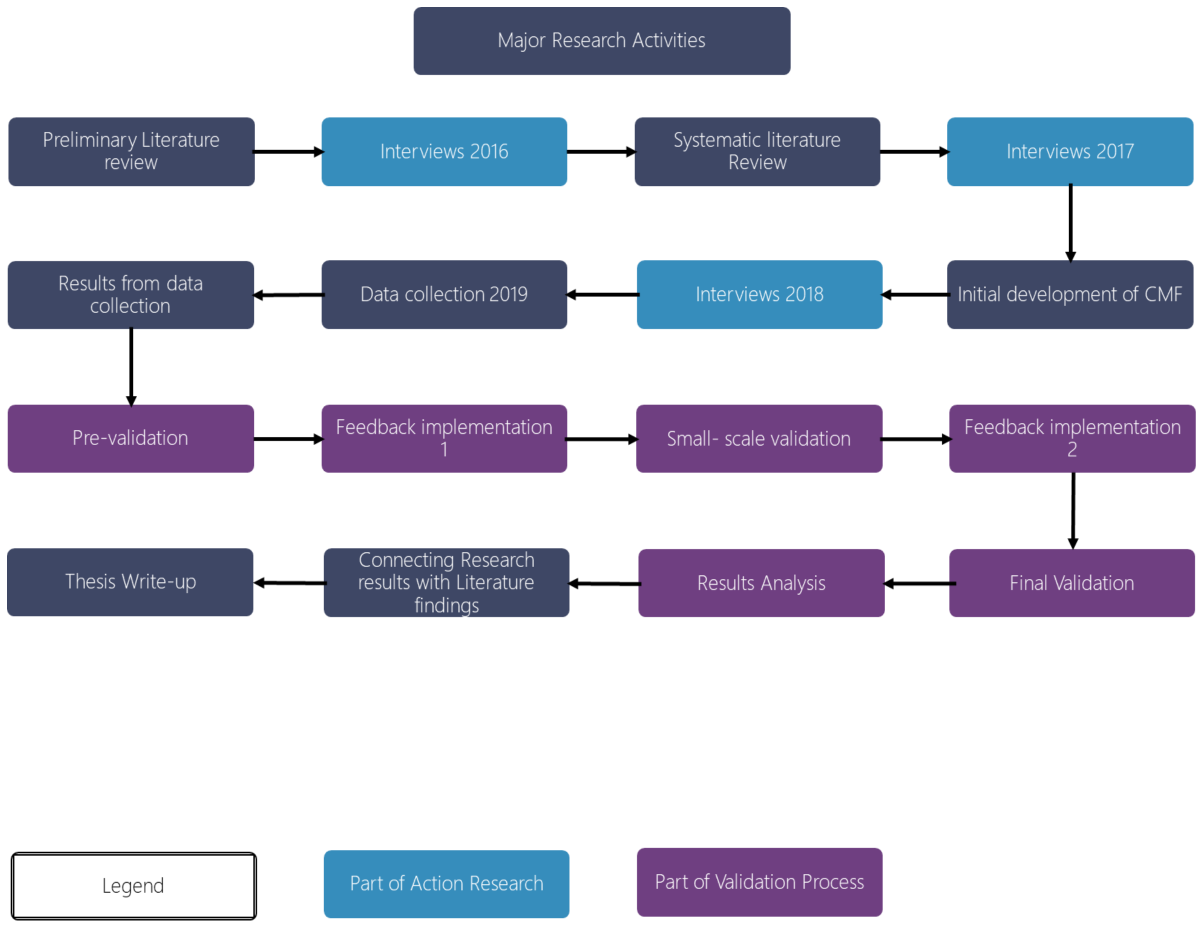


Figure 1.1: Major research activities of this EngD

1.5 Thesis structure

Figure 1.2 below shows the structure of this EngD thesis. Chapter 2 discusses process of reviewing and main findings from literature review. It presents definition of capability and research centres that underpins the research presented in this thesis. Findings from literature review were used to define the focus of this study, i.e. the knowledge gaps.

Chapter 3 explains methodology selected for this study. Methodology discussed in Chapter 3 consists of philosophical assumptions that were used to selected research methods applied in this study. It also presents the connection between philosophical assumptions and research methods.

Chapter 4 describes 3 phases of interviews that helped verify and develop Capability Maturity Framework. Interviews with various participants from research centres helped to uncover modern challenges faced by research centres, but also current issues with other solutions (that are supposed to make participants work easier). Interviews also helped to define most important aspects of CMF and define the most suitable format for novel maturity framework.

Chapter 5 explains structure and mechanism of calculating Capability Maturity Levels, and how Capability Maturity Framework works. This chapter combines information from interviews as well as literature reviews in order to create multidimensional framework applicable to research centres.

Chapter 6 discusses validation process. It discusses the process of preparing validation process which included creation of 3 presentations and 2 surveys. It also describes how the final version of validation process was developed, i.e. it presents information on validation pilot studies that took place before final validation.

Chapter 7 presents results captured through validation process. Hence, it presents outcomes from validation process and categorises answers using thematic analysis, i.e. questions related to specific topic/idea were grouped together. The validation process aims to obtain broader and deeper insight into what research centres need to survive in a contemporary, dynamic manufacturing environment.

Chapter 8 discusses most important results from Chapter 7 together with findings from Chapter 2. It shows correlation between findings from validation process and highlights how this study contributes to academic discussion.

Chapter 9 presents future work, based on participants' suggestions from validation process. Future work presented in Chapter 9 relates not only to modification of CMF but also discusses new areas of research in research centre context.

Finally, Chapter 10 presents final conclusions by summarising whole research. It also discussed strengths, limitations and reflections.

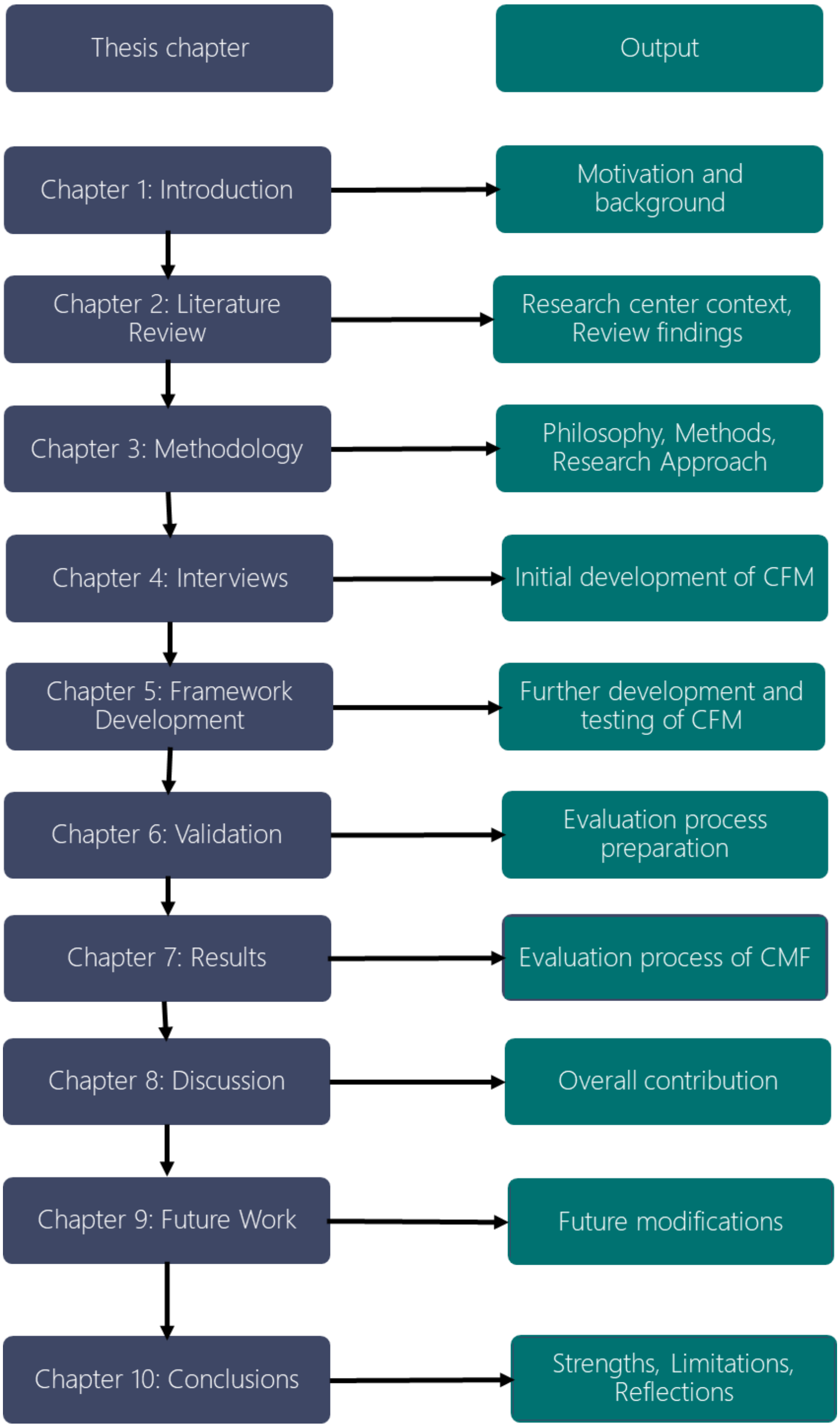


Figure 1.2: Structure of the EngD thesis

1.6 Important definitions

The most important terms used in this EngD are 'research centres', 'maturity', 'capability', 'technological capability' and 'conceptual framework.' As those terms are repeated many times throughout this research, definitions of those terms are included in Table 1.3 below.

Table 1.3: Definitions of most important terms relevant to this research

Term	Definition	Source
Resources	*Resources can be defined as "anything tangible or intangible the firm can use in its processes for creating, producing, and/or offering its products (goods or services) to a market,*	(Lee, et al., 2020)
Capability	*Capability refers to "the ability of an organization to perform a coordinated set of tasks, utilizing organizational resources, for the purpose of achieving a particular end result" (Helfat and Peteraf, 2003:999). Hereby, resources and capabilities need to be treated separately.*	(Liu & Huang, 2018)
	Capabilities denote "repeatable patterns of actions in the use of assets to create, produce, and/or offer products to a market"	(Lee, et al., 2020)
Technological capability	*Technological capability is a key resource. It consists of technological knowledge, know-how engendered by R&D and other technology-specific intellectual property [31]. A firm's technological capability is a kind of tacit resource, which is hard for its competitors to acquire.*	(Liu & Huang, 2018)
Research centre	*A research centre or a Catapult centre is "to provide a formal, above the board, and a relatively effective mechanism for those researchers who wish to commercialise their ideas" (Cunningham, et al., 2020), which means that the centre aims "to 'de-risk' innovation by providing a range of services throughout the research and development cycle" (Kerry & Danson, 2016).*	(Cunningham, et al., 2020), (Kerry & Danson, 2016)
Maturity	*The term maturity is defined as a method of the evaluation of completeness, perfection, growth and development of organizations with respect to their capabilities to handle their operations. Similarly, Kerzner [18] described maturity as the improvement of processes and structures which are monotonous by nature. So, maturity can be understood as the development in each domain of a specific profession or area of an organization*	(Ifran, et al., 2019)
Maturity model	*"the objectives of maturity models are the determination of the current situation, the identification of measures for further development, and the implementation of benchmarking"*	(Moehrle, et al., 2017)
Readiness	*Readiness refers to time. Specifically it means ready for operations at the present time*	(NDA, 2014)
	Readiness, in the situation of a software environment (yet equally true for hardware), to be a measure of the suitability of a product for use within a larger system "in a particular context", i.e., with respect to specific requirements.	(Seablom & Lemmerman, 2012)
Conceptual Framework	*The actual ideas and beliefs that you hold about the phenomena studied, whether these are written down or not; this may also be called the 'theoretical framework' or 'idea context' for the study (p.39)*	(Maxwell, 2013)
Capability Development	*According to (Heimeriks & Duysters, 2007), "requires the interplay between different organizational elements (Helfat and Peteraf, 2003), i.e. it relates to a process where in individual experiences and knowledge ultimately shape the organizational learning process which impacts capability development." Therefore, "capabilities must be built through experience since they are not easily available in the spot market (Teece et al., 1997) and are an outcome of the firm's ability to integrate knowledge (Grant, 1996)" (Heimeriks & Duysters, 2007).*	(Heimeriks & Duysters, 2007), (Teece, et al., 1997)
Capability Maturity	*It is defined in this study as process of "achieving more effectiveness and efficiency" (Silva, et al., 2019) or "to assess and improve the processes of organisations" (Patón-Romero, et al., 2019) when considering their ability to*	(Patón-Romero, et al., 2019), (Qi, et al., 2020), (Wißotzki, 2015)

	deploy its resources, usually in combination, using organizational processes to achieve some desired end result" (Qi, et al., 2020).	
Capability Management	*It is defined as responsibility of managers who are responsible for "achieving and maintaining competitive advantage. The Resources and Capabilities management team is valuable when they exploit opportunities" (Mahoney, 1995)*	(Mahoney, 1995)

1.7 Summary

Literature review identified a number of concerns regarding dynamic capabilities theory as well as resource-based view. On the other hand, literature also recognised shortcomings of industrial solutions like TRL, MRL, etc. in industrial context. Even though literature lacks information about how those industrial solutions are applied (or not applied) in research centres, this study presents first-hand results reported by research centres in the manufacturing sector.

Using information from literature and research centre, action research approach was followed in order to develop capability maturity framework for research centres. Thus, this EngD provides new insight into capability maturity for research centres where scholars have mainly studied DCT, RBV and industrial solutions from companies' perspective.

Chapter 2: Literature Review

2.1 Introduction

This research focuses on capability maturity framework in research centres. Defining terms such as '*capability*' and '*maturity*' as well as '*research centre*' was considered fundamental for this study. While a number of studies discussed '*capability*' and '*capability models*', none of them presented a clear definition of '*capability maturity*' in the research centre context. As '*capability*' might be considered differently (e.g. technological capability (Liu, et al., 2019), (Arana-Solares, et al., 2019), human capability (Zhang, et al., 2003), intellectual capability (Hsu & Wang, 2012), organisational capability (Liu, et al., 2018), etc.), definition of '*capability*' was initially explored. For the same reason, definitions of '*maturity*' and '*research centre*' were also examined.

Even though different '*maturity models*' were created to support industrial companies in various sectors, '*maturity*' was considered a state before '*readiness*' (Tetlay & John, 2009). However, no indication about '*maturity models*' in research centres was discussed in the literature.

Furthermore, when exploring definition of '*research centres*', the lack of uniform definition was identified. It was also identified that research centres do not have the same attention from scholars as industrial companies, i.e. most of the reviewed paper concentrate on industrial aspects, while topics related to research centres (or even SMEs) are not being explored as often. Because of that, research centres' needs and challenges are not reflected in the same degree as industrial challenges in the literature.

Some manufacturing sectors (aerospace, automotive, renewables etc.), and most industrial companies concentrate on a specific technology (e.g. incremental improvements of an engine) that plays a particular role in the final product (e.g. internal combustion engine). It could be one of the reasons why industrial companies are most likely to use some existing readiness frameworks. For example, TRLs calculator software for Turkish defence industry (Altunok & Cakmak, 2010), Manufacturing Capability Readiness Levels (MCRLs) used by Rolls-Royce (House of Commons, 2013), TRLs used in the Department of Defence (US) (DoD) (Brown, 2020), System Readiness Levels (SRLs) (Sauser, et al., 2006), Innovative Manufacturing Readiness levels (IMRLs) (Islam, 2010). It should also be highlighted that a lot of those solutions are based on the original Technology Readiness Levels (TRLs) which was introduced by NASA. TRL 1 means that "scientific research is beginning and those results are being translated into future research and development", and TRL 9 is "a technology that has been proven during a successful mission" (Mai, 2012).

However, literature does not offer a solution/tool that targets research centres. Without such solutions/tools, it is very challenging for research centres to address future challenges, design appropriate roadmap and plan future investments.

It is especially difficult as research centres differ from industry and academia. According to (Hauser, 2014), Catapult centres' aim is "to close the critical gap between research findings and their subsequent development into commercial propositions. It made a case for long-term UK investment in a network of technology and innovation centres, based on best practice in other countries, such as the Fraunhofer Institutes in Germany and TNO in the Netherlands."

Seven Catapult centres, that are part of High Value Manufacturing network, as shown in Figure 2.1, have a collective asset base (including equipment and buildings) totalling £791m, and 3,130 full time employees. Moreover, "in 2019/20 the HVM Catapult's Centres supported companies across 4,646 projects to harness the power of innovation and strengthen their performance" (HVM Catapult, 2020). Hence, HVM research and development network created a considerable economic impact: for every £1 that was received from core public funding, £15 of net benefit was generated to the UK economy (Siora, 2015).

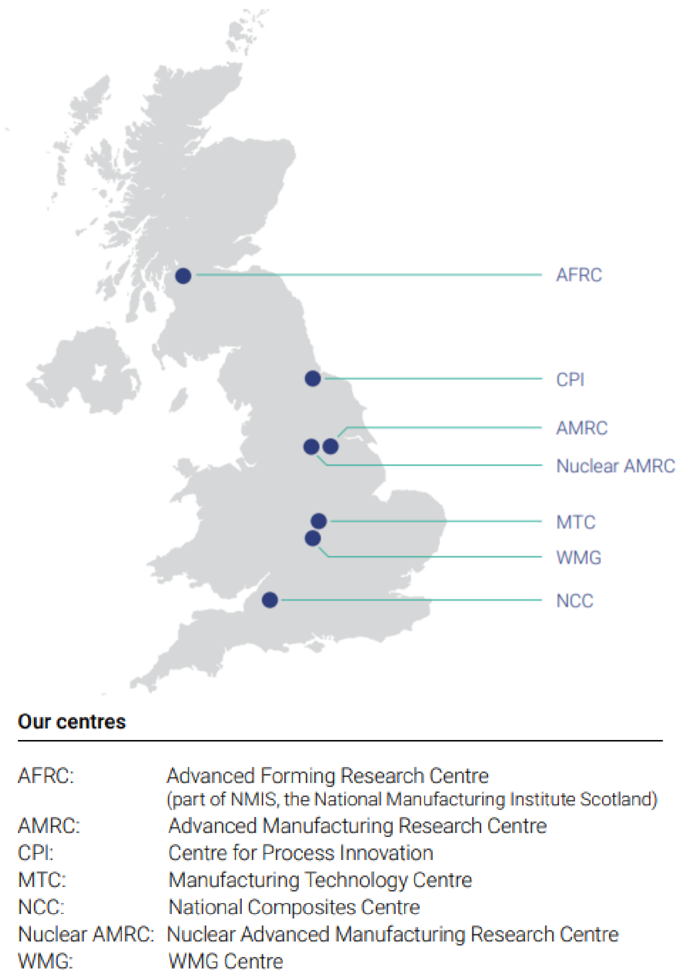


Figure 2.1: HVM Catapult (HVM Catapult, 2020)

Research centres play **critical role in addressing so-called Valley of Death** (VoD). Therefore, they need to know how mature their capabilities are before taking on a project or committing to develop innovation.

Hence, research centres aim "to **'de-risk' innovation** by providing a range of services throughout the research and development cycle" (Kerry & Danson, 2016). However, "**capability is being developed for potential use by multiple end users on multiple applications**" (Ward, et al., 2017). It means that industrial companies might rely on research centres to deliver innovative solutions that they think are specific to a sector, but in fact **research centres need to apply their capabilities to various industrial requirements from multiple sectors**. That is why research centres need to know what they can deliver, and in order to do that they need to know capability maturity.

Literature sources do not offer any solution to address the problem of defining, measuring and evaluating capabilities of research centres, especially when considering long-term projects. Research centres need to have a reliable and structured process which helps with delivering high value technologies.

The systematic literature review aimed to uncover information related to **capability, maturity and research centres.** The goal of this literature review was to identify current developments in the literature as well as knowledge gaps about research centres and capability maturity in the research centre context. Section 2.2 explains the structure of this chapter

2.2 Background and overview

This chapter is divided into six sections. Section 2.1 presented a brief introduction to the systematic literature review (SLR). Section 2.2 is a summary of other sections included in this chapter. Section 2.3 explains how SLR was planned and done. Section 2.4 discusses the major findings of SLR, i.e. what research topics (and their sub-categories) were recognised in selected articles, what are the correlations between topics. Section 2.5 explains most discussed issues in the SLR and correlations with the previously gathered information from research centres' representatives. Section 2.6 is the summary of the literature review findings.

2.3 Review methodology

To present a valuable research on research centres' capabilities in the UK manufacturing sector, SLR was conducted. (Easterby-Smith, et al., 2015) highlighted that the aim of a SLR is to "make an important contribution to the understanding of its field," and that was the purpose of this SLR.

Steps taken during this research "are replicable, scientific and transparent" (Wetzstein, et al., 2016); it means that the results are reliable and robust. The SLR process was also selected for the following reasons:

- It "contains techniques to minimise bias and error and hence are widely regarded as providing high-quality evidence" (Transfield, et al., 2003)
- It "aims to locate, select, and appraise as much as possible of the research relevant to the particular review questions" (Denyer & Tranfield, 2009)and
- "a systematic and transparent synthesis of exciting research enhances knowledge creation and can therefore be of similar importance as new research, as well as provide the best possible answer to a scientific problem" (Wetzstein, et al., 2016).

Therefore, this SLR was based on a number of key steps, which are presented below.

2.3.1 Time horizon

In general, papers published between 1993 and 2021 were mainly reviewed. The year of 1993 was chosen as a start date for this literature review as it is believed that this is when theory of dynamic capabilities started to be examined throughout the literature. The year of 2020 was the last full year from which appropriate information could be found. Therefore, the review covers almost 27 years of information. It is believed that this review strategy would give a good overview over the evolution of the importance and concept of capabilities of innovation providers together with the development of research centres.

2.3.2 Database selection

To deliver a high quality SLR, the following fourteen well-established research publishers were chosen, including Elsevier, SAGE, Academy of Management, Springer, INFORMS, Emerald Insight, IEEE, IET, SITIS, QR2MSE, John Wiley & Sons Inc. Although not all publishers extensively covered both research fields (management and manufacturing), all of them were used to provide the best coverage (Wetzstein, et al., 2016). Table 2.1 shows where selected papers were published. Hence, the steps of SLR could be replicated as these sources are available online.

Table 2.1: Available literature categorised by the publisher

Publishers name	# journals	# papers	Time range
Elsevier	18	75	1993-1995, 1997-2009, 2011-2021
Springer	5	16	1998, 2004, 2010, 2017-2020
INFORMS	1	9	2000, 2002, 2004-2005, 2007-2008, 2010, 2016-2020
Academy of Management	4	21	2001, 2005, 2007, 2009-2012, 2014
Wiley	7	40	1994-1996, 2001, 2003-2014, 2016-2020
SAGE	3	20	1997, 2000-2003, 2007, 2009-2011, 2016, 2018
IEEE	5	5	2019
Emerald insight	1	1	2008
QR2MSE	1	1	2019
SITIS	1	1	2018
IET	1	1	2019
ABA	1	1	2020
MIS Research Centre (US)	1	1	2004
IBIMA	1	1	2020
Total	50	193	1993 - 2021

2.3.3 Journal selection

At first, all of selected journals were engineering, manufacturing or management journals, as those were the three most important themes considered for this study. However, not all the journals could be used in this review process due to large amount of papers that each journal includes. Therefore, an objective approach was needed to perform high quality analysis. As the journals come from different research field, different ranking scales were applied to some of the journals. Hence, the impact factor of 2.6 was applied as a minimum score for each journal. 2.6 was chosen as a minimum score due to the fact that for manufacturing journals the highest impact factor was 5.2. Thus,, journals that achieved 50% of that score were considered for this SLR to gain a broader perspectives, and to increase the chances of finding papers that describe the role, work and importance of research centres. However, as the process went on, after elimination of irrelevant articles and duplications, 50 journals was obtained. Once journals were selected, the process of selecting articles took place, which was followed by articles classification.

2.3.4 Article selection

Once 50 journals were selected, keywords were introduced into the search option. By using search option for each journal, articles related to 'management of manufacturing technology' were identified.

In order to gather as much information as possible, the following procedure was used. When using 'Title' or 'Keyword' search, ***"Technology Management", "Capability Management" or "Maturity Management"*** were entered as it was important to find out how capability maturity is measured and managed in different environments, not only in manufacturing sector. Considering selected keywords confirmed the focus of this research, which is on the maturity of capabilities at research centres.

Using journals from two research areas (management and manufacturing) was more suitable to run the search. The different combinations of those key words were entered in each journals' databases. Even though the intention was to get better understanding of capabilities and management of capabilities in the research centre environment, by selecting different databases, naturally, a large number of articles were retrieved. Total of 2,507 papers were identified when the key words were entered in the manufacturing journals and 5,316 papers were identified when management journals were used. However, it should be mentioned that because the same key words were used in every search, a large number of articles were duplicated.

After checking when the articles were published, keywords of identified articles and restricting to peer-review, 404 articles were selected. Afterwards another round of screening was performed together with finding out citation number for each article. However, sometimes even if the citation number was low (e.g. articles from 2020 would score 1 or 0), they were still selected for further analysis as their title and keywords demonstrated relevance to this study. In addition, at this point, all abstracts were read in order to investigate if articles were relevant.

By applying above steps, and having clear and objective article selection process, 227 papers were chosen for further analysis. Next step required screening the abstract of each of the papers to establish if paper should be included in the further analysis of the SLR. After reading abstract part, better understanding of topics covered in each paper was reached. Therefore, by performing this step, final 193 papers were selected for further analysis of this SLR. Figure 2.2 below shows the process described in Section 2.3.2, 2.3.3 and 2.3.4.

It is important to highlight that SLR followed steps described previously by (Wetzstein, et al., 2016). However, if different set of criteria (e.g. different databases/non-academic journals) were considered, perhaps the findings would have been different. Nevertheless, future work might benefit from adding other sources of literature e.g. technical reports, non-academic papers etc.

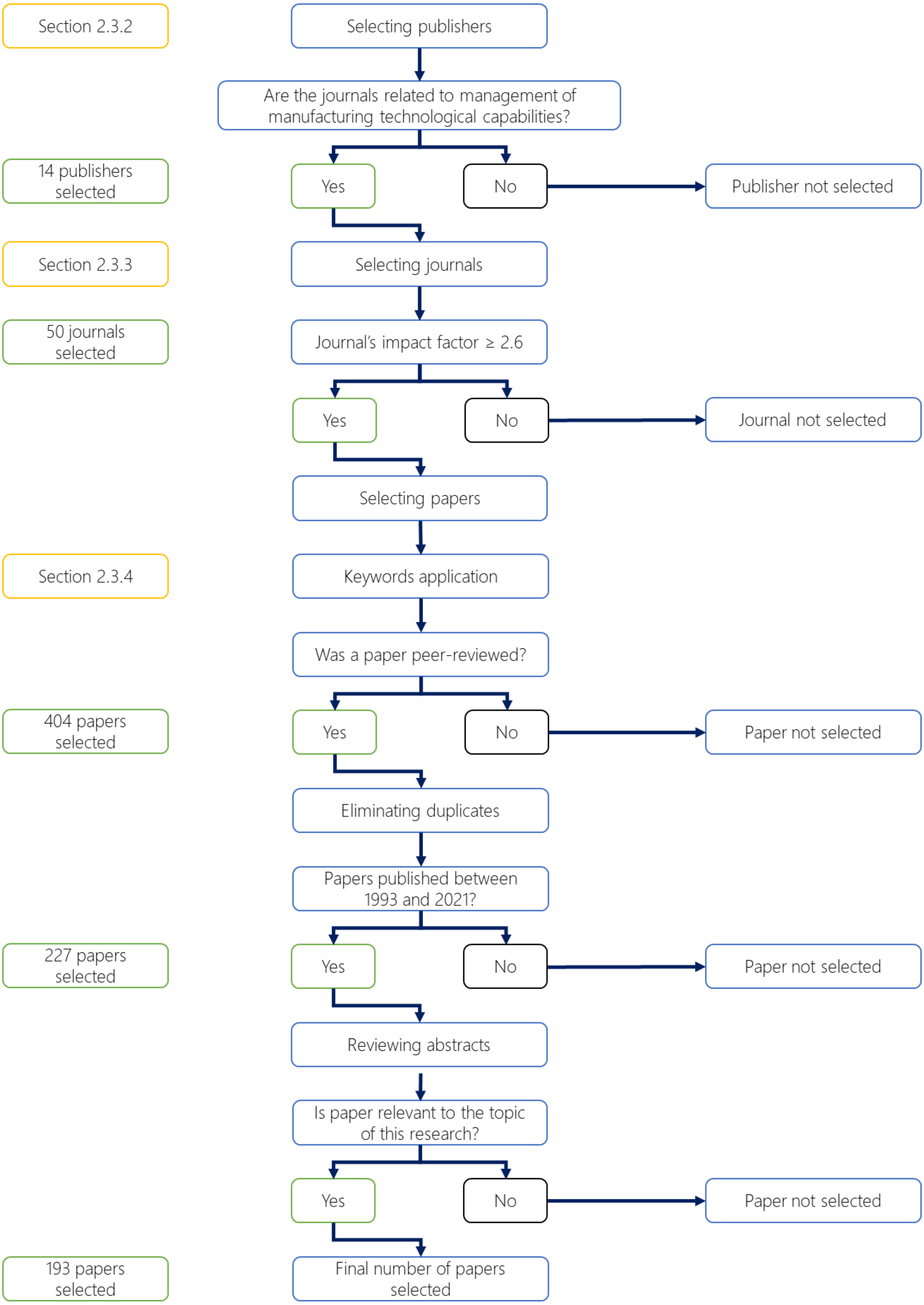


Figure 2.2: Flowchart of SLR process (based on (Wetzstein, et al., 2016))

2.3.5 Article classification

According to (Wetzstein, et al., 2016), this step is important as it investigates and categorizes "the resulting sample to determine 'what' is researched" when key words (as mentioned in section 2.3.4, p.14) are used. In order to create structured database, a number of research themes (RT) were identified and examined. Papers were classified using categorisation process presented by (Wetzstein, et al., 2016), which was also inspired by (Tuomikangas & Kaipia, 2014) and (Sandberg & Aarikka-Stenroos, 2014).

Paper classification was performed using two approaches: qualitative content analysis and quantitative content analysis. Firstly, qualitative content analysis took place, i.e. reading all selected papers it allowed "to acquire a general perspective on the focal research" (Sandberg & Aarikka-Stenroos, 2014) (p.1296). Keeping in mind the aim of this study and the scope, some papers were further eliminated as they did not provide relevance to this research. During that process, an excel file was created which captured summary of relevant terms discussed in each paper. This file was also used for second part of analysis i.e. quantitative content analysis, which was perfumed using the concept-centric procedure (Webster & Watson, 2002). "Accordingly, the key concepts of each paper were extracted and documented" (Wetzstein, et al., 2016).

Afterwards, "the key concepts were grouped together and consolidated into logical clusters, which is a common procedure, e.g. (Tuomikangas & Kaipia, 2014)" (Wetzstein, et al., 2016). Hence, by critically reviewing each of the articles, a number of main research themes were identified. Described approach allowed to address and examine sub-themes under each main research theme leading to a more in-depth discussion. In short, seven research themes were identified: challenges (RT1), maturity (RT2), capabilities & performance (RT3), strategy (RT4), decision making process (RT5), supply chain aspect (RT6) and university-industry collaboration (RT7). Figure 2.3 represents each of the research themes and the relevant subthemes (STs).

The SLR first concentrated on STs, which were later group together into a higher level RT, to simplify the categorisation process (as per (Wetzstein, et al., 2016), (Tuomikangas & Kaipia, 2014) . The RTs and ST emerged based on the content from literature sources. For example if a paper discussed topics like capability development and strategy, that paper was assigned to those two STs. Hence, one paper might be assigned to one or more STs, depending on what was discussed by researchers.

The key words were selected specifically for the purpose of this research and that is why the key words were quite narrow. It is believed that researchers who would like to repeat those steps would came up with the same results. Nevertheless, it should be highlighted that interpretation of literature is often subjective; thus, it is possible that sub-themes could have been modified if someone else had conducted the SLR.

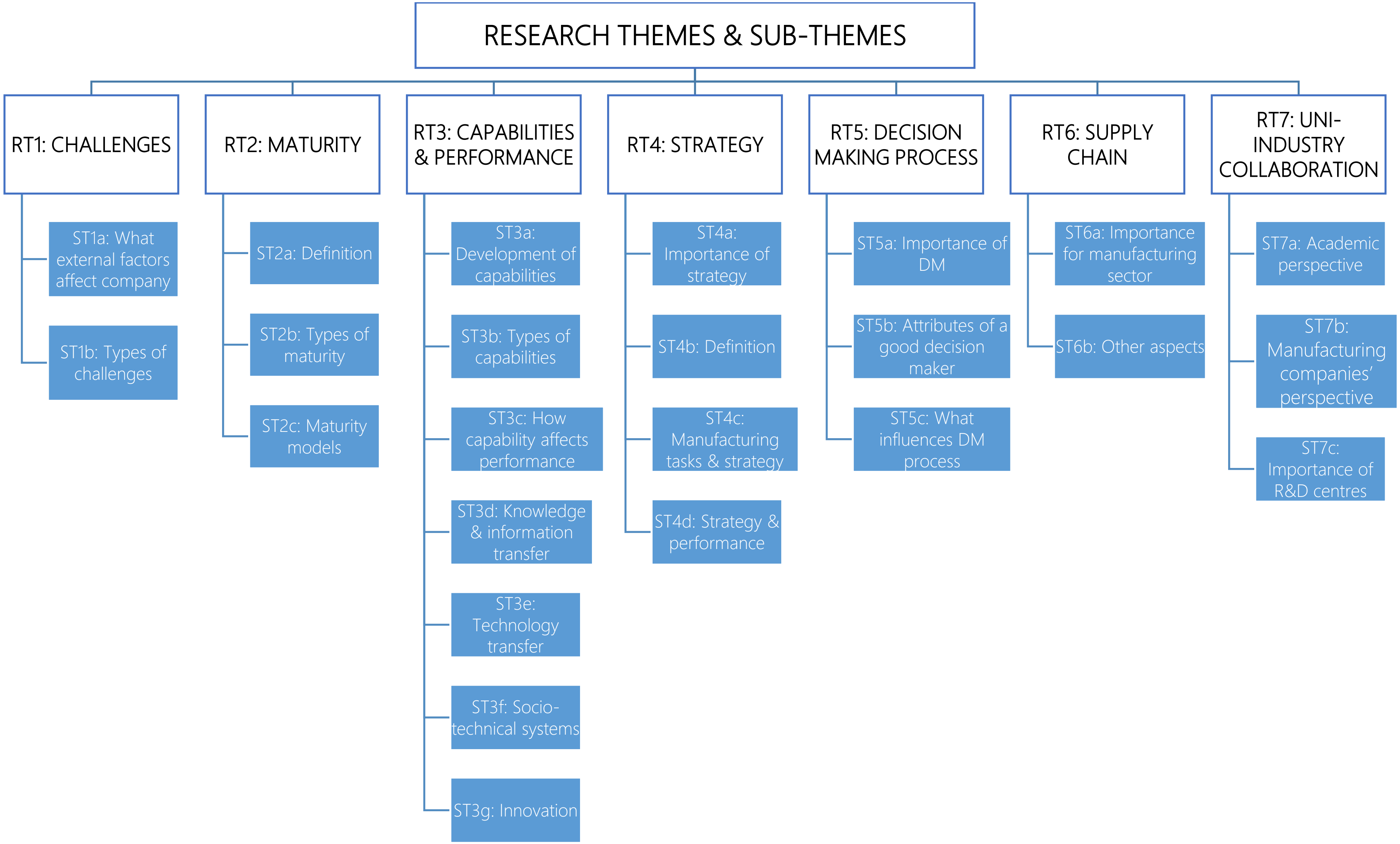


Figure 2.3: Research themes and their sub-themes identified in SLR

Identifying research themes and sub-themes helped to understand what kinds of investigation related to capabilities in the manufacturing sector was already performed; and what are the existing knowledge gaps in the literature. It also helped to highlight how this study contributes to the definition and assessment of capabilities of research centres. Moreover, Table 2.2 shows a distribution of research themes throughout selected journals. By creating Table 2.2, it was possible to observe which journal contained more information about each research theme. The biggest contributor is Journal of Operations Management. This journal covers a broad spectrum in relation to research theme 1b (types of challenges), 3b (types of capabilities) and 3c (how capabilities explain performance). The second and third biggest contributors were Journal of Management Studies and CIRP Annals - Manufacturing Technology. Journal of Management Studies contributed mostly to the research theme 5b (attributes of decision makers) and CIRP Annals - Manufacturing Technology – to research theme 1b (types of challenges). The full version of Table 2.2 is included in Appendix 1.

Table 2.2: Categorisation of identified journals by research themes recognised through systematic literature review

Journals/Research Themes	ST 1a	ST 1b	ST 2a	ST 2b	ST 2c	ST 3a	ST 3b	ST 3c	ST 3d	ST 3e	ST 3f	ST 3g	ST 4a	ST 4b	ST 4c	ST 4d	ST 5a	ST 5b	ST 5c	ST 6a	ST 6b	ST 7a	ST 7b	ST 7c
Journal of Operations Management	15	20	7		6	11	28	21	10	9	18	17	4	3	7	14	8	12	5	5	3	2	6	9
The Journal of Technology Transfer	5	11	6		6	2	5	4	3	3		3	2			1	1	1	3	1		8	3	9
Journal of Management Studies	1	5			1	3	4	6	8	1	1	4	6	4	1	6	2	13	3				2	
International Journal of Production Economics	4	9	3	1	6	4	14	3	1	3	2		3		4	2	3		5			1		2
California Management Review	2	18			1	2	11	2	5	2	4	2	4	1	1	2		5	2			1	1	2
CIRP Annals - Manufacturing Technology	3	22					9	1	2		2		2			2	3		7	2			2	1
Journal of Product Innovation Management	1	9				1	11	2	7	1		6	2			1	2	4				1	3	2
Management Science	2	5	2		3	1	4	1	8		1	2	1			1	2	13	1	1			1	2
International Journal of Management Reviews	4					2	9	2	6		1	7		1		1	1							
British Journal of Management	1	2			1	2	11	2	2	1	3	2				1	1	3				1	2	
Journal of Management	1	5		1			5	1	1		1	1	2	1		2	3	6	1				2	2
Academy of Management Journal		3			1	1	2	3	3		3	3					1	1	1			1		
Academy of Management Perspectives		5	1				1				2	3						3				1	2	3
Technological Forecasting and Social Change	1	1				1	3	1		1		1			1				1		1			
Technovation						1	4		1	1	1				2	1	1	1				1		

2.4 SLR findings

The focus of this section is on previously mentioned research themes (RT). Each of the RTs is described here, together with its sub-themes (ST). Examples from literature are also included to support relevant RTs and ST.

2.4.1 Categorisation of identified research themes in the literature

2.4.1.1 RT1 - Challenges

114 papers were dedicated to Research Themes 1 (RT1) – Challenges. Papers that discuss this topic underline external challenges (RT1a) (e.g. megatrends, market fluctuations) that would influence company's decisions. Some papers also underline that those external factors create a need for "leading companies to continuously fit their capabilities to environmental changes" (Paiva, et al., 2008). Another subcategory in this RT is what kind of challenges (internal and external) various companies actually have to face (RT1b). An example of such challenges would be understating of organisation's operations, limited knowledge about company's own capabilities and how they interrelate to each other, or inadequate knowledge of external factors that could affect organisation's position on the market. Those examples were described by (Machado, et al., 2017), (Fuchs, et al., 2000).

2.4.1.2 RT2 – The Concept of Maturity

57 articles were dedicated to the concept of maturity (RT2). As maturity could relate to many different ideas, literature provides examples of maturity of products and processes (Williams, et al., 1995), (Drejer & Riis, 1999), (Mikkola, 2001), (Harter, et al., 2000), technology (Stock & McDermott, 2001), (Druilhe & Garnsey, 2004) or even industry (Flynn & Flynn, 2004). Therefore, when referring to maturity, one has to be very careful what type of maturity is being described. However, only five papers discussed in detail how concept of maturity affects manufacturing sector. Those papers also discussed what is needed to capture the idea of maturity (RT2b), i.e. the concept of maturity cannot be arbitrary and "the main task is to give meaning to a set of mapped practises in order to relate them to a maturity framework" (Machado, et al., 2017). Moreover, in different sectors, maturity has become an important characteristic, that capability maturity models had to be introduced in order to measure and assess various internal capabilities of a company. For example, according to (Machado, et al., 2017) "maturity models are being applied in different areas such as: quality management (Crosby, 1979), software development (Paulk et al., 1993), supplier relationship (Macbeth and Ferguson, 1994), R&D effectiveness (Swkonyi, 1994), products development (Mcgrath, 1996), innovation (Chiesa et al., 1996), product design (Fraser et al., 2002), collaboration (Fraser and Gregory, 2002) and product reliability (Sander and Brombacher, 2000)".

Therefore, literature sources confirmed that maturity models have been used by different industrial companies and in many different aspects. However, it should be highlighted that each industry (or company) seems to have its own maturity capability model. In that case it could be assumed that depending on the industrial sector and the organization (as each organisation would consider different drivers in order to achieve certain outcomes), capability models would differ from each other. In addition, organisations' vision and values would need to be implemented within the model, i.e. a capability maturity model should acknowledge or help to highlight company's goal, i.e. what it wants to achieve by certain actions.

Furthermore, not every company would have the same objectives. Hence, when creating a capability maturity model, the requirements of an organisation's strategy have to be clearly described in order to create a valuable model. Thus, majority of models described in the literature depend on the organisations' internal capabilities, external factors that affect organisation's performance (i.e. challenges) and also processes that are used in order to improve performance.

2.4.1.3 RT3 – Capability & Performance

113 papers were dedicated to the subject of capability and performance (RT3). Various aspects of capability e.g. development of capabilities (Heimeriks & Duysters, 2007) or types of capabilities (Peng, et al., 2008) were described. The type of capability discussed in a paper was based on 1) type of journal (management or manufacturing) and 2) what type of company is being described (services or product developers/manufacturers or universities). Even though, types of capabilities may differ across the sectors, some similarities in regards to how capabilities influence company (and its performance) (RT3c) were identified (e.g. (Fuchs, et al., 2000), (Paiva, et al., 2008), (Machado, et al., 2017), (Brouthers & Hennart, 2007), (Newey & Zahra, 2009)).

As recognition and development of capabilities (for a company and/or research centre) is a very important aspect, a definition of capabilities need to be adapted in this research. That is described in section 2.5.

Also, in order to develop some capabilities, or to improve the performance external and internal data needs to be transferred between the departments, i.e. a cross –functional activities need to be performed in order to improve collaboration between departments, but also to include lessons learnt between employees. If lessons learnt are not shared between the departments or teams, the possibility of repeating the same or similar mistakes will increase (Heimeriks & Duysters, 2007), (Kim, et al., 2012), (Newey & Zahra, 2009). Therefore, there should be a good flow of knowledge and information transfer (RT3f) between teams.

According to (Paiva, et al., 2008) it is possible to distinguish between what impact information has on company's activities, and the impact of knowledge. In this case, knowledge is considered as more significant factor, but at the same time, information should not be neglected. Hence, there should be a balance between what type of information is passed on (as not all information is significant) and what kind of impact it has on the work of a department/company.

On the other hand, having or not having efficient knowledge affects a lot of decisions, i.e. what type of equipment is/will be operated in the company (especially in the manufacturing sector). Therefore, another important aspect that was mentioned in the literature sources was technology transfer and technology management. Some authors, e.g. (Rosenzweig, et al., 2003), (Arana-Solares, et al., 2019), (Liu, et al., 2019), (Fini, et al., 2019), described how important is technology transfer, but also how technology (and innovation) management is important for companies in order to keep their competitive advantage. In addition, to keep high level of performance, technology needs to be assessed regularly. Even though equipment/machines/software and technology play significant role in the manufacturing sector, it is not the only important thing. Without motivated and experienced team, a company is unable to use its equipment in the most efficient manner. Therefore, socio-technical systems (i.e. employees and equipment) are considered as the most important characteristics of an organisation (Fuchs, et al., 2000), (Miller & Lee, 2001), (Kim, et al., 2012).

Without socio-technical systems, innovation processes would not take place and new ideas wouldn't be created. And that is what sub-theme RT3g focuses on. For example (Kim, et al., 2012) discussed the aspect of innovation and how important it is for some companies, but also what capabilities are chosen in order to encourage innovation increase. Also the cross-functional collaboration within the company would only increase the chances of designing innovative ideas- as described in RT3d.

Therefore, it is clear how internal (i.e. core) capabilities influence the performance of a company. Unfortunately, in the selected literature, there were not enough examples that discuss capabilities, or performance of research centres. For that reason, it was difficult to examine if similar capabilities or activities take place in a research centre environment. It was assumed that 1) a location of a research centre, 2) type of research centre (i.e. what technologies and processes it concentrates on) and 3) level of collaboration with other institutions/organisations would influence what type of capabilities an innovation provider has and should develop (just as those aspect affect the development of capabilities in industry.

2.4.1.4 RT4 – Strategy

Depending on size, type and goals of organisations, different strategies are used, meaning that practices and procedures that work in one company might not bring the same results in somewhere else. That is why a suitable strategy needs to be selected and properly implemented in every organisation (RT4). 101 papers discussed this aspect. RT4a explains the importance of strategy (e.g. (Paiva, et al., 2008), (Gravonski, et al., 2012), and RT4b consist of different authors who offered their own definition of 'strategy.'

Next step was to examine how manufacturing aspect fits into the overall strategy of an organisation (RT4c) ((Paiva, et al., 2008), (Ettlie & Rosenthal, 2011)), and how that process "is therefore a result of resources alignment, including information, knowledge and company's functions" (Paiva, et al., 2008). Also RT4d discussed the impact of the strategy on the company, but also the connection between strategy and performance. Some literature sources also discussed successful and unsuccessful strategies and their consequences (e.g. (Fuchs, et al., 2000), (Machado, et al., 2017), (Paiva, et al., 2008)).

2.4.1.5 RT5 – Decision Making Process

Some strategies depend on the type of leadership, but more importantly on the decision-making processes, which was another research theme found in the literature – RT5. Decision-making processes seemed to be another big area of academic interest as 101 articles related to this RT were identified. This RT was divided into three subcategories: importance of decision-making (27) – RT5a, attributes of a good decision maker (44) – RT5b, factors that influence decision making processes (13) – RT5c. In addition, other aspects related to decision making process (e.g. criteria for selecting a technology or decisions related to product) were discussed in 18 articles.

There are different attributes of a good decision maker (e.g. previous experience), but it is also important to show to employees how certain decision was made, and how the 'path/process' to that decision looked (e.g. (Mellahi & Wilkinson, 2004), (Rosenzweig, et al., 2003), (Paiva, et al., 2008), (Peng, et al., 2008), (Newey & Zahra, 2009)). Hence, open communication with a team affects the willingness and motivation with which a task is performed. Furthermore, (Brouthers & Hennart, 2007) presented two schools of thoughts in regards to what influences decision-making process:

- "decisions are influenced by the managerial background and experience of the decision-making team or of individual decision makers" (i.e. RT5b)
- "strategic decisions are influenced by the decision-making process. The line of research examines the components of this process and how the execution of these components influences the performance of decision outcomes. In general, these studies find that managers who use more formal decision making processes make better decisions" (i.e. RT5c).

2.4.1.6 RT6 – Supply Chain

While making decisions or creating a long-term strategy, external information should also be considered. Hence, understanding of various aspects of supply chain is important (RT6a) but it is specifically important for manufacturers (RT6b). According to (Brusset & Teller, 2017) supply chains "represent vertical inter-organizational networks of firms that are closely linked to their up-stream and down-stream supply chain partners." Hence, even small disturbances in the supply chain would affect manufacturing process. Therefore, the importance of having sustainable, but also reliable supply chain is crucial ((Rosenzweig, et al., 2003), (Machado, et al., 2017)). Once development process begins, appropriate resources have to be available in order to continue the work within an agreed timeframe. If there are any delays, the completion date of each stage of production is delayed. 16 articles discussed the supply chain aspect in this SLR.

2.4.1.7 RT7 – University – Industry Collaboration

Lastly, collaboration between academia and industry (RT7) was described. As research centre perspective was not exclusively discussed in any of the articles included in this study, it was decided that a comparison between academic perspective (RT7a) (e.g. (Fischer, et al., 2017)), and industrial/manufacturing perspective (RT7b) (e.g. (Graff, et al., 2002)) should be included. 33 papers identified importance of research centres/hubs/departments (as part of a company) and that became the last RT in this study – RT7c. The main purpose of research centres, identified by the literature, was "to bridge the gap between the academic and industrial sectors of the R&D economy" (Graff, et al., 2002). However, the topic of how successful research centres are at bridging the valley of death was not discussed in the literature.

2.4.2 Summary of Research Themes (RT)

Table 2.3 represents the categorisation of literature sources related to each research topic identified, as discussed above.

Table 2.3: Summary of research topics classification identified in SLR

RT and its sub-themes		Summary of sub-themes (ST)	Frequency of papers	Literature examples
RT1: Challenges	**1a**: What external factors affects company	What external circumstances affect company; how different trends and drivers affect companies and impact new priorities	42	(Lee & Kang, 2017), (Machado, et al., 2017), (Kalkan, et al., 2014), (Mikkola, 2001), (Koufteros, et al., 2002), (Leischning & Geigenmüller, 2020), (Magistretti, et al., 2020), (Linde, et al., 2021)
	1b: types of challenges	For example: Lack of knowledge about company's own capabilities; integration of capabilities; how internal capabilities can deal with external threats,	125	(Alexander, et al., 2020), (Braglia, et al., 2008), (Cukier & Kon, 2018), (Fainshmidt, et al., 2019), (Fini, et al., 2019), (Vrchota & Rehor, 2019), (Huang, et al., 2019), (Silva, et al., 2019), (Magistretti, et al., 2020), (Kosiedzka, 2017), (Dwivedia, et al., 2020)
RT2: Maturity	**2a**: definition and understanding of maturity	"maturity (…) as the development in each domain of a specific profession or area of an organization" (Ifran, et al., 2019)	20	(Harter, Krishnan, & Slaughter, 2000), (Mikkola, 2001), (Druilhe & Garnsey, 2004), (Ifran, et al., 2019), (Huang, et al., 2019), (Chapman, 2019), (Moehrle, et al., 2017)
	2b: types of maturity	What types of measurement system is needed for organizations; characteristics of such measurement system (simple etc.);	9	(Domingues, et al., 2016), (Moehrle, et al., 2017), (Machado, et al., 2017), (Silva, et al., 2019), (Olechowski, et al., 2015), (Ge, et al., 2020), (Cyfert, et al., 2020), (Issa, et al., 2018), (Noh, et al., 2018)
	2c: maturity models	Maturity models discussed as improvement processes in industry; different sectors where maturity models were used;	36	(Noh, et al., 2018), (Lecluyse, et al., 2019), (Chapman, 2019), (Sanchez, et al., 2018), (Schwabe, et al., 2021), (Olechowski, et al., 2015), (Ge, et al., 2020), (Kosiedzka, 2017), (Issa, et al., 2018), (Ferradaz, et al., 2020)
RT3: Capabilities & Performance	**3a**: development of capabilities	Measuring capabilities, and how they can be improved	40	(Liu, et al., 2019), (Sanjay, et al., 2020), (Schoemaker, et al., 2018), (Qi, et al., 2020), (Enkel, et al., 2020), (Magistretti, et al., 2020)
	3b: types of capabilities	Resources, routines and capabilities; 'bundles' of routines; organisational capabilities, dynamic capabilities, technological	135	(Esmaeel, et al., 2018), (Ojha, et al., 2020), (Vrchota & Rehor, 2019), (Toomey, et al., 2019), (Qi, et al., 2020), (Schoemaker, et al., 2018), (Sanjay, et al., 2020), (Mikalef, et al., 2020), (Lee, et al., 2020), (Linde, et al., 2021)
	3c: how capability affects performance	Alignment between capabilities affects performance of company, examples of well integrated capabilities, when to know when it is time to make changes	60	(Machado, et al., 2017),(Chavez, et al., 2017), (Becker, et al., 2015), (Cukier & Kon, 2018), (Ferreira, et al., 2020), (Toomey, et al., 2019), (Cyfert, et al., 2020), (Tunca & Kanat, 2019), (Vrchota & Rehor, 2019), (Shenoy, et al., 2019), (Liu, et al., 2018), (Silva, et al., 2019), (Sena, et al., 2019), (Magistretti, et al., 2020)
	3d: knowledge & information transfer	Experience; lessons learnt, difference between information and knowledge; cross functional approach;	62	(Kim, et al., 2012) (Newey & Zahra, 2009), (Koufteros, et al., 2002), (Srivastava & Gnyawali, 2010), (Alexander, et al., 2020), (Li, et al., 2019), (Rajalo & Vadi, 2017), (Liu, et al.,

		training and understanding of job and responsibilities		2018), (Patón-Romero, et al., 2019), (Enkel, et al., 2020), (Lee, et al., 2020)
	3e: technology transfer	Technological development and advancements and its benefits	25	(Lee, et al., 2007), (Arana-Solares, et al., 2019), (Shenoy, et al., 2019), (Good, et al., 2019), (Olechowski, et al., 2015), (Magistretti, et al., 2020), (Akkaya & Tabak, 2020)
	3f: socio-technical systems	How equipment and human capital complement each other and how important is that alignment for various aspects of companies	41	(Miller & Lee, 2001), (Kim, et al., 2012), (Cadorin, et al., 2019), (Kalkan, et al., 2014), (Mikkola, 2001), (Drejer & Riis, 1999), (St John, et al., 2001), (Li, et al., 2019), (Liu, et al., 2018), (Arana-Solares, et al., 2019)
	3g: innovation	Importance of innovation	53	(Kim, et al., 2012), (Kalkan, et al., 2014), (Miyazaki & Islam, 2007), (Srivastava & Gnyawali, 2010), (Fini, et al., 2019), (Sminia, et al., 2019), (Spring, et al., 2017), (Qi, et al., 2020), (Magistretti, et al., 2020)
RT4: Strategy	4a: importance of strategy	Importance of strategy for industrial companies	29	(Mikkola, 2001), (Liu, et al., 2005), (Alexander, et al., 2020), (Fainshmidt, et al., 2019), (Hitt, et al., 2016), (Leischning & Geigenmüller, 2020), (Enkel, et al., 2020)
	4b: definition of strategy	Understanding of strategy	10	(Fuchs, et al., 2000), (Stock & McDermott, 2001), (Andersen, 2004), (O'Regan, et al., 2006), (Harreld, et al., 2007), (Kalkan, et al., 2014), (Fainshmidt, et al., 2019)
	4c: manufacturing tasks & strategy	How manufacturing tasks affect strategy; how well defined strategy helps manufacturing companies	18	(Paiva, et al., 2008), (Ettlie & Rosenthal, 2011), (Liu, et al., 2005), (Li, et al., 2019), (Silva, et al., 2019), (Qi, et al., 2020), (Arana-Solares, et al., 2019), (Kumar, et al., 2020)
	4d: impact of strategy on company/strategy & performance	Examples of successful companies and how they achieve successful positions; consequences of static strategy planning	41	(Kalkan, et al., 2014), (Ferreira, et al., 2020), (Sminia, et al., 2019), (Liu, et al., 2018), (Qi, et al., 2020), (Issa, et al., 2018), (Shenoy, et al., 2019), (Arana-Solares, et al., 2019), (Enkel, et al., 2020)
RT5: Decision making process	5a: importance of decision making (DM)	DM process- how important is it and how it impacts company's performance and competitiveness	30	(Peng, et al., 2008), (Lee, et al., 2007), (Srivastava & Gnyawali, 2010), (Fainshmidt, et al., 2019), (Rajalo & Vadi, 2017), (Kumar, et al., 2020), (Dwivedia, et al., 2020)
	5b: attributes of decision makers	Characteristics of decision makers (managers); what type of skills should they have; where should they look for information; how they should communicate with their teams	64	(Mellahi & Wilkinson, 2004), (Rosenzweig, et al., 2003), (Peng, et al., 2008), (Newey & Zahra, 2009), (Mikkola, 2001), (Koufteros, et al., 2002), (Drejer & Riis, 1999), (Lee, et al., 2007), (St John, et al., 2001), (Gupta & Wilemon, 1996), (Fainshmidt, et al., 2019), (Schoemaker, et al., 2018), (Li, et al., 2019),
	5c: what influences DM process	Decisions are influence by managerial background and experience or by the DM process itself; challenges faced during DM process	31	(Brouthers & Hennart, 2007),(Alexander, et al., 2020), (Ifran, et al., 2019), (Li, et al., 2019), (Leischning & Geigenmüller, 2020), (Liu, et al., 2019), (Sena, et al., 2019), (Brusset & Teller, 2017), (Dwivedia, et al., 2020)
RT6: Supply chain	6a: importance for manufacturing	Importance of supply chains companies in the manufacturing sector	11	(Mikkola, 2001), (Rajalo & Vadi, 2017), (Brusset & Teller, 2017), (Rosenzweig, et al., 2003), (Machado et al., 2017), (St John, et al., 2001), (Ge, et al., 2020), (Tassey, 2010)
	6b: other aspects of supply chain	Challenges related to shortages or quality and they impact manufacturing sector	5	(ElMaraghy, et al., 2013), (Brusset & Teller, 2017), (Rosenzweig, et al., 2003), (Paiva, et al., 2008), (Wong, et al., 2011)

RT7: University-Industry collaboration	7a: academic perspective	Impact of university engagement and its relevance in manufacturing sector	18	(Fischer, et al., 2017), (Druilhe & Garnsey, 2004), (Leischning & Geigenmüller, 2020), (Alexander, et al., 2020), (Graff, et al., 2002), (Gupta & Wilemon, 1996)
	7b: manufacturing companies' perspective	Research and development performed by manufacturing companies	25	(Graff, et al., 2002), (Cadorin, et al., 2019), (Spring, et al., 2017), (Kalkan, et al., 2014), (Miyazaki & Islam, 2007), (Olechowski, et al., 2015), (Lecluyse, et al., 2019),
	7c: importance of research centres	The purpose, activities and importance of research centres	35	(Fini, et al., 2019), (Good, et al., 2019), (Leischning & Geigenmüller, 2020), (Corrocher, et al., 2019), (Kerry & Danson, 2016), (Cunningham, et al., 2020)

In general, majority of authors confirmed that identifying capabilities and their development (RT3) is one of the major steps for companies to perform well. Depending on which internal (core) capabilities company wants to develop (e.g. technological, organisational, strategic etc.) a certain plan of action has to be applied. By doing so, a company is able to achieve proficiency in that specific capability. What is more, development of capabilities starts with recognition of what are the strengths and weaknesses of a company, but also what are the challenges (RT1) that a company faces and what capabilities could be improved to overcome those challenges. For example, one of the challenges could be the complexity of manufacturing systems or the market changes that would affect future work of the company. That is why it is important for companies, but also for research centres, to understand what capabilities they have, how mature those capabilities (RT2) are and what should be 'next steps' related to improvement of core capabilities and how will that affect the performance of a company.

However, all case studies described in literature concentrate on industrial companies. That highlights academic gap and opportunity to study capability development in research centres. Hence, the evidence collected by literature review shows that topic of research centres (more precisely, the topic of manufacturing research centres) needs to be investigated in order to address that knowledge gap in the knowledge.

2.5 Discussion

Research centres differ from industry and academia. According to (Hauser, 2014), Catapult centres' aim is "**to close the critical gap between research findings and their subsequent development into commercial propositions**." Hence, research centres aim "to **'de-risk' innovation** by providing a range of services throughout the research and development cycle" (Kerry & Danson, 2016). However, "**capability is being developed for potential use by multiple end users on multiple applications**" (Ward, et al., 2017). It means that industrial companies might rely on research centres to deliver innovative solutions that they think are specific to a sector, but in fact **research centres need to apply their capabilities to various industrial requirements from multiple sectors**. That is why research centres need to know what they can deliver, and in order to do that they need to know capability maturity.

Therefore, research centres play critical role in addressing Valley of Death (VoD), and so they need to know how mature their capabilities are before taking on a project or committing to develop innovation. Nevertheless, literature sources do not offer any solution to address the problem of defining, measuring and evaluating capabilities of research centres.

The SLR aimed to uncover information related to capability, maturity and research centres. Through this process, seven key research themes were identified. However, considering the amount of articles dedicated to each RT, some RTs happened to be more common than others. For example, various aspects of capabilities (development and types of capabilities in different organisations) were described in 135 papers while only 10 papers described the importance of supply chain for manufacturing sector. It is easily explained by the fact that the topic of supply chain was out of the scope of this study and the SLR process was performed by the use of specific keywords. And even though journals from management and manufacturing field of study were used, most of them only mention the fact that supply chain is important to a manufacturing sector or provided explanation of what is understood by supply chain (ElMaraghy, et al., 2013), (Paiva, et al., 2008), (Kim, et al., 2012).

As previously mentioned, this SLR used specific keywords to identify relevant information needed to understand the topic of research centres in manufacturing and management literature. Considering findings from SLR, it is clear that the findings are not only helpful with research centre topic but also when considering other research domains. Figure 2.4 shows how this SLR contributes to other academic conversations. Figure 2.4 shows that the topic of research centre is in the middle of the lemniscate as it related to the topic of technology development, which links to Capability management and Performance capture, which links with Readiness and Maturity topics. That links back to the topic of Research Centres and links to conversation about Innovation, which also has an impact on Strategy management, which in turn affects Operational management. That links back to Research centre topic. In addition, this connection works even if the arrows are placed in the opposite direction.

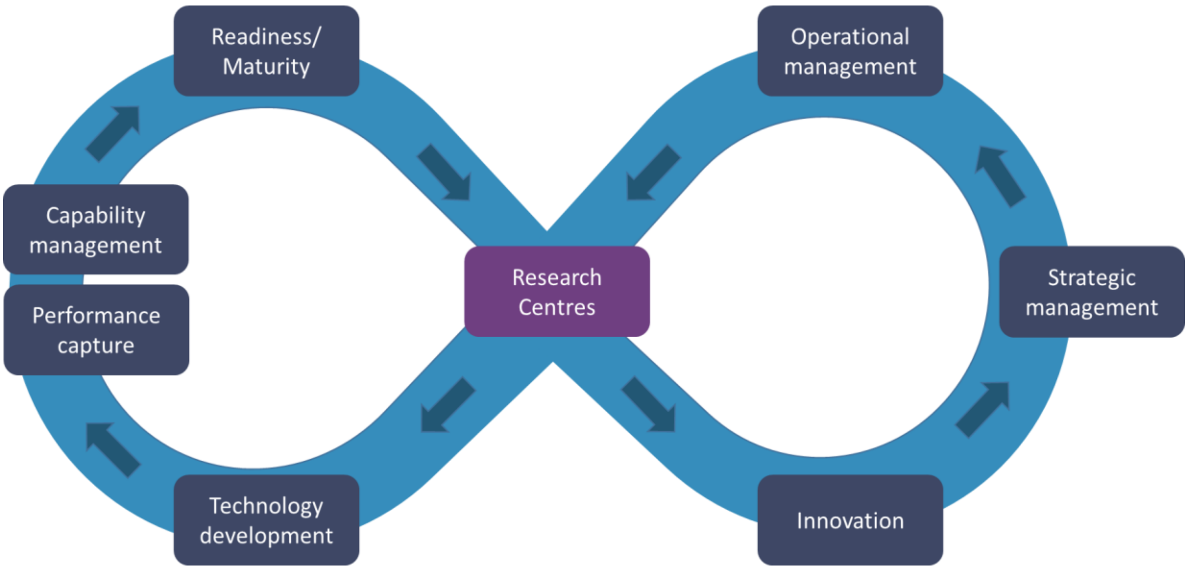


Figure 2.4: Relationship between various academic topics identified through this SLR and related to the topic of research centres

Keeping in mind that this research was conducted in the context of research centres and available maturity models (that are not currently used at research centres). Hence even though ST2c (maturity models) and ST7c (importance of research centres) were not investigated by many researchers (at the time of SLR), those two topics will be discussed in the next section. Therefore, the following sub-themes from SLR will be analysed in next sections:

- Section 2.5.1 Capabilities
    - ST3b: types of capabilities
    - ST3c: how capability affects performance
    - ST3d: knowledge & information transfer
- Section 2.5.2 Maturity models (ST2c)
- Section 2.5.3 Importance of research centres (ST7c)
- Section 2.5.4 Attributes of decision makers (ST5b)
- Section 2.5.5 Strategic decision making

2.5.1 Capabilities (ST3b, ST3c, ST3d)

HVM Catapults were created to help companies to develop new technologies that will overcome valley of death and reach the commercialisation stage. The main goal of HVM Catapults is to reduce level of risk and uncertainty, but also to support companies through the development process. As a result, research centres' involvement also contributes to UK economy and to a manufacturing sector, i.e. "high-income economy must be the high-tech economy" (Tassey, 2010).

However, to become more competitive, organisations need to understand their own capabilities. Understanding strong and weak capabilities will allow organisations to evolve and grow. Therefore,, few literature sources discussed the role of dynamic capabilities in industrial companies; e.g. (Hsu & Wang, 2012) mentioned that "large amounts of R&D investments accumulated by dynamic capabilities to maintain excellent research capabilities and state-of-the-art facilities are especially important for firms to build their technological competences." It means that companies with large investments in R&D create a significant knowledge base, which will help them build a competitive advantage. In addition, by expanding knowledge base, the performance will improve as well, as the understanding of technology will become greater in time, e.g. "the competitive advantage of a firm lies in its ability to create, transfer, assemble, integrate, and exploit knowledge assets" (Soo, et al., 2002). Various authors presented their own definitions of what dynamic capability (DC) means. Table 2.4 below contains some of the definitions of dynamic capabilities found in the literature. The full version of Table 2.4 is in Appendix 2.

Table 2.4: Definitions of dynamic capability – Examples from literature

Definitions	Authors
Dynamic capabilities, which we define as the ***abilities to reconfigure a firm's resources and routines*** *in the manner envisioned and* ***deemed appropriate by its principal decision-maker****(s).*	(Zahra, et al., 2006)
The essence of ***dynamic capabilities is a firm's behavioural orientation in the adaptation, renewal, reconfiguration and re-creation of resources,*** *capabilities and core capabilities responding to external changes.*	(Wang & Ahmed, 2007)

Dynamic capabilities are seen as the firm's ***ability to integrate and change resource bases*** *to address changing environments. Thus, dynamic capabilities can be seen as those* ***processes where resources are acquired, integrated, transformed or reconfigured to generate new value-creating firm-based activities.***	(McKelvie & Davidsson, 2009)
Dynamic capability has been defined as 'the ***capacity of an organization to purposefully create, extend, or modify its resource base*** *(Helfat, 2007, p. 1)'. The dynamic capabilities literature also points out that these capabilities are* ***identifiable organizational processes**, **which are firm specific**, but also* ***share commonalities among firms facing similar environmental conditions***	(Malik & Kotabe, 2009)
Dynamic capabilities are based on collections of organizational routines *and* ***need to be understood as multidimensional constructs*** *(Winter, 2003), reflected by a set of specific routines that represent their dimensions. The term* ***routines refers to rule-based behavioral patterns for interdependent corporate actions***	(Schilke & Goerzen, 2010)
Moreover, ***dynamic capabilities are a source of sustainable competitive advantage when*** *they are* ***based*** *on a configuration of* ***useful skills, resources, and competencies****.*	(Slater, et al., 2014)
Dynamic capabilities are (…) ***a concrete set of mechanisms that help managers address the fundamental question of strategy****, which is to develop a truly sustainable* ***competitive advantage****.*	(Harreld, et al., 2007)
Dynamic capabilities are ***a learned pattern of collective activity and strategic routines through which an organization can generate and modify operating practices to achieve a new resource configuration and achieve and sustain a competitive advantage*** *(Teece et al., 1997, Teece, 2007).*	(Brusset & Teller, 2017)
Dynamic capabilities enable firms to ***identify profitable configurations of competencies and assets, assemble and orchestrate them, and then exploit them with an innovative and agile organization.*** *(…) dynamic capabilities help* ***identify new products and services****, potentially* ***opening new markets*** *where rivals have not yet appeared. Each type is important in different ways.*	(Schoemaker, et al., 2018)
In general, research on DCs is interested in ***how firms build and adapt their resource base to maximize organizational fit with the environment.*** *One of the distinctive features of the DC perspective is the notion that* ***such adaptation can be based on organizational routines - learned, repetitious behavioural patterns for interdependent corporate actions.***	(Ferreira, et al., 2020)
Dynamic capabilities under the capability-building ***mechanism can generate more sustained impacts on organizational performance by enabling firms to constantly renew, reconfigure, and recreate*** *the requisite resources and capabilities for responding to environmental changes*	(Lee, et al., 2020)

The DC theory concentrates on enabling companies to "identify profitable configurations of competencies and assets, assemble and orchestrate them, and then exploit them with an innovative and agile organization. (…) dynamic capabilities help identify new products and services, potentially opening new markets where rivals have not yet appeared" (Schoemaker, et al., 2018). In other words, dynamic capabilities help decision makers to "adapt, integrate, and deploy internal and external organizational skills, resources, and functional competencies to achieve alignment with the changing business environment" (Slater, et al., 2014).

A three-step DC framework was introduced by (Teece, et al., 1997) and (Teece, 2018). These three steps are explained below:

- Sensing concentrates on reviewing of new information and horizon scanning, i.e. reviewing current market changes for new trends and drivers.
- Seizing is about designing and refining of business models and committing resources to new opportunities.
- Transforming is about realigning structure and culture, which means that a firm will align its existing capabilities and as well as invest in additional capabilities in order to manage threats.

However, by reviewing definitions from literature (Table 2.4), it is clear that understanding of DC depends on point of view of each researcher, as they used various terms and terminology to explain what DCs are. For example: capacity, capabilities and organisational processes (Malik & Kotabe, 2009), abilities (Zahra, et al., 2006), organisational routines (Hsu & Wang, 2012), (Schilke & Goerzen, 2010), resources and capabilities (Wang & Ahmed, 2007), core capabilities (Wang & Ahmed, 2007), (Harreld, et al., 2007), a learned pattern of collective active and strategic routines (Brusset & Teller, 2017) , competencies and assets (Schoemaker, et al., 2018). Therefore, **there is a lot of uncertainties related to DCT due to the fact that researchers have different understandings of DCT** (Easterby-Smith, et al., 2009).

Furthermore, according to (Ferreira, et al., 2020), "the concept of DC (…) needs to be explored in SME companies. SMEs in dynamic or sometimes turbulent environments need to anticipate changes and react to them," which is also relevant to research centres. That is also confirmed by (Sanjay, et al., 2020): "young small firms may be more likely to benefit from a proactive approach to growth than from competitive aggressiveness, compared to larger, well-established firms (Lumpkin and Dess 2001), suggesting that they may be more likely to change when encountering environmental uncertainty." What is more, "DCs are far from being a well- defined construct based on a coherent theoretical tradition and validated with strong empirical evidence" (Vogel & Güttel, 2013).

Nevertheless, reviewed papers showed that there is **a clear lack of studies that will show how DCT applies to smaller companies and/or research centres.** Also, there is a need for more longitudinal studies that present implementation and practice of DC over longer period of time (Easterby-Smith, et al., 2009). Such studies would help with understanding of how DC help with development of dynamic capabilities and how they directly influence performance of a company. Moreover, "the creation and subsequent use of dynamic capabilities" depends on senior management team or firm's decisions makers (Zahra, et al., 2006). It means that if decision makers do not see benefits of developing dynamic capabilities, that development process will be stopped.

Another popular theory mentioned by literature was research based view (RBV). Table 2.5 shows definitions from various sources about RBV. The full version of Table 2.5 is in Appendix 3.

Table 2.5: Definitions of capabilities according to RBV – Examples from literature

Definitions	Authors
The RBV argues that firms process resources, a subset of which enables them to achieve competitive advantage, and a further subset of which leads to superior long-term performance.	(Wade & Hulland, 2004)
Tangible resources *can be seen as the* ***physical resources*** *such as plant, equipment, computers and machinery that* ***will allow a new product or service to be produced and/or distributed***	(McKelvie & Davidsson, 2009)
(…) ***resources (tangible and intangible) were bundled to create capabilities.*** *For example,* ***scientific equipment, technology and human capital are bundled to create a research and development capability****.*	(Hitt, et al., 2016)
The RBV suggests that competitive advantage can be ***obtained and sustained over time*** *from the* ***internal organization of resources*** *(Eisenhardt and Martin, 2000).* ***Resources in this context refer to anything that might be thought as strength (or weakness) to the firm such as assets, patents, brand names, capabilities, processes, attributes, distribution locations, information and knowledge****.*	(Chavez, et al., 2017)
These resources are ***tangible or intangible assets such as geographic location, factory equipment, a superior sales force and intellectual property****.*	(Liu, et al., 2018)
Resources include equipment, tools, materials, final products, and in this context also human resources*. The* ***physical assets and humans contain and possess data, information, and knowledge tangible that are important to be shared and processed.***	(Li, et al., 2019)

RBV posits that organizational resources encompass both ***asset-type resources (e.g., physical assets)*** *and* ***capability-type resources (e.g., human capital)***	(Lee, et al., 2020)
The RBV explains that the basis for the competitive advantages of a firm lies primarily in the ***application of the resources at the firm's disposal*** *(Barney, 1991).* ***Resources refer to tangible and intangible assets, such as money, people, technology, routines, knowledge and relationships, that are inherent to a firm*** *(Peteraf, 1993). Firms are heterogeneous and have different capabilities because they have* ***unique bundles of resources*** *(Peteraf, 1993),* ***which are valuable, difficult to imitate or substitute and rare.***	(Qi, et al., 2020)
Resources are "stocks of available factors that are owned or controlled by the firm" *whereas capabilities define a firm's* ***"ability to deploy its resources, usually in combination, using organizational processes to achieve some desired end result"*** *(Amit and Schoemaker, 1993, p. 35).*	(Ojha, et al., 2020)

Similarly, to DC, the issue presented by RBV is "is to define what is meant by a resource. **Researchers and practitioners interested in the RBV have used a variety of different terms** to talk about a firm's resources, including competencies (Prahalad and Hamel 1990), skills (Grant 1991), strategic assets (Amit and Schoemaker 1993), assets (Ross et al. 1996), and stocks (Capron and Hulland 1999)" (Wade & Hulland, 2004). Hence, as definition of 'resources' varied depending on the understanding of researchers, the differentiation between capabilities and resources was not clear (Hitt, et al., 2016).

Also, as (Liu, et al., 2019) highlighted, "merely possessing resources cannot maintain a sustainable competitive advantage. Resources, in fact, tend to be tradable in markets, and few of them can be productive on their own." It links with another challenge of RBV which is a process showing how key resources directly benefit a firm; according to (Wade & Hulland, 2004) this aspect was poorly specified in the RBV."

Using literature findings (identified in Table 2.4 and 2.5), a definition of resources and capabilities is presented below:

Resources *can be defined as "****anything tangible or intangible*** *the firm can use in its processes for* ***creating, producing, and/or offering its products (goods or services)*** *to a market," while* ***capabilities*** *denote "****repeatable patterns of actions in the use of assets to create, produce, and/or offer products to a market****"* [(Wade & Hulland, 2004) in] (Lee, et al., 2020).

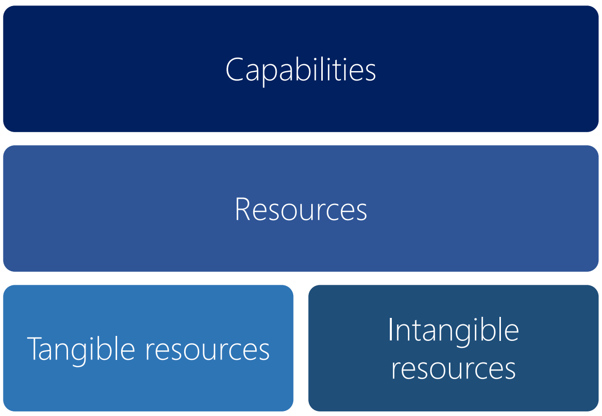


Figure 2.5: Relationship between resources and capabilities

Therefore, resources are understood to be **tangible or intangible** (Chavez, et al., 2017) bundles that together create capabilities (Hitt, et al., 2016). Those bundles "are valuable, difficult to imitate or substitute and rare" (Qi, et al., 2020). Using those resources, firms capabilities become unique and difficult to imitate, as they are developed internally. Hence, Figure 2.5 shows the connection between resources and capabilities in the industrial context (based on the literature findings).

Relationship between capabilities and resources presented in Figure 2.5, has so far been discussed from an industrial perspective. Therefore, it shows the need for exploring those approaches from SMEs perspective, smaller companies, as well as research centres.

SLR also provided many definitions of various types of capabilities (which are presented in Table A1, Appendix 4). Figure 2.6 shows summary of those findings. Literature provided a lot of evidence that technology and human capability are the two basic fundaments that are essential for research and development as well as high performance of any company. As mentioned by (Hitt, et al., 2016), "*scientific equipment, technology and human capital are bundled to create a research and development capability*." Therefore, technology and human capability are major contributors of research and development, and so, within those two capabilities, tangible and intangible resources will need to be identified.

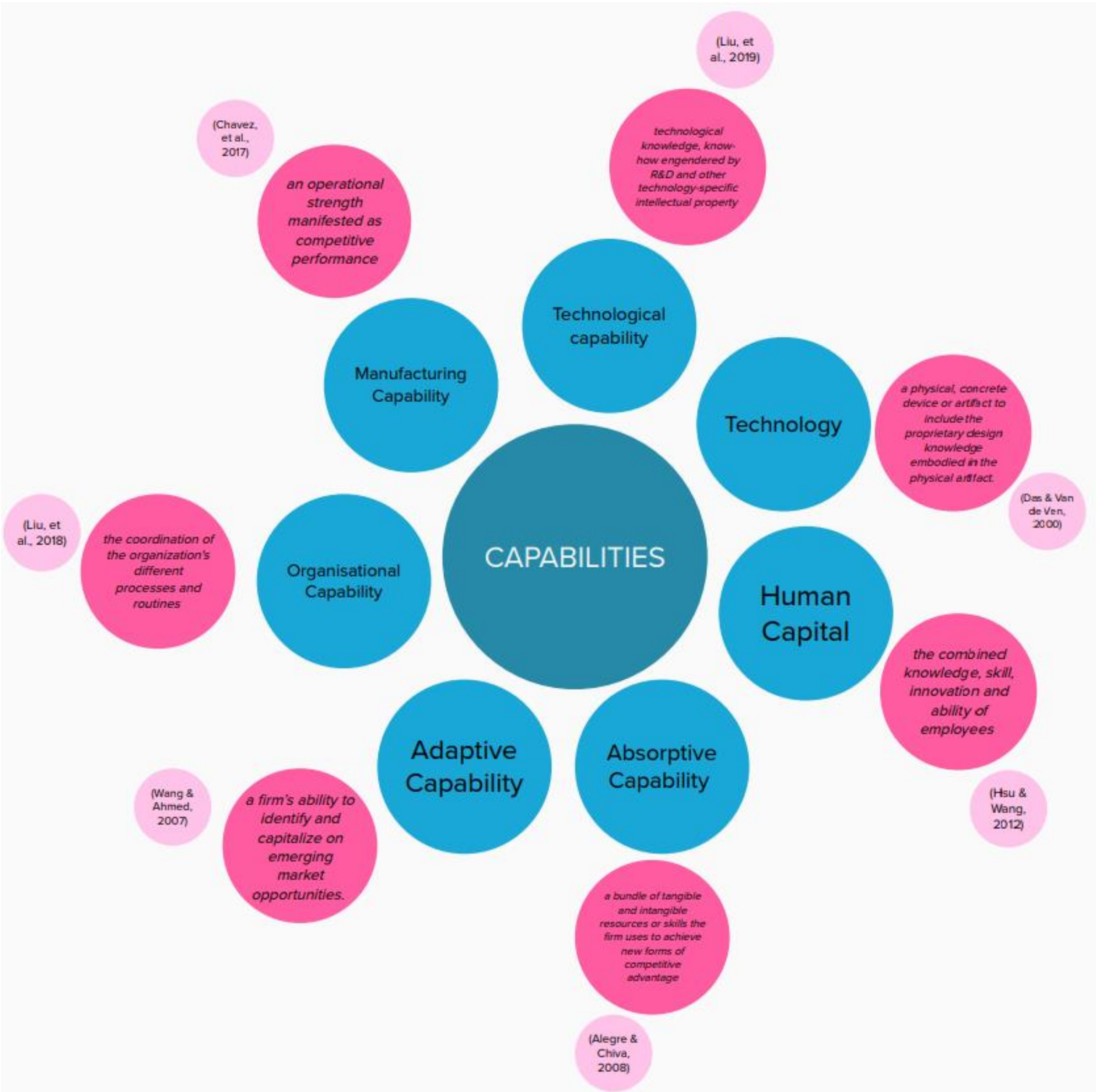


Figure 2.6: Capabilities - examples from literature (based on Table A1, Appendix 4)

On the other hand, findings from literature do not highlight which capabilities are based on tangible or intangible resources. Hence, it was assumed that

- *"equipment, tools, materials, final products, and in this context also human resources"* (Li, et al., 2019) are **tangible resources,**
- *knowledge, "excellent problem-solving skill and the ability to make effective decisions"* (McKelvie & Davidsson, 2009), *"multiple skill sets"* (Zhang, et al., 2003) are **intangible resources**

Skills and knowledge can be further divided into "technological knowledge, know-how (...) and other technology-specific intellectual property" (Liu, et al., 2019). Furthermore, "a firm's resources, particularly intangible ones, are more likely to contribute to the firm's attaining and sustaining superior performance" (Hsu & Wang, 2012). Therefore, it is assumed that in order to stay competitive, an organisation concentrates on tangible assets. However, an organisation has to also understand and manage its own intangible resources, which might take years.

According to RBV, companies can develop specific (tangible and intangible) resources that would (eventually) give a company a competitive advantage (as those resources are rare and valuable and not accessible to any other company). By using those resources and transforming them into capabilities in order to create competitive advantage, an improvement in performance would also be observed (Eddleston, et al., 2008), (O'Regan, et al., 2006).

Literature showed that "merely possessing resources and capabilities does not guarantee the development of competitive advantages. **There is a need for the resource and capability configurations that help firms to achieve a long-term comparative advantage**" (Liu, et al., 2018). To understand such a configuration, a suitable measurement solution needs to be created. For that reason, maturity models are discussed next.

2.5.2 Maturity models (ST2c)

At first maturity models were developed to "reduce defects and increase efficiency through greater focus on organisational practices" (Cyfert, et al., 2020). First maturity model was developed in 1970s, however only in 1980s, there was a growing interest especially after CMM (Capability Maturity Model) was introduced (Cyfert, et al., 2020). The CMM, which was later transformed into CMMI (Capability Maturity Model Integration) (Patón-Romero, et al., 2019), (Huang, et al., 2019), (Silva, et al., 2019), "laid the foundation for many other maturity models" (Moehrle, et al., 2017) in many different research areas, e.g. not only in software engineering but also in business management, risk management: RM-CMM (Domingues, et al., 2016), supply chain management: $SC(M)^2$ – Supply Chain Maturity Model (Domingues, et al., 2016) or project management: (OPM3®) - Organizational Project Management Maturity Model (Silva, et al., 2019).

Literature sources also mention the importance of maturity models in project-based organisation: "maturity models are particularly important in **project-oriented organizations in order to achieve more effectiveness and efficiency.** (...) Processes that depend on the interaction of individuals can be difficult to quantify" (Silva, et al., 2019). That could be one of the reasons why a maturity model dedicated to research centres has not been developed yet. In order to do so, a definition of maturity needs to be introduced first.

According to (Moehrle, et al., 2017), "the basic idea of maturity models consists in the description of key processes or key capabilities in different maturity levels. Following this basic idea, the objectives of maturity models are the determination of the current situation, the identification of measures for further development, and the implementation of benchmarking." Therefore, the maturity models aim to identify strengths and weaknesses of 'current situation' i.e. in the context of research centres that would mean identifying capability gaps and starting discussion on how to improve 'current situation'. Also, it is important highlight that "it is not necessary for a company to aim at the highest maturity level, but merely for the maturity level which best suits its resources" (Moehrle, et al., 2017). Furthermore, the term maturity model "can be defined as a set of sequential levels that, together, describe an anticipated, desired or logical path, from an initial stage to a final maturity stage" (Domingues, et al., 2016).

Therefore, a maturity model should be created based on research centres' qualities, structure and aims, as maturity models are critical in project-based organisations (as mentioned previously). However, literature does not mention maturity models that are currently used in a research centre environment. Some of the maturity models/solutions applied in the industry are presented in Table 2.6 below. The full version of Table 2.6 is in Appendix 5.

The one issue related to maturity solutions mentioned in literature, that should be highlighted is the concern of subjectivity of data provided into maturity models: "Although standardized processes can guarantee the quality of products to a certain extent, when it comes to links that require executive staff to judge subjectively or actively contribute their experience and wisdom, the subjective initiative of the individual can influence the effects of process execution; for example, in the quality assessment audit process, review process, testing process, etc., Therefore, it is necessary to consider people-orientation in these processes. How to motivate people's subjective initiative, invest more detailed and serious work status for the project, and improve the effect of people's implementation of the normative process. This is also crucial for improving product quality, but there is no corresponding process area in CMMI that corresponds to personnel management. This is another deficiency of CMMI" (Huang, et al., 2019). Therefore, it is important to consider above aspects when creating new solution for research centres.

To manage capabilities effectively, a suitable and relevant maturity solution has to be implemented. Different companies will use various tools depending on the nature of business and organisational structure of a company. Table 2.6 presents some of the management tools/methods mentioned in the literature. It also includes disadvantages of those tools and at the same time explains why they cannot be applied in a research centre environment.

Table 2.6: Examples of maturity models/solutions identified in literature

<table>
<tr><th>Solution</th><th>Description</th><th>Disadvantages</th><th>Lit example</th></tr>
<tr><td>Technology Readiness Levels (TRL)</td><td>TRLs are "a type of measurement system used to access the maturity level of a particular technology" (NASA, 2012)
"Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the projects progress. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest" (Mai, 2012)
The TRL scale is regarded as an effective tool to help drive a successful deployment of technological, as well as manufacturing, systems (Islam, 2010)</td><td>It adds a degree of unnecessary ambiguity to a project, i.e. not accurate enough for some projects
It does not apply to system integration
"TRLs are context specific. A technology that is mature in one operating plant cannot be assumed to be as mature in a different one. Even those that appear the same might have significantly different operating conditions" (NDA, 2014)
It does not imply that the technology "will result in successful development of the system" (NDA, 2014)
"Operators use TRL (…) for tracking readiness of all equipment for installation. Every nut and bolt of every equipment is included in an Excel sheet. You can imagine such a spread sheet will become very large (Olechowski, et al., 2015)
"Despite this increase in uptake of practice, little research has been formally conducted to understand and describe TRL application" (Olechowski, et al., 2020)</td><td>(Lee, et al., 2007), (Islam, 2010), (NASA, 2012), (NDA, 2014), (Olechowski, et al., 2015), (Uflewska, et al., 2017), (Olechowski, et al., 2020)</td></tr>
<tr><td>Manufacturing Readiness Levels (MRL)</td><td>MRL 1-3: Pre-Concept Development (Innovation Stage)
MRL 4: Concept Development
MRL 5-6: Technology Development
MRL 7-8: Engineering and Manufacturing Development
MRL 9-10: Production and Deployment</td><td>"It describes today's position, without providing close support (…) in how to plan or execute a specific project or lower level task" (Ward, et al., 2012)</td><td>(Fernandez, 2010), (Ward, et al., 2012), (Uflewska, et al., 2017)</td></tr>
<tr><td>Manufacturing Capability Readiness Levels (MCRL)</td><td>MCRL 1-4: Conception and assessment of Manufacturing Technology
MCRL 5-6: Critical 'pre-production' phase, where expensive full-scale equipment and processes must be used but ahead of product launch, or factory
MCRL 7-9: implementation of the process on the shop floor, and also confirms volume production with assured quality</td><td>In relation to MCRL 4-6: "investment is high, but there is no certainty that (…) the proposed process will be successful" (House of Commons, 2013)
Size of the framework is overwhelming and it is time-consuming</td><td>(House of Commons, 2013), (Uflewska, et al., 2017)</td></tr>
<tr><td>Innovative Manufacturing Readiness Levels (IMRL)</td><td>IMRL 1: Understanding materials' properties at micro and nano-scale, technical and manufacturing strategy planning and detailed design
IMRL 2: Materials processing capabilities, validation, and component technologies dependencies
IMRL3: Adequacy and integration (scale-down challenges), system engineering, prototypes, and overall production preparation
IMRL 4: Combined systems tests, verification, inspection and trial production
IMRL 5: Overall systems are in operation, quality measurement and initial market audit</td><td>Applicable only to micro and nano-manufacturing technologies i.e. not applicable to large/medium technologies/products (due to specific parameters)
Practicability and applicability of this framework is still in question as it is a conceptual approach</td><td>(Islam, 2010), (Uflewska, et al., 2017)</td></tr>
<tr><td>Capability Maturity Models (CMM)</td><td>"Based on the specific software practices adopted, the CMM classifies the software process into five maturity levels. (…) "Maturity levels were associated with a software product based on the maturity level of the IT firm at the beginning of a product's design. The maturity level of a product</td><td>such tool has to be adjusted to the needs of specific industry and addresses common problems that affect multiple actors
subjectivity of data</td><td>(Harter, Krishnan, & Slaughter, 2000)</td></tr>
</table>

	that benefited from process improvements later in the product's life-cycle stages (e.g., coding stage) was assigned a commensurate increase in maturity level."		
Capability Maturity Model Integration (CMMI)	• *In the late 1980s, the software engineering community proposed the idea of improving product quality by controlling and improving software processes with reference to the way the manufacturing industry improved product quality by controlling and improving technological processes. Among such models, the most representative and widely used is CMMI* (Huang, et al., 2019) • *"CMMI divides an organization's research and development capabilities into five levels: the initial level, managed level, defined level, quantitative management level and optimization level."* (Huang, et al., 2019) • *The main objective of this model is to assess and improve the processes of organisations within the scope of the development, operation, and maintenance of information systems and software products.* (Patón-Romero, et al., 2019)	• *"Processes that depend on the interaction of individuals can be difficult to quantify. This leads to the evaluation results that vary according to the context in which they are applied"* (Silva, et al., 2019) • *"Although management and processes are emphasized in CMMI, it lacks corresponding norms and constraints for people who undertake management and processes."* (Huang, et al., 2019) • *"When it comes to links that require executive staff to judge subjectively or actively contribute their experience and wisdom, the subjective initiative of the individual can influence the effects of process execution; for example, in the QA audit process, review process, testing process, etc., Therefore, it is necessary to consider people-orientation in these processes."* (Huang, et al., 2019)	(Patón-Romero, et al., 2019), (Huang, et al., 2019), (Silva, et al., 2019)

Manufacturing companies include a great number of criteria when evaluating new technology and during the process of maturing the technology; that is why tools used by industry tend to be complicated and time-consuming mechanisms, as they have to consider many industrial details at each stage of commercialisation path. However, research centres are (in general) not involved in every stage of development process; they will at some point, hand over the project back to a company. Therefore, at later stages of technology development, research centres will not be as much involved as at the beginning of the project. It means that a capability assessment for a research centre should be simpler and less time consuming, and also more user friendly. Additionally, research centre need to evaluate maturity of their own capabilities to know if they can deliver a project/product/service. Hence, the amount of factors that internally impact maturity process will not change drastically over few months. Moreover, from a research centre perspective, an evaluation tool that delivers results that are later incorporated in the roadmapping process (or any other technology readiness process) would bring additional benefits, e.g. simplifying decision making process and understanding what capabilities are needed for next stage of product development, i.e. delivering transparency.

2.5.3 Importance of research centres (ST7c)

As this project concentrate on research centres, it was important to find definitions and discussions relevant to research centres' topic in literature. However, it should be highlighted that most current papers (from 2017 onwards) offer in-depth discussions about the role and importance of research centres. Hence, it is encouraging to see, that this area of research has started to 'pick up' over the last few years. Therefore, various examples from literature are included in Table 2.7 below. Full version of Table 2.7 is presented in Appendix 6.

Table 2.7: Research centres - definitions, focus, importance (examples from literature)

Definitions	Authors
*The recent emphasis of the UK government's policy initiatives has been on assisting activities that **generate innovation** through the formation of publicly funded **technology and innovation centres.***	(Kerry & Danson, 2016)
*[Catapults are] creating an infrastructure that **bridges the spectrum of activities between research and commercialization of technology**.*	
***Innovation intermediaries (organizations such as CATAPULT Centres)** operate at the overlapping areas of the three helixes and are known to **help facilitate innovation** (Nakwa and Zawdie, 2012). (…) These centres are intended to **increase the level and success of innovation** generating activities and of those involved with them.*	
***Innovation intermediaries such as CATAPULT Centres are ideally placed to play a role in helping drive the adoption of open innovation at a regional level.** The Centres aim to **'de-risk' innovation** by **providing a range of services throughout the research and development cycle**, acting as both an anchor and a catalyst for new markets, innovative sectors, clusters and networks.*	
The Catapult** helps to alter the institutional architecture to **make it possible for UK manufacturing firms to be more competitive.	(Spring, et al., 2017)
Catapults** are (…) '**intermediate research organizations**' in that **they sit between commercial firms conducting private research and universities carrying out publicly-funded research.** After other firms such as suppliers and customers, businesses see **intermediate research organizations** as **the most important external sources of knowledge related to innovation.	

(…) research centre administrations have created ***intermediary organizations to broker between science and commercial applications****. For instance*, ***TTOs, research centres, incubators, accelerators, and broker services*** *have flourished across the globe over the last decade.*	(Fini, et al., 2019)
(…) many universities have established ***technology transfer offices, science parks, incubators, and university venture funds – an organizational assemblage labelled the technology transfer (TT) ecosystem****.*	(Good, et al., 2019)
TTOs *are organizations that have been given the* ***responsibility to facilitate the transfer of technology from a directly affiliated research institution (or multiple research institutions) to market by acting as a bridge between the two environments****.*	
Activities of TTOs: ***Encourage the participation of researchers in technology commercialization****, Build* ***trust and relationships with researchers, Identify high potential technologies*** *and* ***Assess commercialization potential of technologies****.*	
Definitions of the various roles that TTOs should pursue: (…) primarily as a switchboard—and (…) of ***helping two-way communications between*** *HEIs [higher education institutions] and the outside world such as* ***identifying curriculum development needs.***	(Cunningham, et al., 2020)
Overall the main function of a TTO is ***to provide a formal, above the board, and a relatively effective mechanism for those researchers who wish to commercialise their ideas.***	
TTOs *themselves should hire individuals with both research and industry backgrounds and/or experiences in technology transfer with the industry* ***in order to sufficiently support outward technology transfers.***	(Leischning & Geigenmüller, 2020)

Considering information included in Table 2.7, literature does not have a clear definition of research centres. Instead, various terms were used to describe the same concept: Technology Transfer Offices (TTOs), incubators, accelerators, broker services, Innovation intermediaries, technology and innovation centres, and intermediate research organizations. Using only information from Table 2.7, there are 7 different terms used to explain what research centre is. That shows a clear lack of uniformity or consistency about how research centres are presented in the literature. That has a significant impact on the topic, as the lack of consistency in literature limits the possibility of in-depth investigation.

To clarify what is meant by a term 'research centre' or 'Catapult centre' in this project, the following definition will be used:

> A research centre or a Catapult centre is "***to provide a formal, above the board, and a relatively effective mechanism for those researchers who wish to commercialise their ideas***" (Cunningham, et al., 2020), which means that the centre aims "*to* ***'de-risk' innovation*** *by* ***providing a range of services throughout the research and development cycle***" (Kerry & Danson, 2016).

One of the main roles of research centres is "the reduction of uncertainty through the provision of information." (Spring, et al., 2017). Additionally the research centres that are part of HVM Catapult network "help to alter the institutional architecture to make it possible for UK manufacturing firms to be more competitive" (Spring, et al., 2017). It also reported that "between April 2013 and April 2014, the HVM Catapult carried out 24 914 projects, involving 1263 private sector clients" (Spring, et al., 2017), which confirmed the project-based nature of research centres that are part of HVMC network.

Furthermore, there is a clear lack of consistent definition of research centres, i.e., literature does not present an approach applicable to research centres to determine how mature their capabilities are.

As discussed previously (section 2.5.3), maturity models are only discussed from industrial perspective. It means that

1) There is not enough research dedicated to research centres,
2) There is not enough research dedicated to maturity models in research centre environment,
3) There is no generally acceptable approach applicable to research centres, which shows a need for a capability maturity solution developed specifically for research centres.

It should be highlighted that only most recent sources (e.g. (Cunningham, et al., 2020), (Good, et al., 2019), (Spring, et al., 2017)) start to uncover this area of research. Therefore, it shows that there is a gap in the knowledge (highlighted by lack of information about maturity models in the context of research centres) and **this research will deliver significant academic contribution by addressing this gap and creating a solution applicable to research centres**.

2.5.4 Attributes of decision makers (ST5b)

According to (Kyriakopoulos & De Ruyter, 2004): "information is data that give meaning by reducing ambiguity, equivocality, or uncertainty." In a dynamic environment like research centre, access to essential data is important as it enables decision-making process. That is especially important as decision makers do face great amount of pressure that is caused by the external changes (e.g. globalisation, digitalisation, etc.), but might be also caused by internal obstacles (i.e. lack of willingness from team to cooperate etc.). Table 2.8 summarises most mentioned challenges related to role of decision makers. Full version of Table 2.8 is included in Appendix 7.

Table 2.8: Challenges related to decision makers – examples from literature

Challenge	Example from literature	Authors
Identification of opportunity	*The first difficulty facing academic entrepreneurs is to identify and select a viable productive opportunity. Opportunities are objectively identifiable but their recognition is subjective and often depends on access to special knowledge*	(Druilhe & Garnsey, 2004)
	Companies that make **poor choices** *with respect to their new product development (NPD) portfolio run the risk of losing their competitive advantage.*	(Chao & Kavadias, 2008)
Utilization of knowledge/Complexity of operational systems/tools	*Managers face difficulties not in accessing knowledge, but in* ***utilizing knowledge in decision making and in embodying knowledge in products/services and processes****. (…) The trouble (…) is that an effective knowledge management system is in itself a complex combination of a series of organizational subsystems which are themselves complex*	(Soo, et al., 2002)
	Managers need ***models that help them understand the organizational and environmental antecedents and outcomes*** *of detailed but uncomplicated classifications of learning and knowledge.*	(Herrmann, 2005)
Uncertainty	***Making decisions under uncertainty and with incomplete*** *information requires decision makers to draw inferences about future events*	(Nerkar & Paruchuri, 2005)
Learning from mistakes	*"One estimate is that 46 percent of R&D goes toward products that ultimately fail"*	(King, et al., 2003)
Capturing relevant information	*To compete successfully, managers need to be able to scan their environments, identify relevant opportunities and threats (…). Yet,* ***capturing and distilling relevant information*** *isn't a natural capability for most senior management teams*	(Harreld, O'Reilly, & Tushman, 2007)

Communication	*The most sophisticated analyses in the world are* **worthless if findings cannot be communicated to decision makers in ways that will encourage their use**. *Likewise, if decision makers cannot communicate their needs to analysts, modelers, (…), then the entire data-to-knowledge process is at risk.*	(Davenport, et al., 2001)
Recognition and evaluation of skills, capabilities and resources	*R&D managers may want to rethink who they hire and the kinds of skills needed for the new R&D environment. (…), in hiring, the criteria of* **technical expertise; the ability to work creatively and productively across the organizational boundaries; and the ability to understand the commercial goals and requirements of the business.** *These same qualities can be used* **to evaluate one's current personnel.**	(Gupta & Wilemon, 1996)
	Managers of firms seeking to build analytical capabilities **must evaluate the level and structure of skills needed to support their organization's data analysis capabilities.** *If the skill levels of the business analysts, data modelers, and decision makers in an organization are inadequate, then a firm cannot be getting full value from its transaction data.*	(Davenport, et al., 2001)
Responsiveness	*R&D managers* **must respond effectively to changes in domestic and global competition, product and process technologies, customer requirements, regulatory matters, and senior management's perception of the role R&D plays in a firm.**	(Gupta & Wilemon, 1996)
	Decision makers **must make right critical decisions swiftly** *because any delays in taking action will cost lives and economic damage. Decision makers should also maintain constant* **vigilance to identify and assess tipping points and escalation triggers for next steps** *(Aon, 2020). However, making fast decisions can be a huge challenge when decision makers* **face deep uncertainty, high risks and huge pressure.**	(Dwivedia, et al., 2020)

Therefore, as decision makers have to overcome those challenges (probably some of them on a daily basis), they need to be equipped with skills and abilities that will help them to reduce amount of obstacles in the organisation. Table 2.9 shows a summary of necessary skills required of decision makers. Full version of Table 2.9 is included in Appendix 8.

Table 2.9: Required skills/abilities of decision makers (literature findings)

Skills	Description	Authors
Horizon scanning	*manufacturing firms will need managers who understand technologies, can tolerate ambiguity and* **quickly recognise emerging opportunities and can rapidly implement changes**	(St John, et al., 2001)
	Managers must ask not only where are the opportunities, but also **why should their firm be able to capture and exploit them** *better than potential competitors. (…) Inevitably, managers will have to* **shape capabilities according to such related opportunities**	(Miller, et al., 2002)
	considering bottlenecks *and approaches to solve issues related to technology or management, or when external conditions changed and organisation has to adapt*	(Kaplan, 2011)
Vision and integration skills	*Managers' (and entrepreneurs') visions and integration skills that make an important difference in* **directing the development of these capabilities**. *Thus, there is a need for managerial vision in thinking about* **the firm's competitive arena and the trajectory of its future evolution**	(Zahra, et al., 2006)
Leadership	*An effective leader exhibits specific leadership traits: they (1)* **exude passion**; *(2) articulate* **strategic intent and market vision**; *(3)* **imbue technologists** *with a customer value orientation; (4) provide physical protection (insulate the radical innovation organization* **to minimize distractions and short-term pressures**), *psychological* **support and encouragement** *(…); (5)* **dedicate sufficient resources** *and apply appropriately different metrics to assess success than for conventional innovation; and (6)* **recruit, develop, and retain people who have the robust set of skills, knowledge, and mind-set to drive radical innovation**	(Slater, et al., 2014)

Evaluation	*Managers must* ***critically evaluate their resources and talents*** *in looking for hidden gems—trying to determine which are the best employees, which people and units work together best, which technologies show promise, what types of projects and products succeed, and what sorts of customers are attracted to the firm.*	(Miller, et al., 2002)
	Leaders must determine ***which emerging capabilities are most promising and then "select" or embed them as priorities for development****.*	
	Understanding existing knowledge *in the strategic context of the firm also facilitates an understanding of the interfaces among products, product families, and technologies and* ***creates a collective sense of strategic direction***	(Marsh & Stock, 2006)
Review of failures	*Organizations that routinely examine their failures as well as successes may, over time,* ***destigmatize failure****. (…) if failure is destigmatized, it may lead to more experimentation in the organization, which* ***results in improved new product development performance***	(Marsh & Stock, 2006)

The experience and skills of managers is in fact very important when it comes to making decisions. Managers should be equipped with abilities that would help them evaluate capabilities and changing environment, but also be able to communicate clearly with other team members, stakeholders and customers. Therefore, language used by decision makers needs to be understood by all parties involved in the project.

2.5.5 Strategic aspect of decision-making

As shown in Table 2.9, skills like horizon scanning and articulating vision, as well as evaluation of current capabilities, are important in building strategy. According to (Davenport, et al., 2001), *"without a strategic context, a company will not know on which data to focus, how to allocate analytic resources, or what it is trying to accomplish in a data-to-knowledge initiative. (…) The more clear and detailed a firm's business strategy, the more obvious what data and analytic capabilities it requires."* In addition, it is important to highlight that a strategic vision will depend on organisational structure, culture and capabilities. Therefore, in order to set a well-defined strategy, data needs to be available to decision makers: *"Decisions are not made in a vacuum. They are made in the context of a particular business strategy, a particular set of experience and skills, a particular culture and organizational structure, and a particular set of technology and data capabilities"* (Davenport, et al., 2001).

This literature review identified various authors who presented their own definition of strategy (e.g. (Harreld, et al., 2007), (Fuchs, et al., 2000), (Franken, et al., 2009), (Eddleston, et al., 2008)), but for the purpose of this study, the following understanding of 'strategy', reported by (Wißotzki, 2015), will be used:

"The term "strategy" originally comes from the military field and represents an adjustable construct used to convert an actual state into a target state." And so, *"strategy formulation involves the creation of an action catalogue for strategy realization. In order to be effective, such an action catalogue requires an enterprise to have a structured view of its capabilities though."*

Additionally, (Shenoy, et al., 2019) pointed out that "a technology strategy should be developed to advise which areas of technology the industry can invest into."

On the other hand, (Das & Van de Ven, 2000) recognised that every organisation has their own strategy which recognises mechanisms and actions that are repeated in certain manners in order to complete the vision of the organisation. Hence, having a clear strategy shows that an organisation understands its capabilities and resources and know how to effectively manage them in order to perform well. However, 'performance' could be interpreted differently depending on organisations. For example, for manufacturing companies performance might be measured based on economic profits. On the other hand, from innovation providers' perspective, performance might depend if a project deliverables meet customers' criteria. Knowledge-based organisations (e.g. research centres) do not use the same business models as big corporations, and that is why they need to create their own strategies, business models, and also, new methods of measuring performance (applicable to those organisations and based on their own internal criteria). However, new methods have to connect activities with strategies, "monitor changes in intellectual capital, and encourage value-creating work" (Herrmann, 2005). Therefore, the new system should be built and applied in a way that enables users to learn from it as well; thus, a system that would encourage continuous improvement.

Furthermore, to execute strategy, decision makers have to consider how they will communicate their plans to their employees, clients and suppliers. Having open communication and early exchange of information "reduces uncertainty and promotes the early detection of problems, which enables firms to avoid time-consuming changes" (Koufteros, et al., 2002). It also means that collaborators are both sharing the risk involved with the project, but also they exchange knowledge by "pooling complementary capabilities" (Slater, et al., 2014). By communication openly and presenting transparent view of strategy, there is a better chance of exchanging knowledge and creating valuable products and/or services (Chesbrough & Appleyard, 2007).

In addition, (Alegre & Chiva, 2008) described dialogue "as a basic process for building a common understanding in that it allows one to see the hidden meanings of words, first by seeing such hidden meanings in our own communication. In short, the literature understands dialogue to be vitally important to organizational learning." Not having this ability could jeopardize a project (i.e. meaning more time and investment has to be dedicated to a project). Common understanding encourages knowledge exchange and reduces levels of uncertainties at an early stage of any process. In order to have a successful information flow, knowledge structures could be applied to an organisation to help with data/knowledge exchange. Those structures would be a result of "the shared routines that evolve from an organisation's unique history" (Miller, et al., 2007).

What is more, "strategic alliances pose a significant managerial challenge given the complexities and uncertainties associated with managing projects across organizational boundaries. Consequently, it is not surprising that many alliances do not live up to" (Schilke & Goerzen, 2010). It was also noted that apart from having good collaboration, it is important to have the willingness and flexibility of the team. Without supportive and motivated team, the project would have less chances of meeting its objectives.

That is why it is important for any organisation to have a clearly communicated strategy. Explaining long-term strategy and role that each team have in that plan, will encourage team members to contribute more; if team members understand their role and contribution to overall performance of an organisation and its vision, they will be motivated to perm their tasks well. By providing transparency and communicating with their teams, managers will create a sense of importance among their team members and increase morale. Therefore, involving teams, team leads and mangers responsible for technology development would positively influence the process of capability development. Thus, "a formalized technology development process can undoubtedly align the entire organization in terms of the role of technology development for the future performance of the organization" (Magistretti, et al., 2020).

2.5.8 Lack of information about modern research centres in manufacturing sector

Unfortunately, there is not much information about importance and roles pf research centres. Literature sources only explain the importance of having a R&D department/hub in a company and how a financial investment in R&D benefits the company's position in the market. Therefore, Table 2.10 presents some examples of importance of industrial R&D departments.

Table 2.10: Importance of R&D departments – examples from literature

Quote	Source
The degree of new product introduction is again a function of the business unit's R & D effort spurred by commitment to its customers and markets.	(Williams, et al., 1995)
The output from R&D work in industry is primarily intended to contribute to the firm's ability to create value by either increasing market share and revenues or reducing costs. (...). Much industrial R&D is conducted, for example, to generate data for routinely pre-testing drugs, chemicals, and other such products in order to gain regulatory approval	(Graff, Heiman, & Zilberman, 2002)
The high-income economy must be the high-tech economy and this includes a competitive manufacturing sector, as it contains many of the most R&D-intensive industries.	(Tassey, 2010)
The large percentage of industry R&D accounted for by manufacturing companies (70%) means that the demise of a substantial domestic high-tech manufacturing sector would greatly diminish the size and also the efficiency of the overall domestic innovation infrastructure.	

However, (Wirsich, et al., 2016) mentioned benefits of collaborating with research institutes (i.e. research centres) and the benefits of such collaborations

- *Firms that frequently draw on universities as core partners and deeply integrate academics in their R&D processes should focus on fewer research areas to achieve maximum benefits from university-industry collaboration since specialization on focused areas enables mutual learning and optimal comprehension of the novel technologies.*
- *Joint R&D projects with universities or research institutions enable access to valuable resources such as networks of scientists and laboratories, which contribute to the creation of novel and innovative technologies*

The benefits for industrial companies were discussed in various literature sources, but there is a lack of research related to research centres' role, work and importance, it shows that there is a definite need to focus on that field of study. However, it should be highlighted that in the last few years there has been an increase in papers dedicated to role and importance of research centres. What is more, two issues were identified in relation to the topic of research centres:

- Lack of clear and uniform definition of research centres: as discussed in section 2.5.3 using supporting findings from literature (Table 2.7)

- Lack of standardised approach for evaluation of capabilities of research centres:
    - *The functions of university offices of technology transfer are intended to bridge the gap between the academic and industrial sectors of the R&D economy, but just how well they are achieving this is a subject of considerable debate* (Graff, et al., 2002)
    - There is no generally accepted and/or standardised approach that would help research centres evaluate their capabilities.

2.6 Summary

193 papers were analysed through this systematic literature review. Firstly, the research themes found in the literature sources were identified and compared with each other. Secondly, the classification of findings (including time series of research themes, distribution of journals between 1993 and 2021, correlation of research themes and sub-themes, etc.) was performed. Next, the most popular and relevant research themes/sub-themes to this research topic were discussed and analysed.

Moreover, four sub-themes were highlighted as the ones that were examined the most in the literature:

- Capabilities (ST3b, ST3c, ST3d)
- Maturity models (RT2c)
- Importance of R&D (RT7c)
- Attributes of decision makers (RT5b)
    - Strategic aspect of decision making

The above most popular sub-themes helped to identify the major findings, which were summarized in Table 2.11 below.

Table 2.11: Summary of SLR's major findings

#	Findings	Explanation
1	Lack of standardised definition about research centres	Table 2.7 included information from various literature sources. Only in this literature review, seven different terms were identified to define research centre. It shows clear lack of uniformity or consistency about how research centres are presented in the literature. It also has a significant impact on the topic, as the lack of consistency in literature limits the possibility of in-depth investigation. This is one of the major concerns identified by this project.
2	Lack of standardised approach applicable to research centres	It is important to understand at what stage (i.e. how mature) various capabilities are at a research centre. It will help in realising research centre's strong and weak points, and also establishing mechanisms in order to improve low capabilities. After all, having a maturity model that measures current state of capabilities "creates focus for the future" (Noh, et al., 2018). However, **literature does not offer a standardised approach used by**

		research centres. It shows the lack of such solution and highlights the need for a capability maturity solution developed specifically for research centres.
3	Need for structured and logical approach to evaluate capabilities	By **understanding your own levels of capabilities**, it will be easier to **justify** what kind of **funding is needed in order to develop your capabilities further**, or simply what kind of project to focus on. It will also indicate if a research centre should develop capabilities further (i.e. does a research centre have basic capabilities in order to develop certain technologies and become an expert in that area). Therefore, by **having a structured and more formal approach** to decision-making process, **better decisions will be made** (Brouthers & Hennart, 2007).
4	Only most recent literature sources start to concentrate on research centres	Only **most recent sources** (e.g. (Cadorin, et al., 2019), (Lecluyse, et al., 2019)) **start to uncover this area of research**. It shows a clear knowledge gap (highlighted recently by other literature sources) and this research will deliver significant academic contribution by addressing this gap and creating a solution applicable to research centres.

The literature review highlighted the importance of capabilities and provided insight into capabilities that should be measured and managed in the research centre environment. Even though there are many papers that discuss definition, roles and importance of capabilities, **there is still not enough research in that area with focus on research centres**. In addition, newest literature identifies shortcomings of DC and RBV, and shows that there are other environments that **those theories might not fit** (SMEs, young and small companies).More research investigation is needed into research centres areas of study (as well as SMEs).

Moreover, maturity models have been described as solutions that aim to determine 'current situation' of an organisation (section 2.5.3), yet there is no research highlighting maturity models in a context of research centres. It shows that 1) that area of study is not receiving as much attention as other research areas and 2) there is not enough research concentrating on standardising processes that determine maturity of capabilities in a research centre environment. Keeping that in mind, literature offers vast spectrum of information on maturity models applied in industry, which is supported by various research approaches used to investigate industrial perspective. Next, Chapter 3 will describe research approach used in this project.

Chapter 3: Research Philosophy, Methodology and Research Design

3.1 Introduction

This research concentrates on the role and mission of research centres in the manufacturing sector, as well as their current approach to capability maturity. As discussed in Chapter 2, capability maturity is a topic that was discussed by many researchers. However, the concept of analysing capability maturity in research centre is still in its infancy, which was identified as a knowledge gap. Apart from identifying lack of structured approach to capture capability maturity in research centres, there is also a question of how to manage capability (i.e. capability management) once it is developed.

Hence, this research concentrates on lack of structured capability maturity solution for research centres. This study argues that addressing this gap, is essential as it offers lenses for technological capability maturity at research centres. Therefore, a suitable research philosophy, methodology and design had to be selected to address this knowledge gap.

Therefore, section 3.2 explains philosophical assumptions relevant to any research study. Section 3.3 discusses research ontologies and how 'truth' and 'facts' are understood in each ontology presented. Section 3.4 explains the concept of epistemology, as well as important aspects (e.g. the observer, how research progress is measured, etc.) that need to be considered when choosing research epistemology. Section 3.5 explains connection between different ontologies, epistemologies and methodologies. Section 3.6 explains research methodology for this research project. Section 3.7 explains selected research approach i.e. action research and section 3.8 discusses how action research will help to achieve the research aim of this study. Section 3.9 presents a summary of this chapter.

3.2 Philosophical Assumptions

The use of different philosophical assumptions was identified as an advantage as it helps with creating an appropriate research design, i.e. it helps with understanding what data to be collected, how the data is collected and how to analyse the data (Easterby-Smith, Thrope, & Jackson, 2012). Hence, understanding philosophical assumptions increases the quality of research work as well as improves the creativity of researcher (Easterby-Smith, Thrope, & Jackson, 2012) (p.17-18). Figure 3.1 shows a visual representation of philosophical assumptions presented by (Easterby-Smith, Thrope, & Jackson, 2012), and explains definitions of those philosophical assumptions.

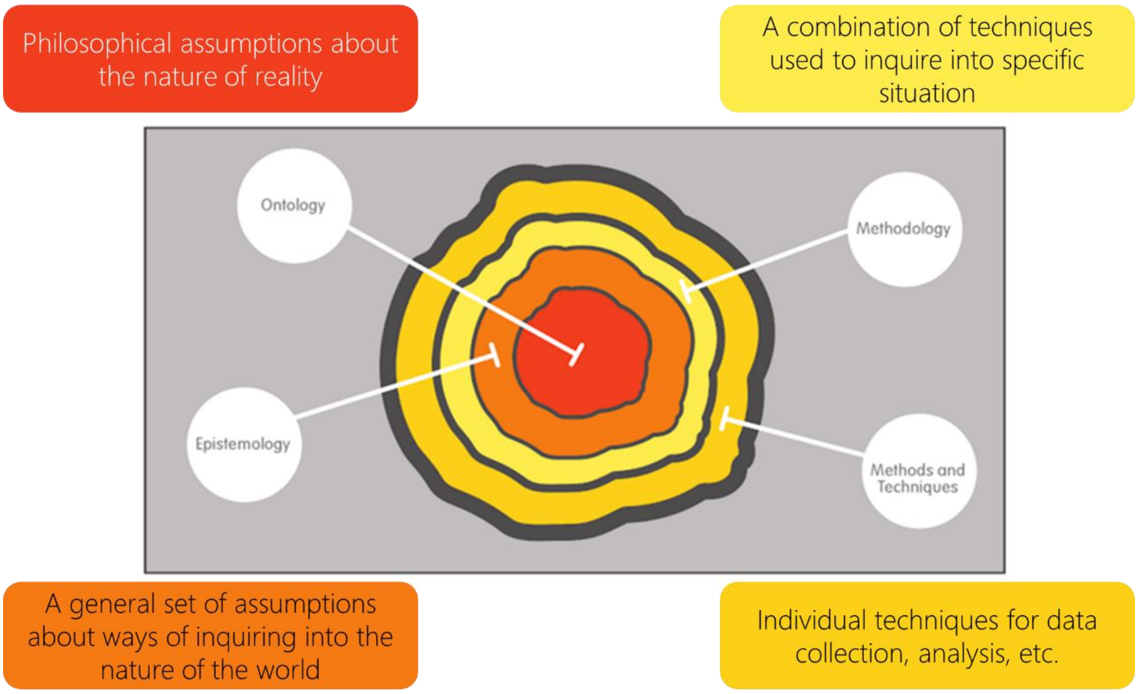


Figure 3.1: Relationships between ontology, epistemology, methodology and methods and techniques (Easterby-Smith, Thrope, & Jackson, 2012) (p 18)

In order to follow the suitable research design, researchers need to understand the difference between different ontologies. Therefore, next sections are dedicated to explain the research terminology related to different ontologies.

3.3 Ontology

Two definitions of ontology were presented in Table 3.1 below

Table 3.1 Ontology - Definitions

Definition	References
"ontology is about the nature of reality and existence"	(Easterby-Smith, Thrope, & Jackson, 2012), (p.17)
"ontology is a branch of philosophy which is concerned with nature of social phenomena"	(Saunders, Lewis, & Thornhill, 2009)'s (p.128)

According to (Easterby-Smith, Thrope, & Jackson, 2012) (p 18), there are four ontologies, and each of them includes its own specific 'truth' and 'fact'. The summary of four ontologies was presented in Table 3.3 below. Table 3.2 explain 'truth', 'facts' and an overview of those four ontologies.

Table 3.2: Ontology Overview (Easterby-Smith, Thrope, & Jackson, 2012) (p 19)

Ontology	Truth	Facts	Overview
Realism	Single truth	Facts exist and can be revealed	• "The world is concrete and external, and that science can only progress through observations that have a direct correspondence to the phenomena being investigated" (Easterby-Smith, Thrope, & Jackson, 2012) (p 19), i.e. it assumes that "the physical and social worlds exists independently of any observations made about them" (Easterby-Smith, Thrope, & Jackson, 2012) (p.345).
Internal Realism	Truth exists, but is obscure	Facts are concrete, but cannot be accessed directly	• "it assumes that there is a single reality, but asserts that it is never possible for scientists to access that reality directly, and it is only possible to gather indirect evidence of what is going on in fundamental physical process" (Easterby-Smith, Thrope, & Jackson, 2012) (p 19). • Internal realism assumes that "reality is independent of the observer, but that scientists can only access that reality indirectly" (Easterby-Smith, Thrope, & Jackson, 2012) (p 342).
Relativism	There are many 'truths'	Facts depend on viewpoint of observer	• "Scientific laws are not simply out there to be discovered, but they are created by people. (…) People hold different views, and their ability to gain acceptance from others may depend on their status and past reputation. The 'truth' of a particular idea or theory is reached through discussion and agreement between the main protagonists. (Easterby-Smith, Thrope, & Jackson, 2012) (p 19). • Relativism assumes that "phenomena depend on the perspectives from which we observed them" (Easterby-Smith, Thrope, & Jackson, 2012) (p 345).
Nominalism	There is no truth	Facts are all human creations	• "The labels and name we attach to experiences and events are crucial" (Easterby-Smith, Thrope, & Jackson, 2012) (p.21). Hence, it suggests that "objects in the world are 'formed' by the language we use and the names we attach to phenomena" (Easterby-Smith, Thrope, & Jackson, 2012) (p.343). • There is no truth; and the interesting questions concern how people attempt to establish different versions of truth." (Easterby-Smith, Thrope, & Jackson, 2012) (p.21)

Hence, the relativist position assumes that participants might have different perspectives and what is considered as 'truth' may differ depending on a place and time (Easterby-Smith, Thrope, & Jackson, 2012) (p.20).

3.4 Why Relativist Ontology is suitable to this research

Considering the four ontologies described in this chapter, the most applicable ontology to this research project is **relativist perspective**, as it assumes that viewpoints can change depending on time and place, i.e. it means that the understanding of 'truth' depends on how many years participants worked in a research centre (have they just started, have they been there for 5/10 years? How the research centres have changed over the years) but also on the place (i.e. have they worked in one place and in the same role or have their roles changed? have they worked in different companies/research centres? Etc.).

Additionally, it assumes that "scientific laws are not simply out there to be discovered, but they are created by people" (Easterby-Smith, Thrope, & Jackson, 2012). As this research will concentrate on participants from research centres (i.e. place), and also their viewpoints depending on their experiences and roles over time (Table 3.3) relativist ontology is the most suitable one for this project. After relativist ontology was selected, next step involves selecting epistemology related to relativist ontology.

3.5 Epistemology

The concept of epistemology considers researchers' assumptions in regards to interactions with the real world, and also how to investigate and analyse existing world.

Identifying appropriate epistemology could be confusing at first, as there are a number of different concepts available to researchers, for example: critical realism, critical theory, pragmatism, hermeneutics, feminism and/or postmodernism. However, the two main viewpoints are positivism and social constructivism (Easterby-Smith, Thrope, & Jackson, 2012). A summary of those two concepts, was presented in Table 3.3 below. A short description of two epistemologies is also included in Table 3.3.

Table 3.3: Positivism vs Social Constructionism (Easterby-Smith, Thrope, & Jackson, 2012) (p.24)

	Positivism	Social Constructionism
The observer	Must be independent	Is part of what is being observed
Human interests	Should be irrelevant	Are the main drivers of science
Explanations	Must demonstrate causality	Aim to increase general understanding of the situation
Research progresses through	Hypothesis and deductions	Gathering rich data from which idea are inducted
Concepts	Need to be defined so that they can be measured	Should incorporate stakeholder perspectives
Units of analysis	Should be reduced to simplest terms	May include the complexity of 'whole' situations
Generalization through	Statistical probability	Theoretical abstraction
Sampling requires	Large numbers selected randomly	Small numbers of cases chosen for specific reasons
Aims	Exposure	Convergence
Starting points	Propositions	Questions
Designs	Large surveys; multi-cases	Cases and surveys
Data types	Numbers and words	Words and numbers
Analysis/ Interpretation	Correlation and regression	Triangulation and comparison
Outcomes	Theory testing and generation	Theory generation
Strengths	• Can provide wide coverage • Potentially fast and economical	• Accepts value of multiple data sources

	• Easier to provide justification of policies	• Enables generalizations beyond present sample • Greater efficiency including outsourcing potential
Weaknesses	• Inflexible and artificial • Not good for processes, meanings or theory generation • Implications for action not obvious	• Access can be difficult • Cannot accommodate institutional and cultural differences • Problems reconciling discrepant information
Overview	• The position of positivist indicates that the researcher is not part of the world that is being observed. • Findings that result from that study must be objective. Therefore, any emotions or feelings connected to the study cannot be considered, and so any subjectivity is hence omitted. • A researcher is independent of the study (i.e. is not "part of what is being observed" (Easterby-Smith, Thrope, & Jackson, 2012) (p.24), and so quantitative methods are required.	• "'Reality' is determined by people rather than by objective and external factors." • "The task of the social scientist should not be to gather facts and measure how often certain patterns occur, but to appreciate the different constructions and meanings that people place upon their experience." • "The focus should be on what people, individually and collectively, are thinking and feeling, and attention should be paid to the ways they communicate with each other, whether verbally or non-verbally" (Easterby-Smith, Thrope, & Jackson, 2012) (p.23-24).

Considering information in Table 3.7, the Social Constructionism (SC) epistemology seems more suitable to this research. First of all, SC's aim is "to increase general understanding of the situation." Secondly, sample requirements dictate "small numbers of cases chosen for specific reasons (and not "large numbers selected randomly"). It is important to highlight that as there are only seven HVM Catapults, and those Research centres were selected for a specific reason, which is the fact that they work independently but also together they create a strong manufacturing research network in the UK, which is unique.

Therefore, novel framework will be constructed based on knowledge from those few places. It means that the novel framework will be created based on limited number of data, which helps with identification of crucial elements of the framework in the context of research centres.

In addition, this research concentrates on developing a novel framework for research centres and with the involvement of research centres (to investigate their needs, requirements and gaps). Hence, stakeholder perspectives is key to this research and that is why SC was selected. Table 3.4 highlights the summary of SC and why it was selected for this research.

Table 3.4: Why Social Constructionism is suitable for this research

	Social Constructionism	This Research
The observer	Is part of what is being observed	Is placed at a research centre able to observe the research centre environment
Human interests	Are the main drivers of science	Are basis for framework development
Explanations	Aim to increase general understanding of the situation	Are used to better understand the problem and create solution suitable to research centres

Research progresses through	Gathering rich data from which idea are inducted	Data is gathered from participants who work at research centres
Concepts	Should incorporate stakeholder perspectives	Are based on participants' perspectives
Units of analysis	May include the complexity of 'whole' situations	Includes complexity of 7 research centres, but also different teams
Generalization through	Theoretical abstraction	Identification of gap in the knowledge, and new concept generation through interviews, observations, surveys.
Sampling requires	Small numbers of cases chosen for specific reasons	There are only seven research centres considered for this research, i.e. there is small number of participants who could contribute relevant information to support this research.
Aims	Convergence	Using already existing theories and merging those with new findings
Starting points	Questions	Staring with questions about how participants define capability? how do they measure capability in research centres etc.
Designs	Cases and surveys	Online surveys, interviews, past case studies (i.e. old skills matrix, past feedback from customers, training reviews etc.)
Data types	Words and numbers	Words and numbers
Analysis/ Interpretation	Triangulation and comparison	Collecting data from various sources
Outcomes	Theory generation	Theory generation and introduction of new solution (i.e. capability framework) applicable to research centres

3.6 Methodology

For this project **constructionism research design** was applied. Constructionism suggests that "there may be many different realities, and hence the researcher needs to gather multiple perspectives through a mixture of qualitative and quantitative methods and to gather the views and experiences of diverse individuals and observers" (Easterby-Smith, Thrope, & Jackson, 2012) (p.26). Such an approach is often described as triangulation, which suggests using various measures "in order to increase the confidence in the accuracy of observations" (Easterby-Smith, Thrope, & Jackson, 2012) (p 346).

What is important for this study is to gather not only technical perspective but also experts' perspective, who are responsible for future direction and vision of a research centres. Therefore, interviews, online surveys and discussions, will allow to develop in-depth understanding of research centres dynamic environment.

Using historical data, is not suitable for this project as data required to develop novel capability maturity framework does not exit. Research centres has not been gathering data needed to address this gap. Hence, strategy that concentrates on review of historical data will not be beneficial in this project.

This research concentrates on research centres "in their natural setting, attempting to make sense of, or interpret, phenomena in terms of the meaning people bring to them" (Denzin & Lincoln, 1994). For that reason, action research is selected as the suitable research approach as "the researchers are often part of this change process itself" and "it is particularly useful for 'how' questions" (Saunders, Lewis, & Thornhill, 2009).

3.7 Research Approach: Action Research

Action research assumes that social phenomena are constantly changing, i.e. they are not static. In addition, "the following two beliefs are normally associated with action research designs:

1) The best way of learning about an organisation or social system is through attempting to change it, and this therefore should be an objective of the action researcher.
2) The people most likely to be affected by, or involved in implementing, these changes should as far as possible become involved in the research process itself.

Action research "emphasises the iterative nature of the process of diagnosing, planning, taking action and evaluating," (Saunders, Lewis, & Thornhill, 2009) (p.147) which is shown in Figure 3.2 below.

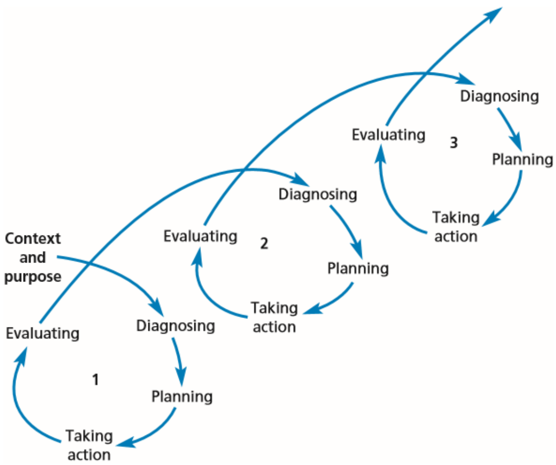


Figure 3.2: Action research spiral (Saunders, Lewis, & Thornhill, 2009) (p.148)

As presented in Figure 3.2, the action research spiral starts with a clear purpose and an explicit context (i.e. a specific objective is clarified). The first step (of Cycle 1) is 'diagnosing' which is often described as "fact finding and analysis" (Saunders, Lewis, & Thornhill, 2009) (p.147). Next step is 'planning' which refers to preparing necessary actions, and deciding of which actions to be taken. Once those actions are taken, they could be evaluated afterwards, which completes Cycle 1 of action research process.

Cycle 2 uses evaluations from Cycle 1 as its inputs and the same steps from Cycle 1 are repeated. Finally, Cycle 3 uses findings from Cycle 2, and again, the same steps from previous two cycles are taken again. "The final theme suggests that action research should have implications beyond the immediate project; in other words, it must be clear that the results could inform other contexts." (Saunders, Lewis, & Thornhill, 2009) (p.147)

"Thus action research differs from other research strategies because of its explicit focus on action, in particular promoting change within the organisation. (...) In addition, the person undertaking the research is involved in this action for change and subsequently application of the knowledge gained elsewhere. The strengths of an action research strategy are a focus on change, the recognition that time needs to be devoted to diagnosing, planning, taking action and evaluating, and the involvement of employees (practitioners) throughout the process." (Saunders, Lewis, & Thornhill, 2009).

Action research is also suitable to this research as it highlights "the importance of employee involvement throughout the research process, as employees are more likely to implement change they have helped to create. Once employees have identified a need for change and have widely shared this need, it becomes difficult to ignore, and the pressure for change comes from within the organisation" (Saunders, Lewis, & Thornhill, 2009).

Addressing need for capability maturity framework, and discussing this need with participants from research centres (as well as current processes used for capability capture) shows alignment with action research. Hence, this project will not only identify a need for change, but also will encourage change from within research centres. Also, participants' involvement is a key aspect of this research as the new framework will be created for research centres and with involvement of research centres.

Thus, three major phases (introduced by Figure 3.2) need to take place. Table 3.5 indicates the three phases, which are also presented in Figure 3.3 below.

Table 3.5: Three phrases of action research implemented in this project

Phase 1	Exploratory study
Phase 2	Framework development
Phase 3	Framework modifications and adaptation

Phase 1 involved talking to participants from 2 industrial companies and 4 research centres. In total 13 participants took part in Phase 1. Results from that study were reported in (Uflewska et al., 2017), and were also part of MSc project (which is an integral part of this EngD). Data was collected through structured interviews (some face-to-face and some through the phone). Those findings are discussed in section 4.2, Chapter4.

Phase 2 involved talking to 7 manufacturing research centres (6 are part of Catapult network, 1 is not). Data was collected through structured interviews, and so 16 interviews were conducted in total in 2017. Those findings are discussed in section 4.3, Chapter4.

Phase 3 an initial framework was developed using results from systematic literature review as well as results from Phase 1. Interviews were conducted at research centre 1 (RC 1) to specifically adjust the framework to research centre's needs and requirements. Hence, 16 participants from RC 1 took part in structured interviews in 2018. Questions were asked in regards to projects management tool/software that is currently in use, customer feedback and funding. Those 3 categories were chosen as in project management time, cost and quality are the three indicators of project's status. This phase of the research project also included interviews with different team members in order to receive feedback and possibly modify the framework further. Those findings are discussed in section 4.4, Chapter 4.

In summary, Phase two used the results from Phase 1 and aimed to asked more specific questions in order to find out how qualitative values as capability could be evaluated using quantitative values that are currently used at RC 1 for project management.

Afterwards, when Phase 3 was completed, results from Phase 3 were taken into consideration in order to create and define capability maturity framework. Feedback gathered during testing phase helped to improve the framework further and help to integrate into a structured approach.

Together with the framework the guidelines how to use the process were created in order to help new users and to explain the process step by step. The three phases were added to action research diagram created by (Saunders, Lewis, & Thornhill, 2009), the completed process is presented in Figure 3.3 below.

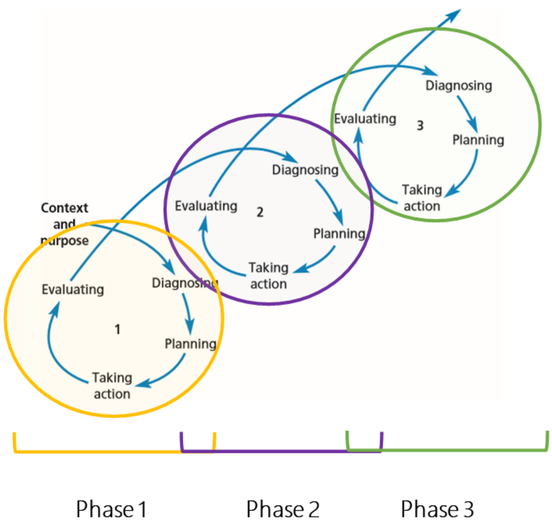


Figure 3.3: Three phases of the project combined with action research spiral

Three phases from Figure 3 are explained in detail in Chapter 4 together with outputs from interviews from each phase.

Due to fact that this research project focused on people's viewpoints, relativist ontology and constructionist epistemology were applied. Hence, structured interviews took place at different research centres. And so, each of the interviews was conducted accordingly to 10 key ethical principles in research. The principles are listed in Table 3.6 below.

Table 3.6: Key principles in research ethics (Easterby-Smith, Thrope, & Jackson, 2012) (p.95)

1.	Ensuring that no harm comes to participants.
2.	Respecting the dignity of research participants.
3.	Ensuring a fully informed consent of research participants.
4.	Protecting the privacy of research subjects.
5.	Ensuring the confidentiality of research data.
6.	Protecting the anonymity of individuals or organizations.
7.	Avoiding deception about the nature or aims of the research.
8.	Declaration of affiliations, funding sources and conflicts of interest.
9.	Honesty and transparency in communicating about the research.
10.	Avoidance of any misleading or false reporting of research findings.

3.8 Summary

To conclude, the research design process is summarised in Table 3.7 below. Table 3.7 summarises all the concepts described in this chapter, and shows what steps were taken in order to construct a reliable and transparent research process. Also, Figure 3.4 illustrates relationships between selected ontology, epistemology, methodology and methods and techniques selected for this research project. Figure 3.4 was created using Figure 3.1 as basis.

Table 3.7: Connecting chosen ontology, epistemology and methodology for this research

Philosophies (Categories)	Selected philosophies	Explanation
Ontology	Relativism	According to (Easterby-Smith, Thrope, & Jackson, 2012), "there are many 'truths'" and "facts depend on viewpoint of observer." Therefore, 'truth' depends on person's perspectives and their role, which is within the scope of this research: it is important to find out how **participants from different research centres**, but also with **different roles and responsibilities** understand capability within the research centre. Also, this project aims to develop a new process around capability maturity concept, i.e. relativism refers to processes, which is suitable for this research.
Epistemology	Social Constructionism	Social constructionism suggests that **the observer is part of what is being observed** (i.e. at a research centre). The aim is to **increase general understanding of the situation by incorporating stakeholder perspectives**, which is true for this research as majority of data came from interviews with participants. Also in social constructionism, **the sample size is small** because samples were **selected for specific reasons**. Hence, this project involved a small number of participants who could contribute relevant information because there are only 7 research centres that are part of HVMC network.
Methodology	Action research	According to (Saunders, Lewis, & Thornhill, 2009), there are two beliefs associated with action research:

		1. "The best way of learning about an organisation or social system is through attempting to change it, and this therefore should be an objective of the action researcher". 2. "The people most likely to be affected by, or involved in implementing, these changes should as far as possible become involved in the research process itself." In order to address first belief, it was important to understand how research centres work and operate, what they struggle with etc. By discussing different issues and topics and by observation, it was possible to understand what elements should be part of CMF. The second belief was addressed by involving as many people who work at different research centres as possible.
Methods & Techniques	Qualitative methods	In the case of this research project, data cannot be captured in any other way then interviews, online surveys, informal discussions and observations as data that was needed for this research has not been captured before. Also, according to (Saunders, Lewis, & Thornhill, 2009) (p.168) qualitative research are used "to develop a conceptual framework and theoretical contribution." As development of novel capability maturity framework and theory contribution are the aims of this project, qualitative methods seem the most suitable.

Figure 3.4: Relationships between ontology, epistemology, methodology and methods and techniques selected for this research project (based on Figure 3.1)

Chapter 4: Investigation through Action Research

4.1 Introduction

As explained in Chapter 3, the method used for this EngD was action research. It meant that one interview would not be enough to capture sufficient empirical knowledge with an aim to develop an applicable CMF. Hence, the plan was to repeat the interview process in order to

a) Identify purpose, requirements and functionality of future CMF from different perspectives
b) Compare new information with previous findings and apply them to CMF.

Hence, four interview phases provided information to this research:

- Phase 1 Interviews in 2016
- Phase 2 Interviews in 2017
- Phase 3 Interviews in 2018
- Phase 4 Interviews in 2019 (discussed in Chapter 5)

The purpose and expected outcomes of interviews are presented in Table 4.1 and Figure 4.1 below that includes the flow chart presenting information from Table 4.1. Manufacturing research centres were contacted during each face and participants were asked to take part during different phases of this research. Table 4.1 shows how many participants agreed to take part in this research during each phase.

Table 4.1: Overview of 4 phases of interviews

Phases	Phase 1	Phase 2	Phase 3	Phase 4
Year	2016	2017	2018	2019
Created based on	Preliminary literature review (included in MSc work and in (Uflewska, et al., 2017), (Ward, et al., 2017))	Systematic literature review (discussed in Chapter 2) and findings from Phase 1	Findings from Phase 1 and 2	Findings from Phase 1, 2 and 3
Purpose of each phase	To understand the scope of the project and to identify gap in the knowledge. The need for CMF was also identified (which provided a motivation for this research).	To confirm findings from Phase 1 and to confirm gap in the knowledge identified through systematic literature review. Understanding of what capability means and what elements should be included (i.e. users' requirements) were identified	To understand who different participants use the same software (for what purpose, how often, what do they struggle with etc.), which will help to avoid aspects that are not beneficial to users at research centre. Functionality of CMF was also identified.	To calculate Capability Maturity Levels in order to gather feedback in the next stage of this study.

Connection with other Phases	Outcomes were used as a basis for systematic literature review (i.e. provided insight into knowledge gap), but also were used as a basis for further investigation in Phase 2, i.e. without Phase 1 Phase 2 could not take place	Provided data about how research centres' expert view capability, and what in their opinion should be included as part of capability (which gave a basis for CMF development)	Provided data regarding functionality of currently used software (i.e. what are the benefits/ disadvantages), as well as information about capturing capability, and the need for transparency between teams	Testing CMF's process; results from this phase are discussed in Pilot Study (Chapter 5)
No of participants (total)	13	16	18	18

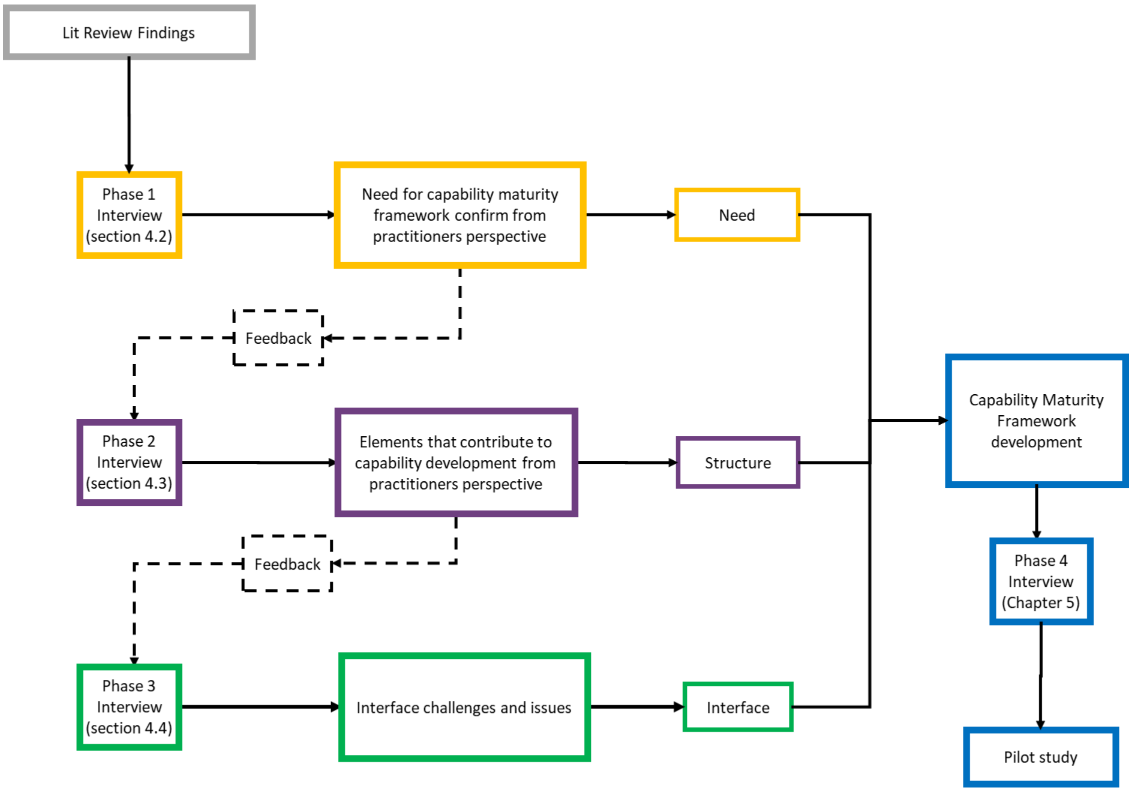


Figure 4.1: Flow chart showing connections between different phases of interviews

The academic institutions were not considered for this research as CMF is developed for the use at research centres. Industrial companies were contacted only during Phase 1 to understand benefits and shortcomings of existing industrial approaches (and to avoid any of those shortcomings in the future). Having said that, it is still important to make sure that CMF can be used and be compatible with industrial approaches in the future. In addition, even though the focus of this research was on manufacturing research centres, there is no reason why the novel capability framework should not be implemented at research centres in other sectors (in the future).

Phase 4 (i.e. interviews in 2019) was used to test the novel CMF process. Data collected in Phase 4 was used to calculate Capability Maturity Levels of various Technological Capabilities at research centres, which was later used in validation stage (Chapter 6) to gather feedback from experts. Results from Phase 4 are discussed in Chapter 5, and feedback from participants related to those results is presented in Chapter 7.

4.2 Phase 1 Interviews

4.2.1. Overview

This section discussed the process of conducting interviews between May and July 2016. By conducting initial literature review (part of the MSc project in Advanced Manufacturing titled 'Development of technology readiness based framework in managing manufacturing improvement within innovation providers') preliminary limitations of TRL-based methods (i.e. readiness based methods) were identified. And so, those findings were used as a foundation for further investigation through interviews. Therefore, Phase 1 allowed to compare findings from interviews with initial literature review. Due to the fact that there was almost no information in the literature about the reason why research centres did not use their own TRL-based approaches, interviews were a great method to learn more about this particular aspect.

Phase 1 contains interviews with four research centres and with two manufacturing companies (part of the MSc project in Advanced Manufacturing titled 'Development of technology readiness based framework in managing manufacturing improvement within innovation providers'). The companies were chosen based on nature of their business, their involvement with technology development process, and the fact that they have been successful for many years. Most importantly, those two companies were chosen due to the fact that 1) they do have knowledge and understanding related to readiness measurement processes and 2) they have their own internal readiness measurement processes. Therefore, this expert knowledge helped to understand readiness based process, which is often not described in literature. Understanding how readiness processes are used in industry also helped to comprehend what information is involved in such process, how long it takes to complete the process and how practical it is. Hence, it helped to comprehend fully why readiness-based processes are not used on a regular basis in research centre environment.

4.2.2. Participants

Participants from research centres were selected based on their knowledge and experience with readiness measurement frameworks. Some participants worked at research centres that are part of HVM Catapult, and some were from 'non-Catapult' centres, but still connected to manufacturing sector. Due to the confidentiality agreement between the companies and the author, the companies were not named, and any details that could reveal their identity were not included in the study. The same process was applied to participants from research centres and to interview Phases 2 and 3 (described in the next sections). In total 13 participants took part in Phase 1 of interviews. The summary of Phase 1 interviews is presented in Table 4.2 below.

Table 4.2: Phase 1: 2016 Interviews

		No of participants	Participants Background	Sector
Industrial Manufacturing Companies	Company A	1	Product Engineer	Automotive
	Company B	2	Manufacturing Partnership, Operations	Marine, Aerospace, Power systems
Research Centres	RC 1	6	Engineering Director, Innovation Support, Business Development	Machining, Materials, Forming & Forging
	RC 2	1	Senior Technology Officer	Additive Manufacturing
	RC 3	1	Research Program Manager	Metallic Materials, Castings, Metallurgy
	RC 4	2	Technical Project Manager	Manufacturing and Advanced Crystallisation

4.2.3. Process

Data was collected **between 17th of May 2016 and 25th of July 2016**. Interviews took place at AFRC or at University of Strathclyde. Most of the data was collected during face-to-face interviews, however when that was not possible to arrange (due to the location of other research centres/companies) – a telephone interview was scheduled instead. Participants were interviewed by one person – the author of this research, and so no third party was present when interviews took place. Data provided during Phase 1 were anonymous and quotes used in this chapter were not referenced.

All the interviews were audio-recorded, and all participants signed consent forms as well as participant information sheet, from which gave the author permission to use the data for the purpose of this research. Due to the confidentially agreement, the companies and research centres involved in all Phases of interviews were not mentioned by full name or any other aspects that could reveal companies' or participants' identity. That approach was applicable to all Phases described in this chapter.

4.2.4. Interview Questions

Questions asked during interviews differed to some extent as industrial participants were believed to have more practical experience in working with readiness measurements framework. All of the questions were based on the findings from initial literature review. That initial literature review was conducted to investigate information in regards to TRL-based methods, their advantages and limitations. The intention was also to understand how the TRL process works (from the industry point of view). However, the identified literature sources did not describe the process itself. Moreover, it was expected to find reasons why research centres have not used TRL-based methods in a way companies have done. Unfortunately that goal was not met either. Therefore, Phase 1 interviews were organised to find out answer that were not described in literature. It was expected to find out more about research centres, the way they obtain excellence level and modern challenges they face through Phase 1 interviews.

Questions were created in order to understand capability maturity and readiness from the research centre's perspective, which is overlooked by the literature. Most of the reviewed papers concentrate on the industrial perspective and this provides a lot of information in regards to how various industrial companies (within and beyond manufacturing sector) tackle modern capability readiness challenges. This will facilitate the comparison between the two perspectives in relation to capability readiness and maturity.

Hence, Phase 1, in the context of research centres, was designed to establish an understanding of:

- How much is known about readiness measurement processes?
- What benefits/drawbacks existing readiness measurement framework have?
- What challenges research centres in UK are trying to overcome?
- Could a new readiness measurement framework help to overcome those challenges?
- Is there a difference between the concept of maturity and readiness?

The interview questions, thus, were constructed to investigate:

- Difference between maturity and readiness, and how participants understand those terms
- Why readiness based tools (e.g. TRLs) are not used at research centres
- Shortcomings of readiness based tools (in order to avoid those when developing future framework)
- A need for a new framework
- Features of future maturity framework (e.g. simplicity, clear benefits, alignment with other frameworks, clear and transparent definitions)
- Applicability to all HVM Catapults

Most importantly, participants were also asked to explain why they chose certain answers, i.e. they were asked to provide justification or explanation to support their answers. By doing so, it was possible to understand reasoning and drivers behind certain decisions. That approach was considered a standard protocol for this study, which was also applied in Phase 2 and 3. Moreover, Phase 1 questions for research centre representatives and participants from industrial companies are included in Appendix 9 and 10 (Tables A2 and A3 respectively).

Transcript from Phase 1 interviews are included in a file called Transcripts: Transcripts 1 and 2. Transcript 1 shows transcript from interviews with participants who work at research centres, and Transcript 2 - with industrial participants who work with manufacturing research centres. Full analysis of Phase 1 Interviews is included in MSc project titled 'Development of technology readiness based framework in managing manufacturing improvement within innovation providers', 2016, as well as in (Uflewska, et al., 2017)

4.2.5. Key Findings

4.2.5.1 Difference between maturity and readiness

Participants were asked 'how do you describe concept of maturity of technology?' and 'how do you describe the concept of readiness of technology?' The answers are presented in Table 4.3.

Table 4.3: How do you describe maturity and readiness of technology?

How do you describe concept of maturity of technology?	How do you describe the concept of readiness of technology?
"moving from one level to the next, it needs to be in terms of meeting certain criteria, so that is possibly the hardest part of the process"	"readiness is all about how proven, how can you measure the technology against your maturity"
"it's a proximity to the market"	"It is a combination of ability, capability and drive of an organisation for change"
"ensuring that you have the robust methodology for developing the technology or the process and validating it to be appropriate level at each stage"	"it's company's ability to put into practise the outcomes of a research project or to use the technology, and its importance for us has to be based on making sure that we don't deliver the projects that they can't apply"
"the technology is mature when it's very proved out"	"Readiness is more subjective because it depends on the research centre"
"how well is the technology behind it, what's the technical understanding of the project, if we do X, would we get Y?"	"how confident are we that when we apply that technology it works and by work I mean it gives us the results that you would expect for the process that you run"
"Maturity for me would be the robustness"	"readiness is much more business view side of things"
"it is how proficient and how expert a group, or a centre or a product or a project team or a business are in being able to deliver something"	"it's the ability of the technology and the confidence that you have in that technology to perform as you expect"
	"It's a combination of factors which allow to take the next significant step in development"
	"it's something wider then maturity"

By comparing all the answers given by participants (from Table 4.3), a word clouds (Figure 4.2 below) for 'maturity' and 'readiness' were created. Those word clouds were created in order to visualise the choice of words (used by participants) when describing those two concepts.

Thus, the most common words associated with 'maturity' were 'process', 'risk', 'important' and 'product'. In case of 'readiness', the most frequently repeated words were 'implement', 'important', 'project', 'use' and 'maturity'. That again confirms that the importance of 'maturity' and that it could be actually regarded as an internal part of 'readiness', which is illustrated by Figure 4.3 below. Therefore, it could be suggested that instead of creating another readiness framework, it would be more beneficial to create a maturity framework for research centres.

Figure 4.2: Comparing participants' definitions of maturity (on the left) and readiness (on the right)

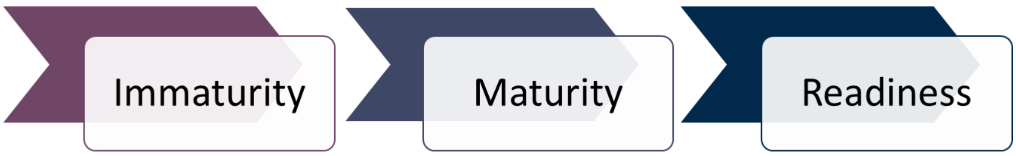


Figure 4.3: Link between readiness, maturity and immaturity

Participants were also asked about reasons why they think maturity and readiness are important. Figure 4.4 below shows answers provided to that question.

Maturity

- "it is about a level of risk, so if you are describing the mature technology to a company that has never used it before, then that would indicate to them a reduction in the level of risk of adoption because it has been proven out"
- "it is how proficient and how expert a group, or a centre or a product or a project team or a business are in being able to deliver something"
- "it requires clear set of criteria"
- "the concept of maturity underpins all sorts of that discussions"
- "moving from one level to the next, it needs to be in terms of meeting certain criteria, so that is possibly the hardest part of the process"

Readiness

- "when you take that next step you have to be absolutely aware of where you are, so that you do not either under-estimating what you're doing in your next step or you over-estimating and over-stretching yourself"
- "you need to match the ability, the capability and drive of a company to the activity of innovation, R&D and implementation"
- "if no one is able to implement a project then project will have no value"
- "Readiness is more subjective because it depends on the research centre"
- "it is really important to have that company readiness quite well marked against the kind of project that you be implementing to, and prove the opportunity for success

Figure 4.4: Maturity and readiness- why are they important?

4.2.5.3 Shortcomings of readiness based tools

Participants were also asked about shortcomings of readiness frameworks. Figure 4.5 below presents the answers to that question.

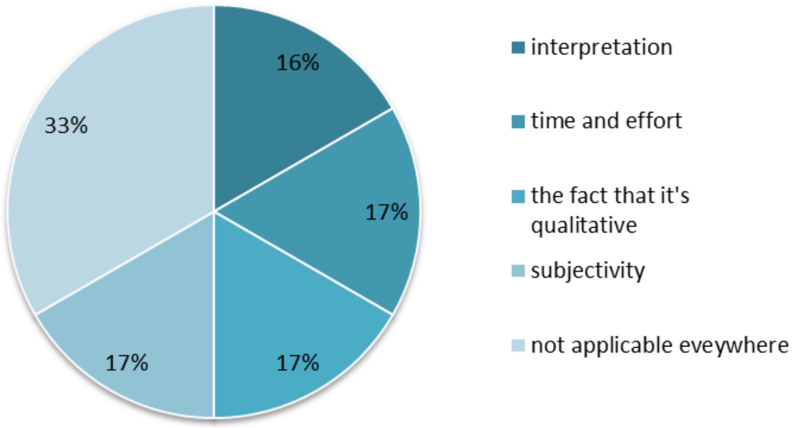


Figure 4.5 Shortcomings of available readiness frameworks

The answer that was repeated the most was that the current readiness frameworks were 'not applicable everywhere', which was also one of the drawbacks mentioned in the literature review. The frameworks were considered to be too general or too specific, and then the initial purpose of framework was usually lost. Another issue was that industrial frameworks did not capture the difficulties that research centre struggle with, or they were difficult to apply because research centres do not operate in the same way large manufacturers do. That is why there could be a problem of not implementing existing frameworks into research centre environment (which has been confirmed through observations). Moreover, many large manufacturers include 'business case' or 'business plan' as part of a framework, which is understandable as they need to think of that aspect of a technology as well. However, research centre does not necessarily have to consider 'commercialisation' stage in their strategy. They could plan for it, in order to have everything in place and meet all the deadlines and make sure that all requirements are met. But commercialisation and business aspect of a product is beyond the scope of work of a research centre, as it often depend on a client. That could be another reason why commercial frameworks were not suitable for research centres.

4.2.5.3 Why readiness based tools (e.g. TRLs) are not used at research centres

Participants were asked why readiness frameworks have not been implemented successfully before. Figure 4.6 presents the summary of the answers. The two most mentioned reasons were that there is "*no need for a framework that combines technical and business aspect*" and that "*the benefits and the purpose of previous frameworks were not shown*". Therefore, again, when creating a new framework, the transparency, the purpose and benefits of the framework has to be clearly shown in order to make sure that the framework would be used again.

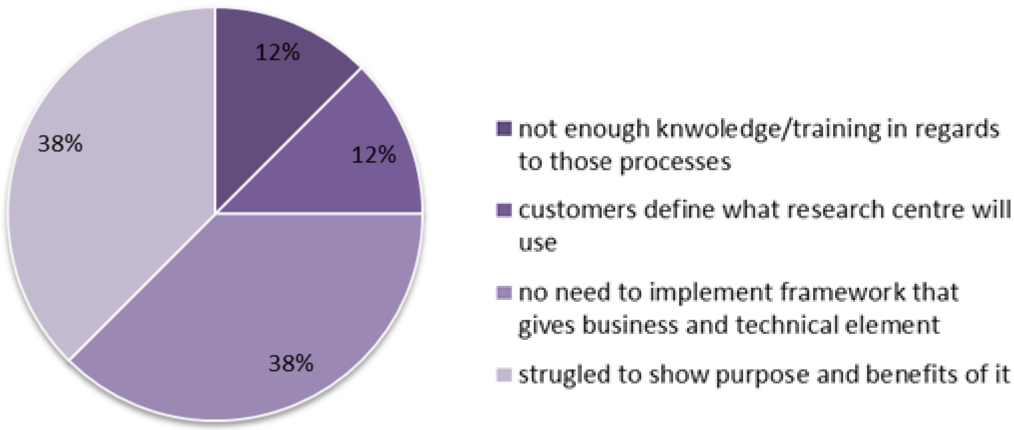


Figure 4.6: Reasons for not implementing a readiness framework at a research centre

4.2.5.4 A need for a new framework

Even though, there were many frameworks used by well-establish companies, there was no framework that could be used by a research centre for internal projects, cross-research centre projects or research centre – SME collaboration. Findings from Phase 1 showed that current (industrial) readiness processes are too complex and do not address goals of research centres. Existing solutions can provide information about development of a product but do not indicate if a research centre has capability to deliver required product/service. Because of that, it is difficult for research centres to acknowledge capability gaps and where development is needed. That as well links to industrial trends and drivers, which change over time. However research centre might not be able to respond to those changing trends if it does not know how mature their capabilities are. That is why they need an evaluation tool that will indicate what capabilities are mature, and which are not.

4.2.5.5 Features of maturity measurement framework

A list of characteristics that new framework should include (based on the participants' answers) was presented in this section.

Simplicity

One of the features mentioned multiple times during interviews was simplicity. The reasons why a framework should be simple and user-friendly were as follows:

- If a framework would be built in the same manner as the industrial framework, it would add unnecessary complexity and would mean that extra time and effort has to be dedicated in order to use framework
- A general framework that could be used, e.g. TRL or MRL, is not applicable to a research centre environment and cannot be used as a maturity measurement tool.

General frameworks have already been available for many years and still they have not been applied at research centres. Therefore, it would be more beneficial if a simple and more 'focused' framework was built for manufacturing research centres. To support that approach, a Throngate's postulate of commensurate complexity could be used. "This postulate states that it is impossible for a theory (...) to be simultaneously general, accurate and simple. The more general a simple theory is, for example, the less accurate it will be in predicting specifics" (Lundberg and Young, 2005). Thus, only two out of three elements could happen at the same time, but never three at the same time. The idea is presented in Figure 4.7.

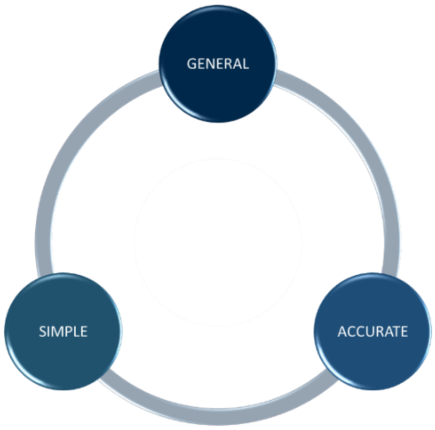


Figure 4.7: Throngate's postulate of commensurate complexity, based on (Lundberg & Young, 2005)

Therefore, as there are already many general frameworks – either they are general and simple, or general and accurate – it would be ineffective and aimless to introduce another framework like that. Hence, it was proposed that a **simple and accurate** framework would be created for the research centres. Those two aspects could be well implemented into a research centre because

- the departments/teams are not as large as in manufacturing companies,
- different drivers are considered at research centre then at industrial companies, and
- a framework needs to be practical and user-friendly in order to bring expected benefits, otherwise it would not be used.

The question now is: what aspects should be considered by the framework (which was identified in Phase 2 of interviews) and what should be most beneficial format of the framework.

Clarity of Benefits

Before implementing the framework**, its benefits must be highlighted**. If the benefits of the framework were not clear, or engineers could not see those benefits – the motivation of using the framework would decrease. That is why **a series of tests should be performed in order to modify possible 'weak points' of the framework**, and eliminate unnecessary waste to make it efficient. Validating the framework through pilot study will help with identification of weaknesses and modifying them. Otherwise, if the framework is not validated, it could become ineffective and it could only discourage future users from using it. As change is usually difficult to manage in any environment, unnecessary complexities should be eliminated.

Potential alignment with other frameworks

As the aim of the novel framework is to determine maturity level of capabilities at research centres, i.e. it will be used before new product development stats, it is possible to align it with TRL and/or other industrial approaches. The idea is that new CMF could be designed in such a way that the two frameworks complement each other. For example TRL/MRL frameworks could be still used to identify readiness of a product, but before that happens, CMF could be used to identify if a research centre can actually deliver the product.

Moreover, it might be more beneficial to create an alignment between specific milestones. Some participants also explained that even though different industrial companies have "*lots of different frameworks in place, each have their own reasons, their internal reasons, for different stages, we just need to align key milestones. I think the company should manage its own, but should align with levels that are in place with their partner company*". Therefore, if framework aligns to key milestones, it would show that an organisations understand which capabilities are needed to achieve those milestones. By having such an alignment, it will be then easier to match it with other scales.

4.2.5.6 Clear and Transparent Definition

One of the industrial representatives mentioned that *"we need to enforce an understanding of each of level. So when you defined that level we need to make sure it's very clear but various results are producing the same level of work to achieve certain purpose, certain level*". Therefore, as long as there are clear and distinct definitions that do not confuse users, everyone who works on a project would share the same terminology. And, as long as definitions reflect the state at which technology capability is, it would mean that transparency has been achieved. That would also encourage cross-centre collaboration, as all Catapults would use same definitions.

4.2.5.7 Use of the standardised framework at HVM Catapults

50% of participants expressed their view that it would be '*very helpful*' or '*helpful*' if a new maturity framework was applied to all HVM Catapults. Participants mentioned the following aspects of using standardised approach:

- *"the key one would be the standardisation, how you can compare things across centres"*
- *"It would help to decide what kind of project to launch"*
- *"it can give a great visibility where we expecting it to become industry ready at this point"*
- *"there is a need to enforce an understanding of each of level"*
- *"it's going to make it very clear who is better at what"*
- *"I would say that it would be better to have that kind of consistency" across the centres*
- *"we do cross-Catapult centre work, which is not customer facing so if you apply it to those projects it would be very useful"*

Even though the results show reasons why such framework would work, there are also **concerns regarding implementation of such framework, e.g. not enough collaboration between Catapults, lack of independent Catapult auditor, evolution of each Catapult at its own pace**. It is also worth highlighting that the approach used to apply framework at each research centre could be a challenge, as various research centres have different styles of working and might encourage different behaviour.

Also, the framework could demonstrate some differences when implemented at different research centres, depending on research centre and nature of the project. Therefore, comparing those differences in application process and verifying them would be a challenge. Another challenge would be **objectivity of users** (i.e. **are they objective when providing data inputs**) and **implementation of the new framework.** Possibly, change management approaches would need to be reviewed and applied in order to implement new framework. Also, by introducing review process the subjectivity concern could be removed or at least minimised.

4.2.6. Why was it Important?

In summary the key findings from section 4.2.5 were:

- Difference between maturity and readiness
- Why readiness based tools (e.g. TRLs) are not used at research centres
- Shortcomings of readiness based tools (in order to avoid those when developing future framework)
- A need for a new framework
- Features of maturity measurement framework
    - Simplicity
    - Clarity of benefits
    - Potential alignment with other frameworks
- Clear and Transparent definitions
- Applicability at all HVM Catapults
- Challenges related to framework implementation

This interview phase was important to this research because

- It confirmed gap in the knowledge
- It helped to understand why readiness framework are not applied at research centres
- It gave an overview of features of a new framework
- It demonstrated the need for some form of clarifying action; an example of such action is standardised approach

4.3 Phase 2 Interviews

4.3.1. Overview

Phase 1 provided information regarding understanding of maturity and readiness concepts, and so it helped identified one of the gaps in the knowledge i.e. shortcomings of readiness tools from research centres' perspective and why research centres have not applied industrial solutions. Those findings provided clarity and helped to understand that maturity aspect is more applicable to the work that research centres perform. Also, Phase 1 findings helped to see another gap in the knowledge which is **lack of maturity frameworks applicable to research centres**. On that basis, Phase 2 interviews were created as a continuation of Phase 1, i.e. Phase 2 questions were designed to understand perspective of research centres in-depth (as a need for novel framework and shortcomings of existing frameworks were already tackled in Phase 1). Moreover, only research centre's representatives took part in Phase 2 (i.e. participants from industrial companies were not involved in Phase 2). Those representatives were asked about their understanding of capability as well as what process would be most helpful when evaluating capability at research centres. Hence, this section discussed the process of conducting interviews in **February 2017**, which was considered a main source of information in regards to aspects that should be included in the novel maturity framework. Findings from Phase 2 interviews were used as a foundation for novel maturity framework structure.

4.3.2. Participants

Phase 2 contains interviews with seven research centres, six of them are part of HVM Catapult, and one manufacturing research centre is not. Participants were chosen based on their knowledge and experience with different manufacturing technologies, strategy and decision making as well as degree to which they are involved in research projects. In total **16 participants** took part in this interview. Due to the confidentially agreement, research centres involved in Phase 2 were not mentioned by full name or any other aspects that could reveal centres' or participants' identity**.** The summary of Phase 2 interviews is presented in Table 4.4 below.

Table 4.4: Phase 2: 2017 Interviews

Research Centres	No of participants	Participants Background	Technology Capabilities of RC
RC 1	1	Engineering	Casting, Automation, Machining, Digital Manufacturing, Metal Forming and Forging, Materials
RC 2	1	Mechanical, Automotive	Casting, Automation, Composites, Electronics, Joining, Metrology, Materials,
RC 3	5	Manufacturing, Metallurgy, Material Science	Materials, Manufacturing Technology Development
RC 4	3	Manufacturing, Mechanical, Automotive, Engineering	Automation, Machining, Materials, Digital Manufacturing
RC 5	2	Mechanical, Automotive	Automation, Surface Engineering, Materials, Metrology, Machining, Digital Manufacturing
RC 6	1	Mechanical, Automotive	Composites, Automation, Materials and Processes, Metrology, Machining
RC 7	3	Metallurgy, Material Science	Casting, Automation, Composites, Electronics, Metal Forming and Forging, Materials

4.3.3. Process

Data was collected between 14th and 28th of February 2017. Interviews were conducted face-to-face at each research centre. Participants were interviewed by one person – the author of the study. Data provided from this stage of interviews were anonymous.

All the interviews were audio-recorded, and all of the participants signed consent as well as participant information sheet, from which gave the author permission to use the data for the purpose of this project. The standard process (as described in Phase 1) was applied in Phase 2 as well.

4.3.4. Interview Questions

The questions asked during interviews were based on findings from Phase 1 (as described above in section 4.3.1) and the literature review (Chapter 2, section 2.5), and so 50 questions were divided into the following sections

- Information about research centre
- Valley of death
- Research centre's capabilities
- Technology maturity and technology development
- Road-mapping and challenges of research centres

Phase 2 aimed to confirm findings from Phase 1 (presented in section 4.2), but also a gap in the knowledge identified through systematic literature review (i.e. lack of structured approach to capture capability maturity at research centres).

Moreover, as Phase 1 concentrated on readiness/maturity aspects (and identified features of future capability solution), Phase 2 focused on what is meant by capability, challenges of research centres, as well as what should be captured by future capability framework (from research centres' perspective):

- What is meant by a capability
- What challenges do research centres struggle with
- What could the framework help with
- What techniques (e.g. road-mapping) are used at a research centre in order to help with decision making process

Thus, Phase 2 aimed to capture experts' knowledge and experience regarding issues mentioned above. Structured interviews contained open as well as closed ended questions some of them using the Likert response scale in order to identify how strongly a participant agrees/disagrees with certain concepts. In total participants were asked 50 questions. Standard approach (previously described in section 4.2.4) was applied in Phase 2 as well.

Interviews were designed so that the data collected would help in establishing

- Definition of capability (from research centre perspective)
- Challenges of manufacturing research centres
- Operating characteristics of manufacturing research centres

Face-to-face interviews helped to understand and capture participants' knowledge about decision-making, i.e. factors, process, mechanism, etc. In addition, it was important to understand how research centres manage their own capabilities. Questions included in Phase 2 are presented in Appendix 11. Transcripts of interviews from Phase 2 are included in a file called Transcripts: Transcript 3.

4.3.5. Key Findings

4.3.5.1 Definition of Capability

Analysis of transcribed interviews provided links to findings from literature review. Phase 2 interview was used to capture valuable information from the participants about capability definition (RT3 from literature review) and the challenges (RT1 from literature review). Table 4.5 and Table 4.6 summarise participants' perspectives over RT3 and RT1 respectively.

Table 4.5: Participants' perspective on definition of capability

Dimensions	Answers	Participants
E	*"Equipment/machines/available technology/scale up facilities/processes"*	1,2,3,4,5,6,7,8,10,12,13
P	*"Appropriate knowledge base"*	1,2,4,5,6,7,8,10,12,13
Pr	*"Capability to justify how the development process took place/scaling up"*	1,3,5,7,12,15,16
P/Pr	*"Right people applied to right projects"*	1,3,4,6,8,10,14
P	*"Combination of academic and industry people, which helps to have appropriate expertise in some areas"*	6,11,15,16
P	*"Ability to process new ideas/deliver new products/ability to adapt to new projects"*	5,8,11
Pr	*"Ability to deliver the expected outcomes within budget and on time"*	5,14
Pr	*"Capability to meet clients' requirements/(industry) demand"*	5,13
DM	*"Capability to make a decision which is the right market based on the resources you already have i.e. you will have high capability in one market but may have very low capability if you move to a new market with new requirements"*	1
DM	*"Capability as a wider view – it will drive the level of investment & rate of progress"*	13
DM	*"Providing body of evidence to show where the technology currently is and show that you are able to scale up– part of building trust – can you show that you will be a trusted partner?"*	4

Note: E - Equipment, P - People, Pr - Projects, DM - Decision Making

Capability is defined by participants as equipment and knowledge which reinforces the importance of both human capability and TC (technology capability). Table 4.8 categorises research centres' capability in three dimensions, **people, equipment and projects**, which together form the basis of decision-making across the HVMC.

In addition, research centres are required to understand in which project/market their capabilities can meet the client needs. There could be some cases that the capabilities of research centre are deemed mature for one project/market, but immature for another project/market, e.g. automotive vs aerospace. Therefore, it is important to acknowledge the fact that challenges related to capability management could be project- or market-driven. However, it should be noted that there might be other areas of interests (apart from project or market) to research centres, and perhaps they could be broken down differently. Due to the fact that participants mentioned project/market split, that is what this project concentrates on.

4.3.5.2 Challenges of manufacturing research centres

According to (Hauser, 2014), "the core rationale for establishing Catapults was that physical centres with associated technical know-how generally operate in the middle levels of technology readiness and provide services that address market failures (…)." (Hauser, 2014) also highlighted that the role of Catapults is to:

- "enhance business access to leading-edge technology and expertise
- reach into the research base for world-leading science and engineering
- undertake collaborative applied research projects with business
- provide skills development at all levels."

However, in order to fulfil their role, research centres have to overcome challenges of various nature and impact. Table 4.6 presents a list of major challenges captured from participants. The challenges are ranked by their popularities, and are associated with CM, OM, or SM (i.e. CM – challenge related to capability management, OM – challenge related to operations management, SM – challenge related to strategic management).

Table 4.6: Participants' perspective on challenges of research centres

Categories	Answers	Participants
OM SM	"Difficult to define strategy for the HVMC: setting strategic direction and allowing us to choose which technologies we should be investing our time and effort into and money. And allowing us to make conscious decisions around what we are not doing, which is just as important as what we should be doing/ We need to fill in gaps in our, at a strategic level, at an overall level/not fully developed strategy for technology/clarity in regards to strategy and capability development." "Each research centre should have a very clearly defined strategic plan of the technologies that they are investing and outputting"	1,5,7,11,12,14
	"Funding related challenges: Funding applications; Different stages of product development require different funding; How the funding is managed i.e. where is the funding coming from?/Not having strategic partner that could invest in specific product development and push it further across the scale"	3,4,5,9,12
	"How important technology is to industry or company- are those technologies right for the company or a product is very tailored for one application – no room for broader picture"	7,12,15
	"Lack of awareness of application because you only consider one market/destination"	9,10

CM OM SM	"Sometimes research and business case are not aligned -finding the demand for technology/which capability should be developed/Connecting technologies with business cases/engagement with industry"	3,4,6,7,9,10,11,12,13,16
	"Many assumptions used when planning long term project"	13
	"Understanding requirements of the projects"	3
	"Training people to be able to use that technology"	9
OM	"Different perspectives between academics and industry people: academics will have different interests and not always will be interested of developing product into the next stages/ bringing people together/ communication between scientists –technology developers, managers"	3,5,6,7,10,11
	"Getting the partners to input into the process"	2,3
	"Not enough technology push/we get a lot of application pull"	9,10
	"The handover at the TRL levels/handover back to customers"	9
CM	"Lack of knowledge/skills/experience in converting ideas into commercial reality/maintaining the skills base"	2,3,11,13,14
	"The input and the intake of the new technologies"	8
	"Taking long time to develop – client may think it's too much time and it's not worth it-proving feasibility of a product"	3
CM SM	"The middle bit of TRL scale (valley of death) i.e. not having technology capability to advance a product/technology development"	3,4,5,7,9,13

Note: CM – challenge related to capability management, OM – challenge related to operations management, SM – challenge related to strategic management

The most popular group of challenges highlights the link between OM and SM. This includes "***difficult to define strategy for the HVMC***", "*funding related challenges*", "*how important technology is to industry or company*", and "*lack of awareness of the market/destination*". This reinforces the fact that strategic and operational decisions are significantly correlated and there is no exception in research centres' environment.

The second most popular group of challenges suggests a strong link between CM, OM and SM. This includes ***"the issue of aligning new technologies with business cases"***, ***"assumption-driven project planning"***, ***"understanding of project requirements"*** and "***technology-specific training***". This group represents one of the main difficulties of overcoming the VoD as capabilities associated with projects without a valid business case will not be strategically sustained. It also dictates how research centres should manage their operations and resources to meet industrial needs.

The third most popular group of challenges describes OM as a standalone issue. This includes "*different perspectives between Academia and Industry*", "*getting partners' inputs*", "*balancing between technology push and application pull*" and "*handover of technology*". This emphasises the importance of getting involvement from key supply chain partners in order to ensure a good balance between supply and demand for each specific TC.

The next group of challenges is relevant to CM which can be described by "***lack of knowledge/skills/experience in bridging the VoD***", "*balancing between effort and benefit from new technologies*", and "*taking long time to develop*". This calls for the importance of research centres' CM approach which helps address important trade-offs when developing/improving/sustaining

TCs. Last but not least, the link between CM and SM is mostly recognised as "*the middle bit of TRL scale*" which is a key step of turning ideas/concepts into commercial application, i.e. VoD.

In this connection, research centres should understand and hence define their own capabilities. Participants explained that "***most of that (capability) justification happens when clients visit research centres and machines are shown to clients; that's a lot of credibility to a lot of things that we claim in terms of saying that we can do this in this amount of time***" (P7). Participants also mentioned that capabilities could be described as "*methodologies*" (P11). Therefore, currently **the process of managing capabilities is informal and inconsistent**, and it **requires *"a leap of faith on their (clients) part"*** (P8). It shows that research centres struggle to **define their capabilities using standard format** and this reinforces the fact that **no existing tool is currently applicable to the research centres** in the HVMC. This gives rise to the need of developing a new CM tool for research centres.

Using participants' comments above, it was also observed that **research centres struggle with articulating clear research vision**. That also affects how much research centres know about their own capabilities (and their maturity). Therefore, the lack of vision affects decisions regarding maturity of capabilities. On the other hand, lack of understanding of capability maturity also impacts research centre vision. Hence, those two issues affect each other equally, as shown by Figure 4.8.

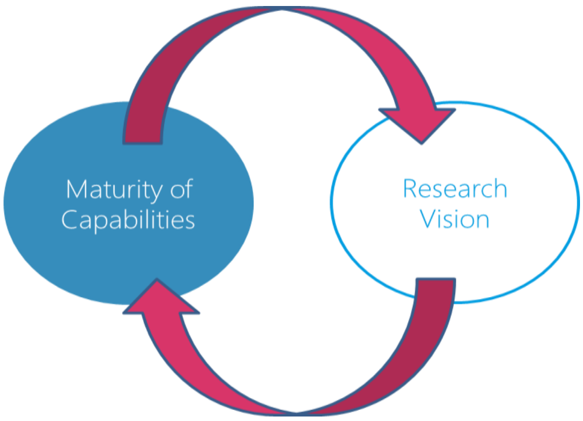


Figure 4.8: Link between Research vision and maturity of capabilities at research centres

Clear vision will help with identifying key capabilities at a research centre, but also with understanding how mature those capabilities are. Capability maturity will be feed back into vision and correct aspects that were assumed in the first place. An iterative process like that helps with initial assumptions and helps research centres evolve. That is why capability maturity should not be evaluated 'on its own' (in isolation). It should be also referred back to research centre activities and repeated on a regular basis, as "static behaviour is very dangerous to any organisation" (Phaal, 2021). As capabilities evolve over time, they will influence strategy and planning process, which are essential for completing one's vision.

Regarding the role of novel capability framework, most participants suggested that it would be more beneficial if the tool can serve as "*capability maturity framework in relation to our centre*" (P1,P9,P10,P12,P13). For example, P10 described the need for capability framework as "*when you look at collaborations on an industrial projects or R&D, understanding where you sit as a centre – compared to other centres and what part you are bringing to the parties is very interesting and very useful.*" On the other hand, the majority of participants replied that the two concepts, **technology and capability, cannot be separated as "*they are so closely linked that you couldn't do one without the other*"** (P2,P3,P7,P8,P11,P14,P16). This suggests that capability should be defined and measured in relation to its maturity rather than its readiness which contradicts the current CM literature (Tetlay & John, 2009). Next, participants were asked about obstacles specific to CM approach of their research centres.

4.3.5.3 Operating characteristics of manufacturing research centres

Building on the obstacles specific to CM approach of manufacturing research centres, their OCs were defined as reported in Table 4.7. Each of these obstacles helps depict a specific OC which also presents an area for improvement towards bridging the VoD. For example, "*load and capacity*" reveals the fact that research centres have been adopting capacity lag strategy to meet the industrial needs. Due to "*unclear definition of maturity*" and "*complexity and dynamism of the research environment*", they have been less proactive in planning ahead. **"*Low awareness of capability*"** and "*managerial issues*" also contribute to the lack of standardised CM approach within the HVMC leading to silo effect. This highlights a revolution that the new framework could bring.

Table 4.7: Operating characteristics of manufacturing research centres

Obstacles	Participant	Quotes	Operating Characteristics
Load and capacity	2	*"The main reason for not doing it is forming that link between what's required to prove progression of that framework and industry"*	Capacity is mostly developed to address the current load (need) not the future load, i.e. capacity lag strategy.
	4	*"Engineers prefer to work on developing a machine or an engineering project"*	
	5	*"Our biggest challenge is sort of keeping work coming through the door and delivering it and building the centre to be what it should be"*	
	6	*"We work with all the customers that we work with, and each one of those is pushing their own agenda to some extent"*	
Maturity of the centres	5	*"The centres aren't that mature"*	Maturity is not well-understood, hence is not associated with capability.
	8	*"It's probably just the age of the catapult. Too early for that"*	
	9	*"Maturity of the catapult"* *"The team working is still trying to be defined"*	
	14	*"In Catapult terms- it's quite relatively early."*	
	16	*"We will have capabilities in 15 or 20 different areas, but we wouldn't have the depth. So this also needs to be managed carefully"*	
	3	*"It was always seen as too big of a challenge."*	

Complexity and dynamism of the research environment		*"It's too complicated to effectively it's always been too big an idea"*	Research need is highly uncertain and difficult to be forecasted. This discourages the use of proactive strategies.
	10	*"Simply because of the challenge of it … it's very dynamic."* *"The rate of change is so rapid. The challenge to understand what is going on and who is doing what etc"*	
	12	*"It's a very difficult task and to make it modular is very challenging."* *"To create a justification of capability is very difficult"*	
Lack of awareness	1	*"No one has thought to do it and no one has a framework to implement."* *"Lack of capability that goes together with strategic level."*	Capability of research centres is not well-understood, hence there is no standard tool to manage it
	8	*"I don't think it's being asked for by clients."*	
	11	*"Maybe lack of awareness of the need for it or benefit of it"*	
Boundaries between centres	11	*"I think partly also maybe due to again the boundaries and uncertainty about boundaries between different catapult centres"*	The silo effect is aggravated by low visibility of centres' capability and low awareness of centres' CM.
Managerial issues	7	*"Without the central catapult pushing it, it's hard to get all the centres to come out and say, yes let's all work together and do it"* *"Having standardised practices and common understanding across the catapults"*	

Interviews highlighted that capability and technology are two key concerns linking to the CM issues across research centres. In addition, a new CM framework is urged to help all research centres understand what capability should be improved/developed, and how. P10 explained further as "*we looked at this across the HVMC and wanted to answer the question – what is our capability. Because fundamentally you want to be able to say we are here – point on the map – we want to go to there – other point on the map. The wide space we have got is between here and there, and we are going to do it by this route.*" Therefore, such a new framework will help assess the current capability of research centres and provide recommendations to enhance their capabilities. Main findings from both literature and interviews are summarised in Table 4.8.

Table 4.8: Major findings identified from literature review and interviews

Literature findings	Interview findings
Lack of standardised definition of what research centre is and what it does. The operating characteristics of research centres are not clearly defined. Hence, their role is vague and this impacts their operating practice.	Unique OCs of research centres are identified as: capacity development is led by needs, maturity is not well-understood and not associated with capability, uncertain needs discourage the use of proactive strategies, no standard CM method is adopted, and the silo effect is aggravated due to low visibility of centres' capability and low awareness of centres' CM.
Lack of standardised definition of maturity which is essential to direct capability development. Existing TRL/MRL approaches only assess "what has been achieved" but do not illustrate "how it has been achieved". Existing maturity models are not specific to research centres and it makes maturity measurement a big challenge.	• The biggest challenge for research centres is to align new technologies with business cases. Hence, a new methodological framework is urged to define and measure capability in relation to maturity rather than readiness. • The new framework is expected to not only assess maturity level as compared to others, but also illustrate "processes" required to achieve the desired level.

	• Two main benefits of the new framework are standardisation of CM practices and unification of terminology while four potential issues are identified as integrability, user engagement, accessibility and IP protection.
Lack of standardised procedure to define and measure capability. Most of the existing CM frameworks/models are not specific to research centres whose CM practices need to be regulated.	Capability of research centres is mostly defined as equipment and knowledge. However, there is a lack of common understanding towards CM across research centres.
DC theory is mainly discussed from an industrial viewpoint and it overlooks both the operating environment and operating practice of research centres.	DC theory is not well-received by research centres.

It is clear that the literature does not standardise the definition of research centres, hence, their OCs as well as operating practice are not well-understood. This study is the first to identify research centres' unique OCs through interviews and this uncovers major reasons why they struggle to manage their own capabilities. It is evident that maturity definition is not standardised in the literature and most of the existing maturity models are based on TRL/MRL approaches which do not illustrate "processes" required to achieve the level desired by research centres. Therefore, due to the **lack of methodological framework, research centres find it challenging to align their capabilities with industrial needs for bridging the VoD**. Without such a framework, CM practices are not regulated leading to **diverse understanding and low awareness of CM** within the HVMC as confirmed by the interview findings. No standardised approach is found to differentiate and benchmark among different research centres. Thus, it is very challenging for the HVMC to decide what capabilities must be improved/developed to support its strategic growth. **Without fully recognising their own strengths and weaknesses, research centres may undertake projects that are not compatible with their own capabilities, or do not create any strategic value** to both themselves and the sector. This pulls research centres apart and develops the silo effect.

Additionally this is also the first study to explore another aspect of capability maturity and its impact on much wider picture of research centre's work. For example, **understanding capability maturity provides foundation for understanding how capabilities are used.** Perhaps certain capabilities are not maturing because they have been applied to the same applications for a long time now and they became so-called 'on-the-shelf' capabilities. For decision makers, this knowledge is significant as this helps decision makers to differentiate between capabilities that immature, and those which are mature to be implement instantly when needed; those 'off-the-shelf' capabilities allow research centres to react quickly to changing environment. For instance, as we have seen over last 12 months, the Covid-19 pandemic have had enormous impact on various aspects of our lives. However, using development of Covid-19 vaccines as an example, it could be argued that mature capabilities are needed in times of crisis. And decision makers need to understand which capabilities are mature (and which are not) in order to act fast. Hence, by being part of the capability maturity process (even by only monitoring the process) decision makers acknowledge which capabilities can be implemented, and which ones need to build on their previous work and continue to mature.

A framework that can assess capability in relation to maturity rather than readiness and provide guidance to escalate centres' capability is appreciated by most of the participants. Surprisingly, although DC is a well-known CM theories, it is not well-received by research centres, perhaps, due to their unique OCs which are different from the industrial ones.

It is important to remember that by taking findings from Table 4.5, it was possible to create dimensions of CMF. Therefore, 2017 interview findings were significant to further development of CMF.

4.3.6. Why was it Important?

In summary the key findings from section 4.3.5 were:

- Definition of capability (basis for framework design)
- Challenges of manufacturing research centres (basis for what novel framework will offer)
- Operating characteristics of manufacturing research centres

That interview phase was important to this research because

- It confirmed gap in the knowledge highlighted by literature review
- Gave an overview of what is considered a capability in a research centre
- It provided understanding of what aspects are important and should be included as part of CMF
- Proved that there is a need for HVMCs to have a standardised approach

4.4 Phase 3 Interviews

4.4.1. Overview

Phase 2 confirmed findings from Phase 1 and the knowledge gap, which was also identified through systematic literature review, i.e. lack of standardised process for research centres to capture their capability. Therefore, Phase 2 provided data about how research centres' experts view capability, and what in their opinion should be considered as part of capability (and also a part of future structure). Phase 2 findings gave a foundation for structure of novel Capability Maturity Framework (CMF). It also allowed Phase 3 to focus on functionality of novel framework (as structure was already discussed in previous interviews). Additionally, Phase 3 aimed to investigate what functionalities would be helpful to future users, and what are the biggest issues with currently used software.

This section discussed the process of conducting interviews in autumn 2018. This stage contains interviews with 18 participants from one research centres (RC 1) (due to availability of participants). Participants who took part in Phase 3 were different from Phase 2 i.e. different group of participants. Participants from various teams (technical and non-technical) were chosen in order to find out more information as to what functionality and features successful tool/software should include. By obtaining feedback from non-technical teams, it was then possible to create a framework that will be relevant not only to technical teams but also to programme management, business development and other teams at a research centre. That feedback provided a wider overview of what are users' requirements.

4.4.2. Participants

In total 18 participants from one research centre took part in Phase 3. The interviews took place between 16th of October and 2nd of November 2018. Out of 18 participants, 8 of them were from Business Development/Programme Management and Quality Control teams, and 10 were from technical teams. 7 participants were also team leads, but it should be mentioned that some of other participants have are senior members of the teams, i.e. they do bring value to the decision making process. The summary of participants who took part in Phase 3 is presented in Table 4.9.

Table 4.9: Phase 3: 2018 Interviews

Team	No of participants	Participants Background	Technology Capabilities of RC 1
Business Development	6	Business Development Manager, Knowledge Exchange Fellow	Casting, Automation, Machining, Digital Manufacturing, Metal Forming and Forging, Materials
Programme Management	1	Programme Manager	Casting, Automation, Composites, Electronics, Joining, Metrology, Materials
Quality Control	1	Quality Control Manager	Materials, Manufacturing Technology
Technical	10	Team leads, Senior Engineers	Forging, Machining, Material Science and Residual Stress, Forming, Metrology, Digital Manufacturing and Lightweighting

4.4.3. Process

The aim of that interview phase was to understand

- Current problems/challenges with the existing project management software,
- Functions and deliverables staff would like to have in a new framework i.e. what would be most useful to them on a day-to-day basis,
- Participants' biggest issues when considering management of capabilities at RC 1.

All questions for Phase 3 are listed in Table 4.13 below. Questions were divided into three sections: 1) project management software/platform, 2) customer feedback and 3) funding. First section included 11 questions, second – 12, and third one – 11. In total employees answered 34 questions.

4.4.4. Interview Questions

Question in Phase 3 were divided into 3 sections:

1. Software X: questions aimed to understand biggest advantages/disadvantages of this software, as it was used (at the time) by various groups at a research centre i.e. people from programme management, project management, technical leads, business development etc., were using this software at the time of Phase 3 interviews. Therefore, to capture

different opinions from various participants with different roles at a research centre. Questions also asked about what functionality is missing or could be added in the future to help research centre.

2. Customer feedback: questions aimed to provide understanding into how projects are managed, and what could be modified to improve project management aspect. Questions also aimed to understand how satisfied customers are with current project delivery process and how customer feedback is processed (i.e. are there lessons learnt). Questions also provided insight into team collaboration and team management at a research centre.
3. Funding: questions aimed to understand what information and what detail of information needs to be provided when applying for funding. Questions also aimed to understand how different information (needed for funding applications) are captured and used.

Again, standard approach (as previously described in section 4.2.4) was applied in Phase 3. All Phase 3 questions are included in Table A5, Appendix 12. All transcribed interviews from Phase 3 are included in Transcript 4.

Full version of all the transcripts is also available online through the following link: https://app.mural.co/t/afrc0564/m/afrc0564/1617028970161/9de9dedde403c8d741bc61ece26c4266a75c4bca .

It should be highlighted that Software X used across different teams at RC 1 is a web-based software used for project management. Also, it was customised specifically to RC 1 needs, and so it is unique to the research centre.

4.4.5. Key Findings

Some of the above categories were out of scope of this research, but it was still helpful to find out more from participants and discuss what challenges they experience when using already existing tools at RC 1. For example, Software X, which is a project management tool, was used at the time by various teams at a research centre. The reason why Software X was selected as part of Phase 3 was because different teams (i.e. programme management, technical, business development etc.) all used that software. Therefore,, participants could share their experience of using it (providing different perspective, depending on what team they were in and what did they use the software for). At the time it was the only software used by different teams, and so it helped to understand what went well when implementing and using Software X, and what did not go well i.e. what different teams struggled with. The aim of asking questions regarding Software X was to understand which problems could be avoided in the future when introducing CMF to a research centre. It was also important to find out what functions participants struggle with, and functions they need to work in order to complete their regular tasks.

4.4.5.1 Challenges of Software X

Software X was selected because it was used across RC 1 by various teams (i.e. technical teams, programme management, quality, business development) at the time of Phase 3 interviews. Various participants (depending on their roles) offered different perspective based on their experience of using the software. Summary of benefits and shortcomings of the software is presented in Figure 4.9 below (Fig. 4.9 was created using participants comments).

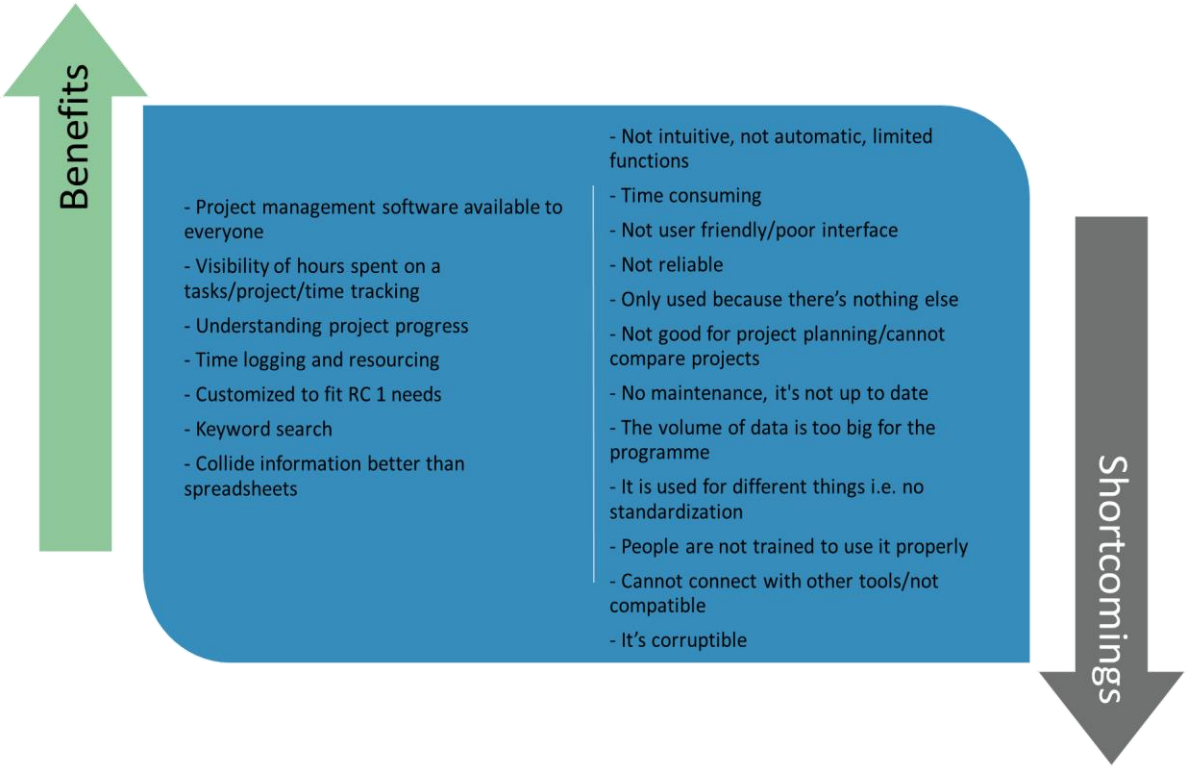


Figure 4.9: Benefits and shortcomings of Software X

Discussions about functionality and issues of Software X with participants from different teams provided a sensible overview of that software. Those discussions provided helpful insights about current disadvantages of the software. And so, this feedback helped to avoid repeating the same mistakes when creating CMF. Table 4.10 below shows challenges identified in regards to Software X. Detailed version of Table 4.10 is included in Appendix 13.

Table 4.10: Challenges regarding Software X

Challenges	Explanation	Frequency
Not intuitive, not automatic, limited functions	It requires additional steps in order to modify data or to see different visual results	10
Time consuming	It affects team's efficiency, requires extra time to add/modify information	9
Not user friendly/poor interface	Hard to find information, difficult to upload information, a lot of manual manipulation is needed, it's not automatic, it's slow	9

Not reliable/outputs are not reliable	It crashed before and lost a lot of data if information showed is wrong- you cannot see if it is wrong, the visual representation does show every information – it's not accurate	8
Only used because there's nothing else	It is used out of necessity	6
Not good for project planning/cannot compare projects	limited access to use it/poor usability, difficult to add new tasks It doesn't show baseline information for the whole team It's difficult to check progress	6
No maintenance, it's not up to date	No ownership of the programme, no one can fix the bugs	5
Scalability is not possible	The volume of data is too big for the programme	3
It doesn't work people are using different things i.e. no standardization	No standard procedure in terms of how teams capture data and compare projects, therefore every project summary is different	3
People are not trained to use it properly, to its full ability	No training was provided to teams, hence teams don't know how to take full advantage of the programme	2
Cannot connect with other tools/not compatible	Not able to add it to MS Project or Power BI etc	
It's corruptible	People can 'trick' the system	1

Table 4.10 already highlights certain aspects that users would like to avoid, e.g. **the tool is not intuitive, is time consuming and is not user friendly**. Therefore, it already gives a good indication of what future users of CMF will look for when it comes to users' expectations.

The benefits and the aspects of programme management tool are not included in this chapter as it is out of the scope of this research.

4.4.5.2 Centralised database

At that point in time participants were asked if a centralised database would be helpful for the centre. That question was asked in relation to Software X and project management issues. 83% of participants confirmed that such database would be helpful. 6% did not see benefits to team leaders or team members and only mentioned that such database would only be useful to senior management. Another 6% were not sure about the helpfulness of such database. Main reasons for having a centralised database are included in Table 4.11 below. Full version of Table 4.11 with quotes from participants about centralised databased is included in Appendix 14.

Table 4.11: Why would a centralised database/system be helpful at the research centre?

Category	Frequency
Access to information and transparency across RC 1	8
Centralised system/database controlled by RC 1	7
Managing workload within the team and outside the team	5
Introduction of standard method to collect and present information	2
Useful for management	2
N/A	2
Not useful to have database	1

Improvements listed in Table 4.11 were mentioned in relation to project management issues (as Software X was a project management software). Most participants mentioned that the two main benefits of having centralised database would be **access to information and transparency**. That aspect relates to transparency of load/capacity and projects' progress, which is connected to 'Managing workload within the team and outside the team'.

Furthermore, having centralised database was mentioned as Software X was previously customised for RC 1 but afterwards, there was no 'software champion' who could have addressed/implemented any modifications. Hence, participants were upset that certain changes could not be made (which is certainly an important point that needs to be considered during implementation phase, i.e. **having a 'CMF champion'**).

Next, two participants agreed that it would be good to have **a standardised method to collect and present information**. Even though that answer was provided in relation to project management, it was highlighted that **standard approach might add consistency across the centre**.

On the other hand, one participant mentioned that having database would not be useful: "that might be for the director, I'm not sure how much use that would be to me. I think my answer to that would have to be no not really" P8. Therefore, it shows that a centralised database is not a priority.

4.4.5.3 Customer Feedback

Currently, the research centre has a customer feedback form that is send out to customers after the project is completed. There are five questions that customers are asked to answer, those questions relate to responsiveness, quality, deliver, working relationship and recommendations. Hence, participants were asked if they would change anything in relation to customer forms but also how the centre currently handles the projects.

Firstly, 33% of participants confirmed that the centre needs to manage customers' expectations better: "***there's an expectation and the skills are already there**, **you are already the expert** and you're going to deliver work like in a consultancy approach, which is not the case in research. I think the expectations are different*" P16. It also links with another identified improvement, supported by 28% of participants, i.e. "Asking how delivered service/product impacted the business". For example: "*I think it would be useful to know how more specifically the customer feels from the outcomes of the project. So the impact, yes, to have a little bit more information available*" P9.

Other aspects related to customer feedback resulted in suggestions for quality control team, and so summary of relevant comments was send to Quality Control Manager. All suggestions related to customer feedback are presented in Table A6, Appendix 15.

4.4.5.4 Teams' collaboration

The other aspect that has significant impact on how the whole research centre performs is collaboration between teams. 56% of participants agreed that **teams have to see a bigger picture rather than concentrating only on separate, team-based targets**. It is clear connected to another issue, i.e. the fact that financial targets are imposed on all the teams, and financial targets might drive wrong behaviour (50%), e.g. "*they would see it from the point of view that they don't want some other team to take their job, because of the financial point of view*" P7. Also, 50% replied that **lack of communication between teams** and the fact that sometimes assumptions are made about other teams without any prior conversations, causes issues that later affect performance and delivery of a project. In addition, 50% of participants also mentioned that the structure adapted at the research centre does not help, as "*there's certainly an element of compartmentalisation*" P8. Other issues in relation to teams' collaboration at the research centre are listed in Table 4.12. As issues identified in Table 4.12 are not directly related to capability management, the full version of Table 4.12 is included in Appendix 16.

Table 4.12: Teams' collaboration at the research centre - identified issues

Identified issues	Frequency
Teams need to see bigger picture	10
Lack of communication/lots of assumptions	8
Structure does not encourage the collaboration	8
Financial targets drive wrong behaviour	8
Need for project managers/cross-team coordinators	3
Inconsistent approach on how teams operate	2
Lack of rules enforced by management	2
Most meetings are not effective	2
Resource constrains	2
Need contingency plans when planning a project	1
Slow in terms of decision making	1
Lack of interest	1
Collaboration between different teams across centre	1
Team Leads' behaviour/attitude	1

4.4.5.5 Capability capture

The participants were asked about techniques or tools that they used to capture existing capabilities at research centres. 56% answered that they **capture or find out about existing capabilities through conversations with team leads, senior members of the team or business development person working for the team**. In addition, 33% mentioned that for machines there is an **inventory list that is updated on a yearly basis**, and it includes all the equipment that is available at the research centre. Further 22% admitted that there used to be a skill matrix that was supposed to capture different capabilities, however staff did not use it and so it was updated for last few years. Another 22% added that the **research centre does not capture capabilities and there is no database that could be used when measuring what kind of capabilities the centre has.** Other responses related to capability capture are included in Table 4.13.

Table 4.13: How is capability captured at the research centre?

Summary	Quotes - Example	Frequency
Conversation with team leads/senior members of a team/BD	*"It (the conversation) might be with team leader it might be with business developers, if you need to. Depends on a team. Some of the team would not be interested, BD would be more interested. Some of the teams they, the team would be more approachable then the BD person. So it's easier to go through team leads. Just depends on the person"* Participant 5	10
	"Yes if I have a specific, team leaders or maybe some senior people in the team, you know if I have a specific project and some, in my team I know the skills, but if I have something, if I need something from the material team, yes, they do this type of test, I don't know who can help, maybe me or somebody in the team I say go and speak to the team leader or one of their assistants, senior, to understand if they can help us with this and who can, so we speak with each other, so there's collaboration for this yes." Participant 16	
Inventory list for equipment	*"And in general, yes we have an RC 1 equipment list, so that's updated regularly to reflect new equipment."* Participant 2	6
No-one is using skill matrix/not updated	*"For skills we have a skills matrix, have you seen that? It's huge, because you can imagine we have lots of skills. Too detailed. No it's not used"* Participant 1	4
	"there is no used skill matrix on site, which is a great pity, and not everyone, not all the management do development plans with their staff, so that is an issue as well, that makes it difficult to know who is doing what all the time, but with a bit of common sense and some conversations usually we can get to the point of who could do this or who has the skills to do this." Participant 4	
Using experience from similar projects	*"It is about what my knowledge is from working in the centre for the last six years, and some of it is about asking to get updated, because always there's new equipment coming in and new capability."* Participant 6	4
	"I've been here long enough to gain an appreciation of what skills we have, what the teams are actually capable of, and from that I can then roughly start to determine who I actually want engaged in the program." Participant 12	
We don't capture capabilities/no database about capabilities (skills/processes)	*"we will need to develop more accurate formal system to capture this."* Participant 16	4
	"I think we had it [skills matrix] ages ago, and I don't think it has been updated, so since many people join the AFRC and many people have left the RC 1, so that becomes you know a bit tricky. So but what we do based on, we go based on experience. (...) I think since we're growing and we've got different you know activities around the centre, I think it would be very helpful to have one, something which is perhaps in house or maybe we get some subscription to some other like a very helpful software which are available on the market, then using them, yes." Participant 7	
	"so the other thing is that I think that there is lack of data to the matter of the process." Participant 17	
No information about availability of people	*"the quote has got to be reflective of the effort of the costs and of the capability and availability, and it may be the case, and I don't know, it's not been my experience but it may be the case that from what I have heard that sometimes that does not a good correlation between the paperwork and the actuality."* Participant 8	2
	"How do I identify who in teams is available, coming into the project who are specialists in aluminium for example, so this would allow me not to have to look for team leaders (...) they hold projects back, so if I have information at my fingertips who is aluminium expert, then I could at least kind of like suggest or advise them into the discussion." Participant 9	

Checking previous applications	*"in my opinion is just asking the experts to write something down to say look this is what we're really good at, this is what we can do, this is what we've done in the past. Maybe making use of previous applications where you know it's kind of generic information, kind of pulling that out of previous applications."* Participant 15	1
Roadmaps	*"if you're writing a bid sometimes it is asking you a specific sort of type of question, so it might drive you down a particular answer but, if it's my area, with other bids that we can pool information from or we can a lot of time, within my head, but then other times, now recently, road maps."* Participant 18	1
Skill matrix	*"For skills we have a skills matrix, have you seen that? It's huge, because you can imagine we have lots of skills. Too detailed. No* ***it's not used, so it's basically, the people who are doing the bits know people who have skills.*** *But* ***obviously that's a point of failure****, yes because if they leave then the database goes with them."* Participant 1	1
N/A	Participant 3	1

4.4.5.6 RC 1 challenges (based on the previous categories)

Considering all the information collected through interviews during Pahe 3, a list of main challenges was created and presented in Table 4.15 below. Firstly, the main issues are connected to difficulties with the project management tool, and they were mentioned by all the participants. The second challenge (not related to programme management tool) is the fact that interviewed participants focused more on teams' target, not on the overall performance of the whole centre. This challenge might be only related to this group of participants, however, participants came from different teams and had different background (e.g. technical, business development etc.), so it was concluded that this issue affects all teams. Hence, it shows that a framework that provides information about different teams and adds element of transparency could help with overcoming this challenge and support overall performance of a research centre. Thirdly, the fact that **capability capture** happens through conversations with several people, and **it's not recorded anywhere**. Those are only three main challenges recognised through data collection process. The rest of the challenges is presented in Table 4.14.

Table 4.14: Summary of challenges mentioned by participants during Phase 3 Interviews

Summary	Frequency	Percentage
Issues with project management software	18	100%
Software is not intuitive, not automatic, manual work needed, limited functions	10	55%
Teams need to see bigger picture/limited cross-team collaboration	10	55%
Software is time consuming	9	50%
Software is not user friendly/has poor interface	9	50%
Limited access to information	8	44%
Structure does not encourage the collaboration	8	44%
Financial targets drive wrong behaviour	8	44%
No centralised system/database for research centre/no transparency	7	39%
Lack of understanding of the market/sector/commercial awareness/idea is not linked to industry	7	39%
Project partners pull out/not enough support from a company	7	39%
Applying for calls that are not aligned with our capability/targeting wrong criteria	6	33%
Managing customers' expectations	6	33%

Difficult to manage workload within the team and outside a team	5	28%
We don't capture capabilities (skills/processes)	4	22%
No information about availability of people	2	11%

Table 4.14 shows challenges discussed by participants in Phase 3. Capturing those challenges helped to understand what issues participants are having with current software (marked in blue) i.e. what participants would like to avoid when future solution is applied. Additionally, challenges marked in green could be addressed by future capability maturity framework (as they highlight capability challenges experienced by participants).

Through the data collection process three main challenges at the research centre were recognised:

- Project management software is Not reliable and not practical enough
- Limited cross-team collaboration
- Lack of capability capture tool

4.4.6 Why was it Important?

In summary the key findings from section 4.4.5 were:

- Challenges of Software X
- Centralised database
- Customer feedback
- Teams' collaboration
- Capability capture
- RC 1 challenges (based on the previous categories)

This interview phase was important to the research because

- It confirmed that research centre had no tool for capturing/defining/measuring capability
- It provided information about future implementation of CMF and what errors should be avoided when implementing new tool across a research centre
- It presented challenges that can be addressed by CMF e.g. mechanism for capability capture
- It highlighted some operational challenges that are related to CMF e.g. lack of transparency between teams or information about what skills a research centre already has, which will be addressed by CMF

4.5 Summary

This chapter contains a lot of information, and so key findings from each phase of interviews is presented in Table 4.15. Table 4.15 presents the summary of each interview phase, and highlights importance of each step. Findings from each Phase contributed to various aspects of CMF. Chapter 5 presents in-depth description of CMF structure and mechanism.

Table 4.15: Summary of key findings and their importance to the research

Interviews	Key Findings	Why is it important?

Phase 1 Interview	• A need for a new framework
	• Features of maturity measurement framework
	  o Simplicity
	  o Clarity of benefits
	  o Potential alignment with other frameworks
	• Clear and Transparent definitions
	• Use of the standardised framework at HVM Catapults
		• Confirmed gap in the knowledge
		• Provided insight into understanding of maturity and readiness
		• Showed why existing readiness tools have not been applicable to research centres
		• Identified features of future framework
		• Proved that there is a need for HVMCs to have a standardised approach

Phase 2 Interview	• Definition of capability (basis for framework design) • Challenges of manufacturing research centres • Operating characteristics of manufacturing research centres	• Confirmed gap in the knowledge highlighted by literature review and Phase 1 • Gave an overview of what is considered a capability in a research centre • Provided understanding of what aspects are important and should be included as part of CMF (i.e. basis for framework design) • Confirmed a need for HVMCs to have a standardised approach • Highlighted link between challenges related to capability management and operations management • Showed that capability and technology cannot be separated
Phase 3 Interview	• Challenges of Software X used by various users/teams • Centralised database • Customer feedback • Teams' collaboration • Capability capture • RC 1 challenges (based on the previous categories)	• Confirmed that research centre has no tool for capturing/defining/measuring capability • Confirmed that there is no (or limited) transparency between teams • Provided information about future implementation of CMF and what errors should be avoided when implementing new tool across a research centre • Presented challenges that can be addressed by CMF e.g. providing transparency between teams • Highlighted some operational challenges that are related to CMF e.g. lack of transparency between teams or information about what skills a research centre already has, which will be addressed by CMF

Findings identified through three phases of interviews reflect issues and perspective of participants. Each interview phase focused on small number of people, who were selected based on their knowledge and experience of working at research centres in the manufacturing sector. Perhaps if more participants took part in this research, different concerns would have been captured (or perhaps it would have confirmed above findings). However, future work could verify that.

Chapter 5: Capability Maturity Framework Development

5.1 Introduction

Findings from interviews (Phase 1 and 2) in Chapter 4 confirmed that research centres need to be aware of their own capabilities, and how mature those are. Hence, **it is of vital of importance to manage research centres' capability maturity through dedicated tools/processes, which are lacking in both the literature and the sector** (Ward et al. 2017). Without such tools/processes, it is very challenging for research centres to address future challenges, design appropriate roadmap and plan for future growth.

It is especially difficult as research centres differ from industry and academia. According to (Hauser, 2014), Catapult centres were created "to close the critical gap between research findings and their subsequent development into commercial propositions. It made a case for long-term UK investment in a network of technology and innovation centres, based on best practice in other countries, such as the Fraunhofer Institutes in Germany and TNO in the Netherlands."

As discussed in earlier chapters (Chapter 1, 2 and 4), research centres play critical role in addressing so-called Valley of Death (VoD). Therefore, they need to know how mature their capabilities are before taking on a project or committing to develop innovation.

Hence, research centres aim "to 'de-risk' innovation by providing a range of services throughout the research and development cycle" (Kerry & Danson, 2016). However, "capability is being developed for potential use by multiple end users on multiple applications" (Ward, et al., 2017). It means that industrial companies might rely on research centres to deliver innovative solutions that they think are specific to a sector, but in fact research centres need to apply their capabilities to various industrial requirements from multiple sectors. That is why research centres need to know what they can deliver, and in order to do that they need to know capability maturity.

By keeping track of capabilities at research centres, senior management benefits from transparency of technological activities, which further supports data-driven decisions and plans. To address the knowledge gap and need of manufacturing research centres, a Capability Maturity Framework (CMF) has been created to standardise the process of managing capability maturity with an aim to support decision-making and strategy building activities within research centres' environment.

In order to better measure the maturity of each Technology Capability possessed by a research centre, a straightforward 9-point index was developed. The Capability Maturity Levels reflect the level of maturity of a specific Technology Capability and it is based on dimensions of CMF (previously introduced in Chapter 4 – Interviews Phase 2). Table 5.1 shows all Capability Maturity Levels (CML) from 1 to 9, in which larger numbers represent higher level of capability maturity. Moreover, Table 5.2 presents dimensions used to measure each CML listed in Table 5.1. As the starting point for this research was 9-point TRL scale, CML was also created as a 9-point scale.

Table 5.2 presents shorter description of each sub-dimensions used to calculate CML. More detailed definitions for each sub-dimension are included in Table 5.3-5.5.

Table 5.1: Capability Maturity Levels

Capability Maturity Level	CML Labels
CML 1	Immature Capability
CML 2	Basic Capability
CML 3	Defined Capability
CML 4	Intermediate Capability
CML 5	Upper Intermediate Capability
CML 6	Pre-Advanced Capability
CML 7	Advanced Capability
CML 8	Strategic Capability
CML 9	Fully Matured Capability

Table 5.2: Dimensions and sub-dimensions of Capability Maturity Levels

Dimensions	Sub-dimensions	Descriptions	References (examples)
D1 People	D1.1 Experience	Embodied by creative, bright and skilled employees who have expertise in their roles.	(Alexander, et al., 2020), (Li, et al., 2019), (Cadorin, et al., 2019), (Cukier & Kon, 2018)
	D1.2 Technical skills	Technological knowledge and skills that provide cutting-edge R&D services to industry/business.	(Leischning & Geigenmüller, 2020), (Alexander, et al., 2020), (Liu, et al., 2019), (Cadorin, et al., 2019),(Wade & Hulland, 2004), (Cacciolatti, et al., 2017), (Hauser, 2014)
	D1.3 Transferable skills	Personal attributes that enhance an individual's interactions as well as job performance and career prospects.	(Ferreira, et al., 2020), (Spring, et al., 2017), (Cunningham, et al., 2020), (Cadorin, et al., 2019), (Saddozai, et al., 2017)
D2 Equipment	D2.1 Uniqueness	A state-of-the-art equipment to help firms with a range of activities from proof-of concept to production validation.	(Toomey, et al., 2019), (Sminia, et al., 2019), (Spring, et al., 2017), (Kerry & Danson, 2016)
	D2.2 Effectiveness	Enhanced through increasing process effectiveness and reducing cost.	(Liu, et al., 2019), (Esmaeel, et al., 2018), (Noh, et al., 2018)
	D2.3 Level of understanding of the equipment	A good working knowledge of the connectivity, specifications and operations of equipment.	(Toomey, et al., 2019), (Hitt, et al., 2016), (Becker, et al., 2015), (Braglia, et al., 2008)
D3 Projects	D3.1 Impact and collaboration	Stronger collaboration enables lower risks and higher impact upon project completion.	(Klessova, et al., 2020), (Tunca & Kanat, 2019)(Linde, et al., 2021), (Magistretti, et al., 2020)
	D3.2 Deliverables	Advanced and innovative solutions deliver new methodologies and bigger impact	(Silva, et al., 2019), (Vrchota & Rehor, 2019)
	D3.3 Project management expertise	Coordination of non-technical tasks in order to successfully manage project requirements and team work	(Silva, et al., 2019), (Vrchota & Rehor, 2019), (Jabbouri, et al., 2019)

Assessments can be done by each participant to each dimension and sub-dimension of capability maturity of each technology capability possessed by a research centre. The assessment results can then be transformed into CML to direct the development of each technology capability. The development of these dimensions and sub-dimensions will be explained in the next section.

Before moving on to next sections, a few important definitions are defined below in order to help understand the CMF mechanism described in the following sections:

- Technology Capability (TC): "Technological capability is a key resource. It consists of technological knowledge, know-how engendered by R&D and other technology-specific intellectual property" (Liu & Huang, 2018) (as previously described in Chapter 1). In this research Technology capability includes 3 dimensions: people, equipment and projects.
- Team Lead or Team Leader (TL): senior member of a team who is responsible for all projects that team is undertaking, and in the most recent time, TLs are also responsible for helping "their teams transition from face-to-face to virtual teams in order to maintain accountability and connection with one another" (Reyes, et al., 2020). Additionally, TLs "may affect work team processes and results" (Santos, et al., 2015)
- Technology Theme Lead (i.e. Technology Capability Lead or TC Lead): from observations at RC 1, it was noticed that teams are split into Technology Themes, which has their own leads responsible for a specific theme. From discussions at RC 1 with team leads and technical theme leads, it was decided that those Technical Themes represent Technology Capabilities essential to teams as well as to RC 1. Also, when visiting HVMC website, Technologies are referred to as 'technology innovation and scale-up capabilities' (High Value Manufacturing Catapult , 2020). Combining information from HVMC website and observations gathered through working at RC 1, it was decided that what HVMC refers to at its website as Technology, and what RC 1 refers to as Technology Theme, are the same thing, and in this research those two terms will be defined as Technology Capability.

5.2. Defining dimensions and sub-dimension of Capability Maturity Levels (CML)

Table 5.2 above shows all dimensions and sub-dimensions developed to measure the CML. The idea of creating 3 dimensions of Capability Maturity Level was based on interview findings in 2017 (Phase 2, section 4.3.5) One of the key findings identified in Phase 2 (chapter 4), was how participants (of Phase 2) defined capability. Capability was defined by participants as equipment and knowledge/experience, but also application of both of those elements, i.e. projects. Those findings corresponded with findings from literature, which were summarized in Table 5.2 above. Literature findings related to each dimension of CMF, are described in sections 5.2.1 – 5.2.3.

The following sub-sections will describe each dimension/sub-dimensions and how they were developed and applied.

5.2.1 D1 People

This dimension includes 3 sub-dimensions: D1.1 Experience, D1.2 Technical Skills and D1.3 Transferable Skills. Each of the 3 sub-dimensions is classified into 9 levels, starting from 1 (lowest) up to 9 (highest), which is consistent with the 9-point index of CML. This dimension was mainly developed with respect to the current human resource (HR) requirements focusing on three important elements: experience, level of technical and transferable skills.

Human aspect has been widely highlighted in various management areas. Particularly, **empirical knowledge** is emphasised as one key feature of human capability (Alexander, et al., 2020), (Cadorin, et al., 2019), (Li, et al., 2019) (Cukier & Kon, 2018). People are unique in learning as "it is in these employees that firms not only find the greatest repertoires and diversity of knowledge but also the most flexibility in acquiring new knowledge" (Liu, et al., 2019). **Technical skills** is deemed as another key feature (Alexander, et al., 2020), (Leischning & Geigenmüller, 2020), (Liu, et al., 2019), (Cadorin, et al., 2019). Being able to learn and improve, technically skilled personnel provide many organisations "a basis for developing national competitiveness" (Cacciolatti, et al., 2017) as well as "cutting edge R&D services" (Hauser, 2014), both are essential to overcome VoD.

Literature also highlighted the importance of **soft/transferable skills**. As reported by (Cacciolatti, et al., 2017), such skills stem from "personal attributes that enhance an individual's interactions as well as job performance and career prospects". Employees need to "be good communicators, ambitious and team players" and motivate others to make independent yet prompt decision making. People with good soft skills have positive influence on the culture and structure of an organisation (Cadorin, et al., 2019) and this also helps firms achieve exceptional outcomes (Ferreira, et al., 2020), (Spring, et al., 2017), (Saddozai, et al., 2017).

In addition, through work at one of the research centres, it was observed that few years ago a skills matrix was created but never implemented at a research centre. However, skills included in that matrix were used as a starting point for creating sub-dimension D1.2. Later on (during pilot study, described in section 5.6), participants were able to add and remove skills relevant to their TC. That contributed significantly to creation of D1.2: Technical skills, which is presented together with D1.1: Experience, and D1.3: Transferable skills in Table 5.3.

Table 5.3: Definitions for three sub-dimensions of D1 People

Numeric Indicator	D1: People		
	D1.1: Experience	D1.2: Technical Skills	D1.3: Transferable Skills
0	Not Relevant	Not Relevant	Not Relevant
1	(Intermediate) Apprentice Programme/Equivalent educational level: 5 GCSE passes*	General theoretical knowledge about this particular skill	Person pays attention to details, is organised and has knowledge of basic processes related to technology capability
2	Advanced Apprentice Programme completed/Equivalent educational level: 2 A-level passes/Level 3 Diploma/International Baccalaureate*/Delivers general help	Basic Knowledge demonstrated, but no practical skill/Beginner level	Knowledge of regulatory issues affecting work and safety in relation to this technology capability
3	Higher Apprentice Programme completed/Foundation, Bachelor's or Master's degree completed*/Limited practical experience/Need more training/Still needs supervision and guidance	Knowledge demonstrated but still requires more practice/Needs more training in order to develop the skill	An ability to work as part of a team/Good presentation skills and experience of presenting to a range of audiences/Follows instructions given by supervisor/senior member of staff
4	PhD/EngD in relevant research area completed OR equivalent work experience received through full time employment and/or completed apprenticeship/Theoretical knowledge in the general field is quite high	Learner knowledge demonstrated/Skills developed under supervision	Person receives a general guidance from Team Lead, but is able to work independently on a number of projects/Ability to develop technical skills and potential to support team's performance but still needs supervision and guidance
5	Person has demonstrated their engineering knowledge relevant to his/her current research and contributed to successfully completing various projects OR person is Charted Engineer	Skill developed and demonstrated through multiple trials/projects	Ability to work autonomously and to plan and prioritise his/her own workload with minimal inputs from higher management; also and developing evidence of leadership.
6	Person has a successful track record of leading various projects /Expert - Research Centre Level/'Go to' person at the research centre in that area	Skill mastered/no supervision needed in application of skills/Proven track record	Ability to lead in and take technical ownership of research and development areas, manage the work of R&D engineers, and mentoring colleagues/Person is able to successfully guide/mentoring/training other members of the team
7	Expert- HVMC Level/Nationally recognised expert/Track record of nationally and internationally recognised research	Advanced/in-depth knowledge and skill level developed by experience gained through multiple projects/applicability of knowledge and skills in everyday work	Person leads the development and submission of proposals to appropriate external bodies for research funding of substantial value, manage grants awarded and guide other team members in establishing their own leadership in this area.
8	Person is an acknowledged expert in research which is consistent with the strategic direction of HVMC with an established national and emerging international reputation.	Advanced/in-depth knowledge and appropriate skills mastered through multiple (innovative and standard) projects	Ability to influence stakeholders, internally and externally, at varying levels and ability to convey compelling arguments with complex technical information/Person has proven staff and project management skills and excellent interpersonal and communication skills
9	Person works closely to established national manufacturing network of research centres/Person has led and developed national and international projects	Continuous skill improvement/further development of additional skills/Mastering broader spectrum of knowledge that could be applicable in a new implementation	Person carried out senior functions, participating in relevant School/Faculty/University committees as required/Person encourages innovation/innovative solutions

*based on "The Complete Guide to HIGHER AND DEGREE APPRENTICESHIPS" accessed through gov.uk

5.2.2 D2 Equipment

This dimension includes 3 sub-dimensions: D2.1 Uniqueness, D2.2 Outcomes delivered and D2.3 Level of understanding of the equipment. All 3 sub-dimensions have definitions that reflect 9 levels, starting from 1 (lowest level) up to 9 (highest level).

Definitions were based on interviews discussed in 2016, 2017 and 2018. Depending not only what kind of equipment a research centre has (i.e. uniqueness), but also what do we actually use it for (i.e. do we use it at all? Should we be using it more? Should we start projects that require the use of this equipment?). Therefore the first two sub-dimensions of D2 were inspired by interviews with participants. However, having equipment in the research centre is only one part of it, as research centre also needs to understand who is trained to use it. For example, one participant confirmed that a certain manufacturing research centre had purchased an equipment, but there was no one there who could use it. And so, a research centre needed to book a consultant who would come over and set up the machine.

There was also a different example were an equipment had been purchased but because of some malfunction no one used it for a great amount of time. Hence, again, a research centre had to wait for a consultant who would come over and fix it. However, due to the fact that it was a specific type of kit, there was a waiting time, as the person who knew how to fix it had other appointments in other places. Therefore, a research centre can have a unique equipment, but no one to use it, and so there will be no outcomes delivered by the machine. On the other hand, a research centre can have an ordinary machine, but few good engineers who know who to use it and fix it, hence the outcomes delivered by the machine might be of higher level than expected.

By using findings from interviews as a starting point, the literature review also provided examples of aspects of equipment that are important to consider. (Toomey, et al., 2019) highlighted that "suitable environment, equipment and software are, of course, essential for any research project." In a research centre environment, suitable would mean **unique or specialist equipment** (Spring, et al., 2017), or "a state-of-the-art equipment and capabilities" to help firms overcome VoD (Hauser, 2010). Such equipment is vital to support the development of advanced manufacturing technology in enhancing firms' competitiveness, sustainability and social responsibility (Sminia, et al., 2019). Therefore, another concern is **the effectiveness of equipment** which is defined as the ability of equipment to enhance manufacturing process effectiveness and reduce cost (Esmaeel, et al., 2018).

However, equipment uniqueness/effectiveness alone does not guarantee successful outcomes and "it should go hand in hand with human capability" (Liu, et al., 2019). This can be assessed by the **level of understanding of equipment** – employees' working knowledge towards the connectivity, specification and operations of the equipment (Toomey, et al., 2019). Such understanding not only can prevent manufacturing losses, hence improve effectiveness (Becker, et al., 2015), but also protect research projects from human-related disruptions (Braglia, et al., 2008).

Detailed definitions for D2.1 Uniqueness, D2.2 Outcomes delivered and D2.3 Level of understanding of the equipment, are presented in Table 5.4 below.

Table 5.4: Definitions for three sub-dimensions of D2 Equipment

Numeric Indicator	D2: Equipment		
	D2.1: Uniqueness	D2.2: Outcomes Delivered	D2.3: Level of understanding of the equipment
0	Not Relevant	Not Relevant	Not Relevant
1	Equipment not based in the centre/Available in other research centres	Equipment has not been used yet	Beginners knowledge on equipment's' functionality/Process of understanding the behaviour of the machine initiated
2	Typical equipment found in many research establishments	Generic test piece / sample (e.g. coupon)/Special purpose for test rig/Test rig or mocked-up equipment/Process of identifying projects requirements and which projects could the equipment be used for	Basic understanding of few features/Still requires more learning/training/Apprenticeship level of understanding the machine
3	Somehow specialised but seen in several research established	Customer defined test piece / sample (including characteristics of eventual application)/ Not achieving correct standard yet /Investigating stability of the machine	Good understanding of key features/ Training in progress
4	Important to centre portfolio, but may be duplicated in different national centres/Standard features	Development standard output/Correct standards achieved	Clear understanding of how to use the machine in order to deliver standard solutions/Making use of key functionality but more advanced features not used
5	Some non-standard/unusual features which make the equipment more unique/hard to duplicate	Confirming optimal specifications/Equipment used in a variety of projects	Key features understood well but still learning additional/advanced/unusual features
6	Extensive unusual features or size/scale, making equipment more unique and important to research centre allowing to apply innovative solutions	Development standard output (plus at least one-off to production standard)/Proven track record within the scope of use	Operator level achieved-able to train others and explain behaviour of the machine/Making full use of additional/advanced/unusual features
7	Demo functions at a local level/Locally or regionally important/Key local differentiator for centre	Production standard output (multiple-off)	Fundamental process understanding of basic and additional features confirmed and demonstrated on variety of projects
8	Nationally recognised demo function/Demonstration equipment for HVMC	Using standard machine in a non-standard way/Testing other aspects of the machine for innovative solutions/processes	Fundamental process understanding of basic and additional features defined through methodology
9	Globally unique equipment/Equipment cannot be replicated elsewhere/ Highly important to manufacturing research centres	Other non-standard aspects confirmed through successfully completed trials/Proven track record within and out of scope of use	Supervision level achieved-able to train others and to supervise others who use the equipment/Continuous improvement/further understanding of the equipment and how it's features could be used in non-standard/innovative way

5.2.3 D3 Projects

This dimension includes 3 sub-dimensions: D3.1 Impact and collaboration level, D3.2 Outcomes delivered and D3.3 Project areas covered. All 3 sub-dimensions have definitions that reflect 9 levels, starting from 1 (lowest level) up to 9 (highest level).

As mentioned in previous chapter, customer feedback was one of the discussion points during 2018 interviews. 33% of participants mentioned that the future customer feedback could be more detailed and customers could be asked more qualitative questions in order to help the centre understand what aspects could be improved in the future, e.g. "It can have a good relationship and it doesn't mean that you do a good job" P17. Moreover, 28% mentioned that customer feedback forms should include questions about impact, i.e. "asking how useful it actually was to the customer, you know so how effective it was, so that the customer receive that they are then seeing the benefits that they thought they were going to see in their industry" P3. Therefore, it gave motivation to create sub-dimension D3.1.

Additionally, supportive information was identified in the literature. For example, according to (Silva, et al., 2019), maturity frameworks are imperative to achieve effectiveness and efficiency in project-oriented working environment, which is a key OC of research centres (Klessova, et al., 2020), (HVMC website, 2020). In particular, the collaborative nature of projects has been stressed as foundation to project success (Tunca & Kanat, 2019). Such collaboration would encourage teamwork between different stakeholders to create an impact on industry.

Furthermore, some participants (during Phase 3) mentioned that even though they have strong engineering skills, there could be a time when we need more project managers who would manage the non-technical workload. But in order for project managers to know what is the biggest issue (for technical teams), technical teams need to highlight what are the most challenging aspects, do they struggle with them constantly or only with bigger projects? Is it because of the lack of resources? Is it because of the long administrative procedures? Hence, that was a reason for creating the sub-dimension D3.3: Project areas covered, i.e. to find out which areas are the most problematic and to identify corrective actions (which could be applied potentially to more than one team, if other teams struggle with similar issues).

Another aspect is to make sure that project outcomes can meet project requirements, i.e. deliverables. While a wide variety of project management tools is readily available to help project-oriented organisations (including research centres) fulfilling requirements (Silva, et al., 2019), there is no panacea given the dynamism associated with the current state and target state of a project (Vrchota & Rehor, 2019). Therefore, research centres need to keep track of what has been delivered by a project and learn from any deviations. It is, thus, essential to have the appropriate non-technical expertise across key knowledge domains by including "specialists from different areas and the coordination amongst different departments and companies" (Silva, et al., 2019). This also enables project managers to "get acquainted with the latest developments from project management" (Vrchota & Rehor, 2019)and manage different project areas as a whole.

Detailed definitions for D3.1 Impact and collaboration level, D3.2 Outcomes delivered and D3.3 Project areas covered, are presented in Table 5.5 below.

Table 5.5: Definitions for three sub-dimensions of D3 Projects

Numeric Indicator	D3: Projects		
	D3.1: Impact and collaboration level	D3.2: Outcomes delivered	D3.3: Project areas covered
0	Not Relevant	Not Relevant	Not Relevant
1	No projects in that research area	No projects in that research area	Manufacturing Process (what is the technology area/what are we testing)
2	Internal project/standard (or repeated) work that was required before/Low impact on the research centre /No equipment used i.e. desk work/Basic trial demonstrating concept and application	Basic trial demonstrating concept and application/Read across from academia/Academic partners leading development/Desk based work	Materials/Impact of manufacturing process on material/Can we complete the material testing?
3	Project involved only one stakeholder i.e. directly reporting to one client/ standard work required, no innovative aspects	Initial work underway to identify key process variables/Understanding how the change of parameters/requirements will affect the results, and to what degree/ Understanding customers' specifications/ Read across from other sector	Product requirement/What are the requirements?/What are the components?/How will we validate the component testing?
4	Project involved only one stakeholder involved/standard work with elements of innovative activities required to complete the project	Trials phase(s) demonstrate(s) all key aspects of fundamental process understanding/Understanding what materials/components can be test by the equipment /Independent verification of the feasibility of achieving acceptable standards	Operational/do we have operational target and plan to achieve them?/ Is there a process understood from operational viewpoint?
5	Project involved more than one stakeholder involved/Mostly innovative work required with some standard aspects included	Probable key process variables and method of control identified/Solidifying the methodology process/ Clear understanding of the process and being comfortable how to re-use it in the future	Data and systems/ do we have all necessary data and systems in places to achieve and analyse results? Are there any changes in the system that are not approved by research centre's standards?
6	Collaborative project/Medium impact on UK sector(s)/Mix of standard and innovative work/Building up methodology for process control/Benchmarking with results from other places	Work completed on representative standard kit / Process control strategy demonstration on representative production equipment	Programme of work/Project Management /Risk Management
7	Nationally recognised project/Collaborative project/Different stakeholders involved/High impact of the project on UK sectors/Innovative project with some bits of standard work	Initial, low rate production trial confirms all aspects of a new product/process/Early stage or sub-optimal factory production	IP/ do we have procedures to manage IP process? How IP generation process is being protected- do we have that in place?
8	Nationally and internationally recognised project/A range of different stakeholders involved/High impact of the project/Highly innovative project	Work on a live production process/Process parameters confirmed and sealed/Statistically significant production trial confirms all aspects of new product/process	Quality Assessment/Continuous Improvement/ do we have quality assessment process in place?/have all processes and operators passed the quality control/are the necessary qualifications completed (i.e. for operators and machines)?
9	Globally recognised projects/Collaboration with major companies/A range of stakeholders involved/High Impact/Highly innovative project	Continuous improvement/Stable process achieved/Process methodology developed, tested and applied through different technology capability	Sourcing and Supply Chain/is there a supply chain in place?/do we need to seek suppliers in any of the areas of the supply chain?/are there any approvals needed to set up new supply chain?/ Finance/Business case/Funding

5.2.4 Definition of Capability Maturity Levels

Once all dimensions and sub-dimensions were defined, it was possible to measure the CML. In other words, each CML can be defined in terms of the three dimensions, D1, D2 and D3, which in turn can help define each sub-dimension of each dimension, i.e. D1.1-D1.3, D2.1-D2.3, and D3.1-D3.3. Since each sub-dimension is classified into 9 levels, each level can then be defined to match with the same level of CML, .e.g. matching level 1 of D1.1, D1.2 and D1.3 with CML1. Next, the same can be done across all sub-dimensions in order to complete the measurement of one CML. The whole process can be repeated to define each CML and differentiate a lower CML from a higher CML, e.g. from CML 1 to CML 2, CML 2 to CML 3, etc. Table 5.6 shows the definition of CML in terms of the three dimensions, D1, D2, and D3. The measurement of CML will be discussed in the next section. Table 5.6 is a shorter version of CML. Full version (which is combined from Tables 5.3-5.5) is included in Appendix 17.

Table 5.6: Capability Maturity Levels – definitions

CML	D1: People	D2: Equipment	D3: Projects
CML 1: Immature Capability	• Limited number of skills or only theoretical knowledge demonstrated • Team has little experience in TC and needs to develop their skills and knowledge.	• Equipment is not based at the research centre (offshoring) or it has not been used yet. • No or minimal understanding of equipment for this TC.	• No completed projects in this TC.
CML 2: Basic Capability	• Basic knowledge and skills demonstrated by team members. • Practical skills in need of further development. • Knowledge of regulatory issues affecting work and safety. • A need for guidance and support is clear.	• Equipment/machines are placed at the research centre however, those are typical machines that could be found in other research centres. • Basic understanding of the equipment has been shown. • A basic understanding of a few features has been shown • Process of identifying projects requirements and linking projects with necessary equipment has been demonstrated.	• Small, internal projects with low impact • Projects that involve desk work or basic trial demonstrating concept and application, i.e. read across from academia. • Only one area covered: product requirements, no practical/physical trials started.
CML 3: Defined Capability	• Team members demonstrated some technical knowledge • Team is still required to continue improving their skills and expand their knowledge. • Team shows good organisational and interpersonal skills. • Guidance and support from team lead or other (more senior team members) is needed.	• Machines located in the research centre for this TC are somehow specialised but seen in several research centres already. • Team is still investigating stability of machines. • There is a good understanding of key features, but training and further understanding of the machine is still needed.	• Projects involved one stakeholder i.e. directly reporting to one client and only standard work required (i.e. something that was done before, no innovative aspects). • The completed projects involved work that identified key process variable, understanding effect of parameters' modification etc. Two areas covered: product requirement and manufacturing processes
CML 4: Intermediate Capability	• Team has demonstrated some experience successfully but certain skills need further development. • There is a potential to develop advanced level of skills among team members. • Team works well together however communication problems took place before	• Standard features of the equipment understood and used during several projects, i.e. standard outputs achieved. • More advanced features still need to be understood	• Some projects completed, mainly involved one stakeholder. • Standard work performed, minimal innovative activities shown. • Projects mainly involved trial phases to demonstrate key aspects of fundamental process understanding/ what materials can be tested by the equipment/ verification of the feasibility of achieving acceptable standards.
CML 5:	• Team members have high level of experience through their previous work experience	• Equipment with some non-standard features is based at the research; hard to duplicate	• Projects involved one or more stakeholders • Mostly innovative work has been completed with some standard processes included.

Upper Intermediate Capability	• Technical/practical skills were demonstrated on a variety of projects. • Team members are mostly able to work autonomously given guidance from team lead or senior management.	• The understanding of machines is advanced i.e. standard features are well understood but a further training is needed to understand additional, non-standard features and manage them with confidence.	• Projects delivered key process variables and identified method of control, i.e. projects solidified the methodology process.
CML 6: Pre-Advanced Capability	• Team has demonstrated their skills and creative thinking by come up with innovative results on number of occasions • Team members support each other and share knowledge related to various topics related to this TC. • Team members are able to work autonomously with minimal guidance.	• Equipment has extensive unusual features which makes it more unique to research centres. • It allows to apply innovative solutions which has not been demonstrated elsewhere. • Machines were used to develop standard outputs (plus at least one-off to production standard). • Equipment has been used within full scope of use. • Equipment is well understood by the team, and some team members are able to train others	• Projects (some of them collaborative) had medium impact on UK sectors. • Combination of standard and innovative work was performed. • Projects results were compared with results from other places in order to build a robust methodology for a processes involved. • Projects involved work that was completed on representative standard kit, and so process methodology was demonstrated on representative production equipment.
CML 7: Advanced Capability	• They have advanced/in-depth knowledge and practical skills in a various areas of this TC. • Applicability and high level of skills can be observed on a daily basis and through various past project. • Some team members know how to manage grant awards and can train others in doing so. • Some team members also showed leadership skills	• Equipment for this TC is recognised regionally and it is a key local differentiator for the centre. • It possesses demo functions at a local level. • It was used on a variety of projects, from basic standard activities, to innovative solutions where production standard output (multiple-off) was demonstrated. • Fundamental processes as well as additional features were confirmed and demonstrated on a variety of projects	• Projects completed at this level were highly collaborative with various stakeholders involved. • Completed projects had high impact on UK sector and on companies involved. • Projects involved innovative applications with some bits of standard work. • Projects also confirmed aspects of new product/process when applied to low rate production trial. • Projects also involved early stage or sub-optimal factory production
CML 8: Strategic Capability	• Team members develop knowledge and skills through various projects in alignment to HVMC strategic direction. • Team members have the ability to influence stakeholders and convey compelling arguments with complex technical information. • Team manages projects with high organisational level and resolve any	• A key piece of equipment which can be also used as demonstration equipment for HVMC. • In-depth understanding of the machines based on conducting innovative tests and using machines in non-standard ways. • With the increased usage of equipment the understanding also increased and a defined methodology for new features has been created.	• Highly innovative projects with multiple stakeholders involved were completed successfully with high impact • Projects involve extensive knowledge of production processes, which was demonstrated by the team. • Team has broad understanding of project management and wider view of external factors that are affecting the research centre.

	challenges through advanced communication and problem-solving skills.		
CML 9: Fully Matured Capability	• Team members continue to work on implementation of technical knowledge and skills in innovative solutions. • Team members also show high level of organisation and transferable skills, as well as communication. • Team works well together and supports each other when technical challenges arise.	• Unique equipment that cannot be replicated elsewhere, i.e. it has significant impact on a research centre and HVMC. • Advanced level of knowledge in relation to the equipment is advanced and there is a proven track record within and out of scope of use. • Other non-standard tests had also delivered satisfying results.	• Challenging projects that involved major industrial companies were completed successfully. • Completed projects provided evidence of highly innovative approaches and significant impact on manufacturing sectors • Through those projects team demonstrated that they have continuous improvement process in place and methodology has been tested and applied trough this TC

5.3. Measuring Capability Maturity Levels- How does it work?

5.3.1 Background Information

(Clapham & Nicholson, 2005) defined vector as term that "is used to describe a physical quantity like velocity or force that has magnitude and a direction. Sometimes there may also be a specified point of application, but generally in mathematics that is not of concern. Thus a vector is defined to be 'something' that has magnitude and direction." Additionally, (Shenoy, et al., 2019) discussed the importance of vectors and matrices in managerial decision-making, as well as in "marketing, finance, production, accounting and personnel." Moreover, "matrices provide a compact way of writing a system of equations and a method of representing large quantities of data" (Shenoy, et al., 2019).

Using above references, the following advantages of vectors calculations were noticed

- Vectors have magnitude and direction, i.e. when represented graphically it is easy to identify if vector if 'moving' in the right direction
- Vectors could be represented as matrices, which could help with understanding mathematics behind final results
- They are scalable, i.e. if a weight (represented by a scalar) is added to a process, it is easy to implement: "let $\boldsymbol{a}$ be a non-zero vector and $\boldsymbol{k}$ a non-zero scalar. The scalar multiple of by $\boldsymbol{k}$, denoted by $\boldsymbol{ka}$, is the vector whose magnitudes $|\boldsymbol{k}||\boldsymbol{a}|$ and whose direction is that of $\boldsymbol{a}$, if $k > 0$, and that of $-\boldsymbol{a}$, if $k < 0$" (Clapham & Nicholson, 2005)
- Vectors and matrices are part of "practical analysis, but with the emphasis always on practical algorithmic ideas rather than mathematical technicalities" (Trefethen & Bau III, 1997)
- The process is replicable, as the same properties hold for vector calculations.

This study required an approach that can accommodate different elements of technology capabilities (i.e. 3 dimensions) but that is also repeatable regardless of TC. What is more, it needs to use simple equation to present the results. The idea of using vector equation in a 3D plane is based on the fact that research centre's TC has 3 dimensions: people, equipment and projects (and so each dimension is treated as a separate plane). In mathematical terms, the three axis (three planes) are independent from each other, but combined together (from each other), together they represent maturity level of a TC. It means that using magnitude of a vector equation a measurement is calculated using all three dimensions to get one single result for a TC. The CML of a TC, expressed as a magnitude of a vector in a 3D plane, can then be computed by aggregating the performance presented at each of the 3 dimensions.

What is more, by presenting each TC as a magnitude of a vector, it is possible to compare different TCs and even compare different research centres' overall capability maturity (by adding all vectors together and representing it geometrically). This approach delivers clarity over TCs which i.e. answering the question about are we (as a research centre) mature enough to deliver this product/project.

The 9 sub-dimensions are therefore used as basis for vector calculation to compute CML for each TC. Each dimension has 3 sub-dimension, three vectors are calculated. Using 3D plane and equation for a magnitude of a 3D vector (equation 1 below), the 3 vectors are then used to create a 3D vector with a magnitude that combines all 3 vectors (based on sub-dimensions). The combined 3D vector starts at the origin of the plane i.e. at point (0,0,0). As the magnitude of the vector increases, it means that more mature TC becomes.

In order to calculate the magnitude of a vector, this requires a basic knowledge of linear algebra and its approach of viewing 3D planes. According to (Clapham & Nicholson, 2005), magnitude of a vector is defined as

if vector $\boldsymbol{a}$ is given in terms of its components (with respect to standard vectors $\boldsymbol{i}, \boldsymbol{j}$ and $\boldsymbol{k}$) in the form $\boldsymbol{a} = a_1\boldsymbol{i} + a_2\boldsymbol{j} + a_3\boldsymbol{k}$, the magnitude of $\boldsymbol{a}$ is given by the formula

$$|\boldsymbol{a}| = \sqrt{a_1^2 + a_2^2 + a_3^2} \tag{1}$$

Equation (1) can be changed into equation (2)

$$|TC| = \sqrt{X^2 + Y^2 + Z^2} \tag{2}$$

where X, Y and Z are $\boldsymbol{x}$ (or $\boldsymbol{i}$), $\boldsymbol{y}$ (or $\boldsymbol{j}$) and $\boldsymbol{z}$ (or $\boldsymbol{k}$)components (respectively) in a 3D plane. For example, if X is equal 14, Y is equal 23 and Z is equal 16, then (using equation (2)) |TC| is equal to 31.32. Figure 5.1 shows an example of 3D vector with a magnitude of 31.32.

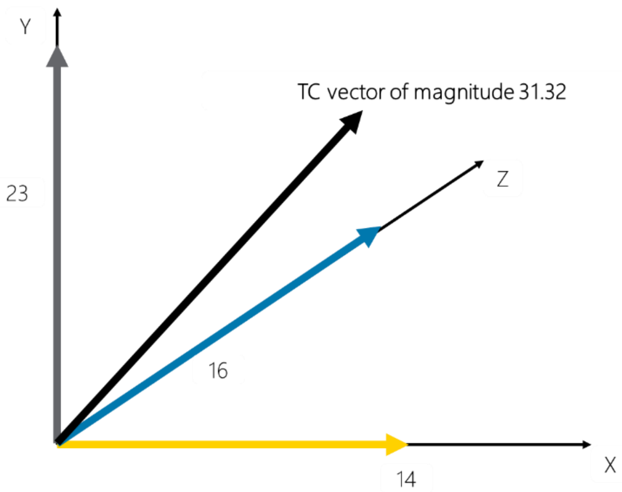


Figure 5.1: Example of visualisation of Capability Maturity Level for a TC

There are many examples where linear algebra and vector equations were used in the literature. Usually those examples involve technical and engineering research e.g. communication signal (LI, et al., 2012), but also in medical science (Zayed, 2019), finances (Katsikis & Polyrakis, 2012), accounting (Ajogbeje, 2012), business management (Chen & Hsiao, 2008), as well as operations management (Gupta, 2007) and decision making (Chen, et al., 2019), (Srdjevic, et al., 2013), (Yue, 2012).

There are many linear algebra-based approaches that researchers used, even for non-mathematical research, e.g. business studies. Table 5.7 shows some of the approaches used for more than just mathematical applications, e.g. decision-making or prioritisation.

Table 5.7: Summary of examples of mathematical approaches from literature

Approach	Application	References	Why those approaches are not applicable in this study
Support vector machine	Business environment/business crisis	(Chen & Hsiao, 2008)	It requires financial data, but this study only considers expert judgement
Genetic algorithm	"used to solve global optimization problems (...); Every individual in the population means a possible solution, referred to as a chromosome"	(Chen & Hsiao, 2008)	Chromosomes are usually defined in 1 or at most 2 dimensions. But this study requires 3 dimensions to define capability maturity, and optimisation is not a scope of this research (not at this point)
VAHP: the conventional AHP formulations to a Euclidean vector space	"The VAHP enables us to analyse the decision problems in a geometrical sense and the similarities between decision makers can be treated in terms of the scalar product of two preference vectors"	(Zahir, 1999)	The prioritisation of objects in the decision making process is not suitable to this research
Weighted approach (ordered weighted averaging)	The approach includes orness (i.e. proximity) operator, and it requires few mathematical theorems which would make this particular problem more complicated.	(Chen, et al., 2019)	Prioritisation of answers would deliver subjective results to senior management where high objectivity is required in this study
MADM (multiple attributes decision making) method	This method requires weighting and ranking not only the experts involve in decision making but also ranking the alternatives.	(Yue, 2012)	Weighting and ranking of alternatives scenarios is outside the scope of this study

Table 5.7 reports a collection of complex approaches that use linear algebra. However, they also consider aspects (such as prioritisation of alternatives, weighting of objects and decision makers, financial data, etc.) that are not relevant to this research. This study does not take into consideration any financial data and, all dimensions and sub-dimensions of each TC are equally important. Hence, the CMF requires a simple yet comprehensive mechanism. The simplest way is to treat each TC as a vector in a 3D space (corresponding to 3 dimensions: people, equipment and project), which will help measure its capability maturity (i.e. various TCs) analytically (i.e. data-driven) and geometrically (i.e. easy to understand and apply).

One main reason why approaches presented in Table 5.7 above are not applicable is that they are mostly used to resolve a well-defined problem. However, part of this research was to define a new problem and then develop a new framework. As this is a novel research regarding capability maturity of technology in a research centre environment, the problem/inputs might change as the CMF evolves and refines. Therefore, the above approaches could be used in the future once the CMF reaches the full implementation stage with sufficient amount of operational data. In the meantime, in order to capture and define capability in a research centre, a simpler approach is applied. As discussed before, (Shenoy et al., 1991) mentioned how "vectors and matrices play an important role in modern techniques of quantitative analysis of managerial decisions. Matrices provide a compact way of writing a system of equations and a method of representing large quantities of data." In other words, vectors and matrices use large quantities of data and through mathematical calculations, transform those large quantities of data into simple numerical solution. Hence, it is useful as it allows taking large quantities related to each technology capability, and

transforming them into a simple number, which is easier to understand then going through large datasets.

The other benefit of vector approach is **replicability of the process**, as the same properties hold for vector calculations for every technology capability and every research centre. Therefore, the calculations can be (in the future) be easily transferred into a digital and automated environment.

Apart from that, in this study it was important to use structured equation that will give overview of three separate elements (people, equipment, projects) and that is why an equation of magnitude of a vector was preferred approach in this research.

5.3.2 Calculating sub-dimensional maturity levels

5.3.2.1 Ratio of *Current scenario* and *Best-case scenario*

For each of 9 sub-dimensions, a sub-dimensional maturity level (SML) is calculated. Each SML is based on a ratio between *Current scenario* (assessment provided by participants) and *Best-case scenario* (where all individual data points are rated as 9- the highest value of assessment that participant could provide). The result will depend on number of people/equipment/projects i.e. n. Assuming that *Best-case scenario* will happen if everyone/everything that is part of a TC achieved 9, therefore $n \, x \, 9$ will provided highest result (i.e. *Best-case scenario*). On the other hand, *Current scenario* will depend on the assessment by a TC lead, by summing up all assessments together. Hence, the ratio is calculated as follows:

$$\frac{Current\ scenario}{Best\ case\ scenario} = \frac{(sum\ of\ all\ assessments\ provided\ by\ a\ TC\ lead)}{n\ x\ 9\ (9\ being\ the\ highest\ possible\ score)} \qquad (3)$$

This approach was selected due to its simplicity and the fact that this aspect was one of the features mentioned by participants in Phase 1 interviews (Chapter 4). The other reason was that it can be changed into weighted approach if needed (in the future). Therefore, by using this ratio approach, a weighted elements can be added to specific sub-dimensions (e.g. depending on which sub-dimension is most important to a research centre) or even to single assessments (e.g. adding a weight factor based on the strongest member of a team, most used machine, etc.). Lastly this approach can be applied to a variety of data sets (regardless of their size) i.e. its process is **repeatable** and objective (as currently no weighted element were added to calculations).

5.3.2.2 Ratio of *Current scenario* and *Best-case scenario* – Example

This section is using approach introduced in section 5.3.2.1, but with a numerical example to explain the approach. For example, if a certain TC has 7 individuals who contribute to the maturity of that TC, i.e. TC lead will be required to evaluate all individuals using the people dimension. Hence, TC lead might give the following assessment scores (example is presented in Table 5.8 below).

Table 5.8: Example of data points for dimension D1.1

Person ID	Score assigned by TC lead
Person 1	6
Person 2	4
Person 3	4
Person 4	3
Person 5	4
Person 6	4
Person 7	5

Current scenario is calculated as sum of those scores (which is 30), and *Best-case scenario* is calculated as if all individuals score 9 (which is 9*7=63). Next step is to compute a ratio by dividing *Current scenario* over *Best-case scenario* using equation (4):

$$\frac{Current\ scenario}{Best\ case\ scenario} = \frac{30}{63} = 0.476 \tag{4}$$

In this example, 0.476 is considered the value that is now assigned to dimension D1.1 of this TC. This ratio is useful to indicate the gap between *Current* and *Best-case scenarios* as well as the potential for future improvement. Upon knowing the value of sub-dimension D1.1, the next step requires assigning a sub-dimensional maturity level to that value, which is explained in the next section.

In addition, that number of team members between different TC will differ, and while one TC might have 7 team members (as described above), there could be smaller teams with only two or even one person. It is also true that even in teams that involves 7 people (or more), there could be one person with high (i.e. advanced) skills and knowledge. It means that a lot of work depends on that person, and if that person is not available (or decides to leave a research centre), that team will lose significant amount of knowledge/experience/skills. That creates a huge risk to TC and research centre. Therefore, the aim of CMF is recognise those gaps and deliver visibility and transparency of various capabilities across research centre.

5.3.2.3 Calculating Lower and Upper limits for Sub-dimensional Maturity Level

As explained in the previous section, sub-dimensional maturity level (SML) depends on the ratio between *Current scenario* and *Best-case scenario*. *Best-case scenario* illustrates a case were all assessments are equal to 9 (the highest possible score), as previously described in section 5.3.2.1: $n\ x\ 9 = Best\ case\ scenario$, assuming that n is number of people/equipment/projects in a team, e.g. if there's 7 people in the team, then $7\ x\ 9 = 63$:

$$\frac{Current\ scenario}{Best\ case\ scenario} = \frac{63}{63} = 1 \tag{5}$$

As the *Current scenario* cannot be larger than *Best-case scenario*, the ratio of the two values is equal to 1, which is the upper limit for SML. If the ratio is larger than 1, then it means that there was an error when entering data points because *Current scenario* to *Best-case scenario* ratio cannot be larger than one. Error like that might not happen often, however, due to the fact that data inputs are entered manually, there is a possibility of human error. To avoid carrying that mistake further in calculations, 'error' message will appear if wrong data inputs were entered into CMF.

On the other hand, the assessment could be the worst (the lowest possible score). Assuming that all assessment scores are equal to 1, equation (5) will change into

$$\frac{Current\ scenario}{Best\ case\ scenario} = \frac{7}{63} = 0.111 \tag{6}$$

Also, let's assume there is a new team including only one person with a specific skill but at the very beginning of their career, then equation (6) will change into

$$\frac{Current\ scenario}{Best\ case\ scenario} = \frac{1}{63} = 0.016 \tag{7}$$

Even though, the likelihood of that event is small (and out of scope of this project), the mechanism of CMF should consider all possibilities. Hence, even with small possibility of happening, CMF will be able to support the evaluation of capability maturity.

Therefore, the lower limit for SML is 0, and the upper SML is 1. As there are 9 SMLs, values between 0 and 1 need to evenly fit into those 9 levels. Hence, equation (8) was used to identify the numerical difference between levels:

$$\frac{(\max value - \min value)}{9} = \frac{(1-0)}{9} = 0.111 \tag{8}$$

The value of 0.111 is used to represent the numerical difference between each SML. In addition, it relates to the fact that if all assessment score are equal to 2, then *Current* to *Best-case scenario* ratio is equal to 0.222, i.e. the difference is 0.111. Table 5.9 below represents differences between examples where it is assumed that all assessment scores are equal the same value.

Table 5.9: Example of *Current* to *Best-case scenario* when all data points are equal

If all data points are equal to	Current scenario/best case scenario
1	0.111
2	0.222
3	0.333
4	0.444
5	0.555
6	0.666
7	0.777
8	0.888
9	1

In other words, the numerical gap between two adjacent SMLs is equal to 0.111. Therefore, the lower and upper limits for each SML are presented in Table 5.10 below.

Table 5.10: Sub-dimensional Maturity Levels (SML): Lower and Upper Limits

Sub-dimensional Maturity Level	Lower Limit	Upper Limit
1	0	0.111
2	0.111	0.222
3	0.222	0.333
4	0.333	0.444
5	0.444	0.555
6	0.555	0.666
7	0.666	0.777
8	0.777	0.888
9	0.888	1
ERROR	1	

5.3.2.4 Calculating Lower and Upper limits for CMLs

Table 5.10 shows that there are 9 sub-dimensional maturity levels which also have their own limits. Those limits are based on *Current scenario* to *Best-case scenario* for each sub-dimension for each TC. Therefore, in this case sub-dimensional maturity levels vary between 0 and 1 (because through data collection, participants could put zero when evaluating people/equipment/projects or they can put any value between 1 to 9, 9 being the highest; i.e. when choosing 9 for all data entries, they give the highest score and so that highest score compared to *Best-case scenario*, i.e. scenario when all data entries scored 9 for a sub-dimension. Therefore if you calculate ratio of that it will be $\frac{9}{9} = 1$).

Therefore, sub-dimensional maturity levels have their own limits, which are presented in Table 5.10 below. Using those limits from Table 5.10 above, it should be highlighted that when calculating CML, the lowest score will be 1 for each sub-dimensional maturity level, and the highest will be 9.

Hence, assuming that we want to calculate a scenario when TC scored the lowest possible points, i.e. all sub-dimensions received sub-maturity level 1, then the TC vector will be calculated as follows:

$$|TC| = [x_1 + x_2 + x_3, y_1 + y_2 + y_3, z_1 + z_2 + z_3] \tag{9}$$

$$|TC| = [1 + 1 + 1, 1 + 1 + 1, 1 + 1 + 1]$$

$$|TC| = [3,3,3]$$

$$|TC| = \sqrt{3^2 + 3^2 + 3^2}$$

$$|TC| = 5.20$$

Hence, 5.20 is the minimum value that can be reached by a Technology Capability.

$$|TC| = [x_1 + x_2 + x_3, y_1 + y_2 + y_3, z_1 + z_2 + z_3]$$

$$|TC| = [9 + 9 + 9, 9 + 9 + 9, 9 + 9 + 9]$$

$$|TC| = [27,27,27]$$

$$|TC| = \sqrt{27^2 + 27^2 + 27^2}$$

$$|TC| = 46.77$$

46.77 is the maximum value that can be reached by a Technology Capability. Therefore, the values for Capability Maturity Levels cannot be lower than 5.20 and higher than 46.77, i.e.

$$5.20 < CML < 46.77$$

In order to create 9 CMLs the following equation was used

$$\frac{(\max value - \min value)}{9} = \frac{(46.77 - 5.20)}{9} = 4.62 \quad (10)$$

4.62 is a numerical difference between two adjacent CMLs. Table 5.11 below shows lower and upper limit for each CML from 1 to 9 (as presented before in Table 5.10 above).

Table 5.11: Capability Maturity Levels (CML): Lower and Upper Limits

Capability Maturity Level	Lower Limit	Upper Limit
1	5.2	9.82
2	9.82	14.44
3	14.44	19.06
4	19.06	23.68
5	23.68	28.29
6	28.29	32.91
7	32.91	37.53
8	37.53	42.15
9	42.15	46.77

5.3.2.5 Using SMLs to calculate CML

In order to calculate CML, the magnitude of a vector can be computed using equation (9),

$$|TC| = [x_1 + x_2 + x_3, y_1 + y_2 + y_3, z_1 + z_2 + z_3]$$

$$|TC| = [X, Y, Z]$$

$$|TC| = \sqrt{X^2 + Y^2 + Z^2} \quad (11)$$

$$|TC| \in \leq 5.20, 46.77 \geq$$

Using information from previous section (section 5.3.2.4), the value of any TC magnitude vectors (before assigning CML) will vary between 5.20 and 46.77. Using equation (9) and equation (11), it is now possible to calculate value of a 3D vector. In order to do so, values from 9 sub-dimensions will be used. Values for $\frac{Current\ scenario}{Best\ case\ scenario}$ for each sub-dimension (as presented in Table 5.12) were calculated using process explained in section 5.3.2.3 Given Table 5.10, Table 5.12 shows how SML is assigned to each sub-dimension, e.g. if the ratio of *Current* and *Best-case scenario* of D1.1 is 0.476, SML is 5 as 0.476 falls between 0.444 and 0.555, etc.

Table 5.12: Translating sub-dimensional values into sub-dimensional maturity levels (SML)

Sub-dimensions	D1.1	D1.2	D1.3	D2.1	D2.2	D2.3	D3.1	D3.2	D3.3
$\frac{\textbf{Current scenario}}{\textbf{Best case scenario}}$	0.476	0.414	0.524	0.979	0.610	0.819	0.827	0.753	0.056
SML	5	4	5	9	6	8	8	7	1

Once SML is assigned to all sub-dimensions, the next step is to calculate CML. In order to do so, we need to find vector coordinates at 3 dimensional planes: X, Y and Z, or, in this case, D1, D2 and D3. Hence, sub-dimensions included in D1 will be added together. The same process is repeated for sub-dimensions in D2 and D3. Once vale for each dimension is calculated, vector magnitude for the overall TC can be obtain using equation (14). Table 5.13 shows this process.

Table 5.13: Calculating magnitude of a TC vector

Sub-dimensions	D1.1	D1.2	D1.3	D2.1	D2.2	D2.3	D3.1	D3.2	D3.3
SML	5	4	5	9	6	8	8	7	1
Original equation	$x_1 + x_2 + x_3$			$y_1 + y_2 + y_3$			$z_1 + z_2 + z_3$		
Transformed equation to use SMLs	$D1.1 + D1.2 + D1.3$			$D2.1 + D2.2 + D2.3$			$D3.1 + D3.2 + D3.3$		
Value for each dimension	14			23			16		
Dimensions	D1			D2			D3		

Using information from Table 5.13, we can use equation (10) and (12) in order to get vector magnitude value for a TC. Hence, equation (10) will change into equation (13)

$$\left|TC\right| = [x_1 + x_2 + x_3, y_1 + y_2 + y_3, z_1 + z_2 + z_3] \tag{9}$$

$$\left|TC\right| = [D1.1 + D1.2 + D1.3, D2.1 + D2.2 + D2.3, D3.1 + D3.2 + D3.3] \tag{12}$$

$$\left|TC\right| = [5 + 4 + 5, 9 + 6 + 8, 8 + 7 + 1]$$

$$\left|TC\right| = [14,23,16]$$

Next, equation (11) will change into equation (13)

$$\left|TC\right| = \sqrt{X^2 + Y^2 + Z^2} \tag{11}$$

$$\left|TC\right| = \sqrt{D1^2 + D2^2 + D3^2} \tag{13}$$

$$|TC| = \sqrt{14^2 + 23^2 + 16^2}$$

$$|TC| = 31.32$$

Knowing the value of magnitude of a 3D vector representing a specific TC, which is equal to 31.32, it is now feasible to transform (or translate this value into a CML.

5.3.3 Calculating Capability Maturity Level for Technology Capability

CMLs are treated as a magnitude vector in a 3D space. Therefore, if for example the position of a vector is [14,23,16], the CML for that particular Technology Capability (TC) will be calculated as

$$|TC| = \sqrt{14^2 + 23^2 + 16^2}$$

$$|TC| = 31.32$$

According to previously mentioned Table 5.11 below, value of 31.32 lies between 28.29 and 32.91, which means that this technology capability has achieved CML 6.

Furthermore, previously mentioned TC example can be presented visually. By presenting TC's CML, it is possible to compare it against other TCs and to check how its dimensions are performing against each other. Therefore decision-makers are able to check if one sub-dimension stronger than others, or are all sub-dimensions showing equal maturity. For example, if TC=[14,23,16], Figure 5.2 (a), (b) and (c) show how TC vector (which would be equal to 31.32) could be visualised.

Figure 5.2 (b) does not include SMLs nor CMLs. It only shows values (minimum and maximum) that each dimension might obtain but adding SMLs for relevant sub-dimensions. Therefore, the minimum value for each dimension will be equal 3, due to the fact that the lowest score that each sub-dimension can achieve is SML=1, as shown in equation (14). On the other hand, the maximum value that each dimension can achieve is 27, and that will happen when each relevant sub-dimension has achieved SML=9, as shown in equation (15).

$$Minimum\ value\ for\ a\ dimension = 1 + 1 + 1 = 3 \tag{14}$$

$$Maximum\ value\ for\ a\ dimension = 9 + 9 + 9 = 27 \tag{15}$$

Another aspect worth mentioning is the legend attached to all three figures presented below (Fig. 5.2 (a), (b) and (c)). The idea of visualising results (with different level of detail) was inspired by previous work of (Ward, et al., 2017), where the same legend was presented first. Legend indicates minimum standard for customer application (indicated by green line in Figures below, the minimum standard was selected randomly only for the purpose of presentation), as well as three levels that help understand results by simply looking at the visualisation:

- Demonstration level sort of minimum standard (red arrow)
- Demonstration level ahead of minimum standard (blue arrow)
- Demonstration level aligned to minimum standard (green arrow)

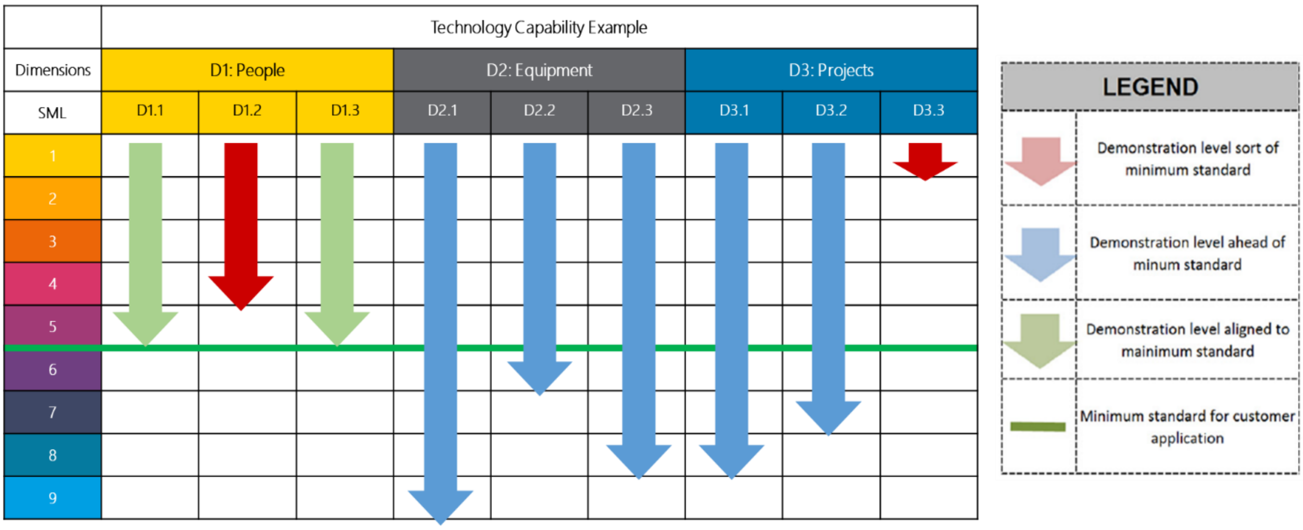


Figure 5.2 (a): Example of visualisation of Capability Maturity Level for a specific TC (detailed view), using information from Table 5.11 and legend from (Ward, et al., 2017)

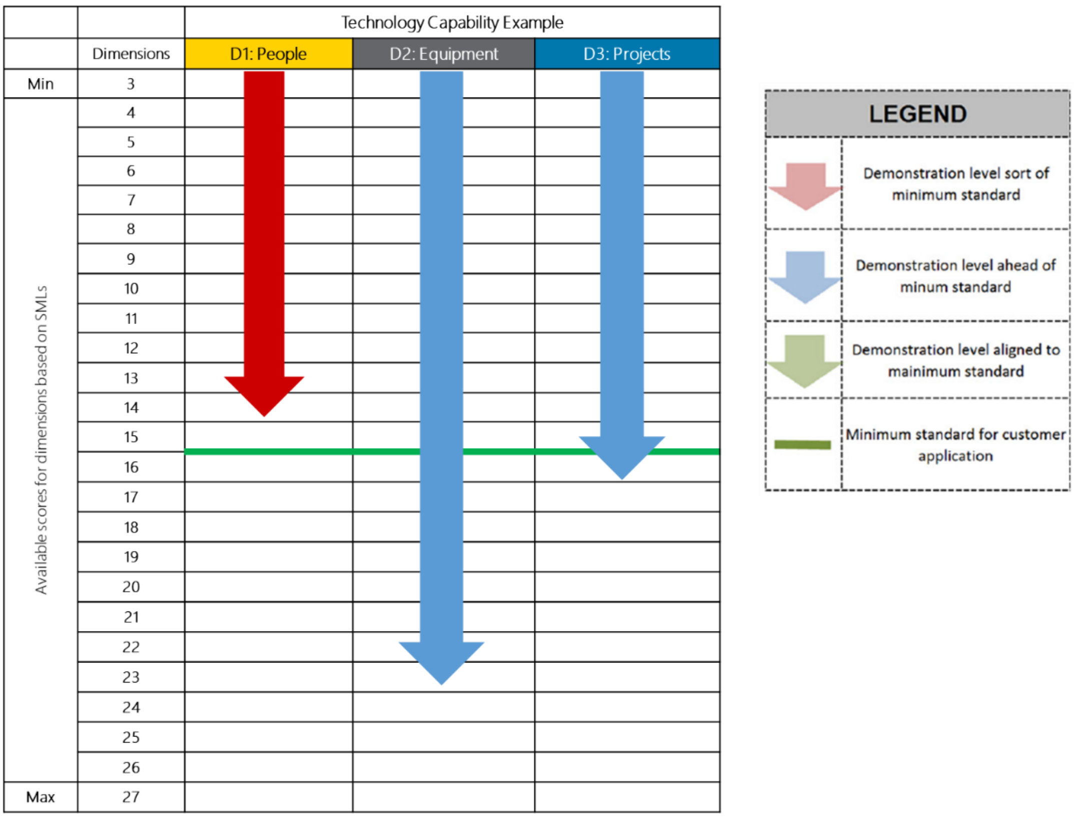


Figure 5.2 (b): Example of visualisation of Capability Maturity Level for a specific TC (3 dimensions view), using information from Table 5.11 and legend from (Ward, et al., 2017)

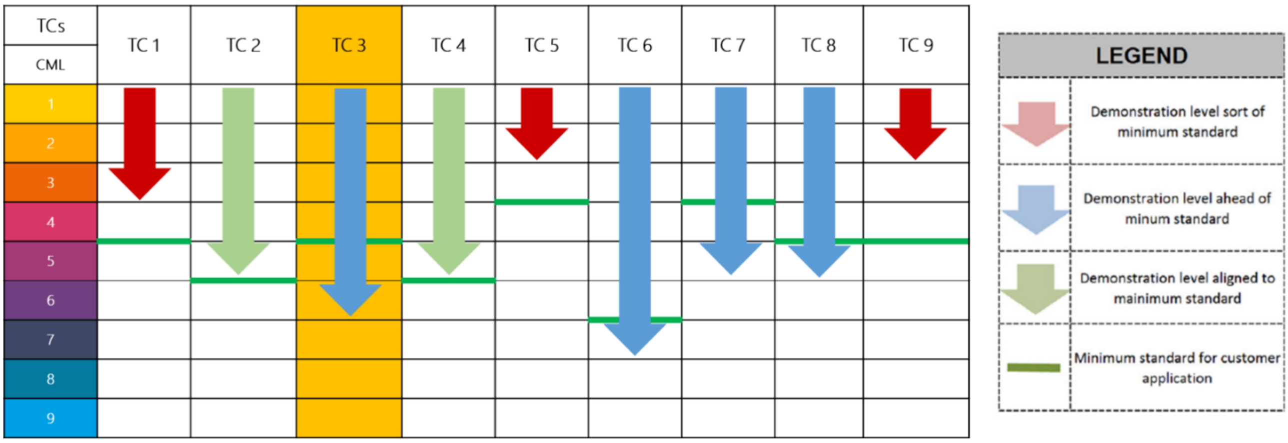


Figure 5.2 (c): Example of visualisation of various Capability Maturity Levels for a specific programme/application (high level view) using legend from (Ward, et al., 2017); Yellow column represents example of TC shown in Fig.5.2 (a) and (b)

5.4 Managerial Implications

Figure 5.3 shows the mechanism described in this section. Each step shows how it is linked to another (through inputs and outputs). In the end, the CML for a Technology Capability is calculated, as presented in Figure 5.3.

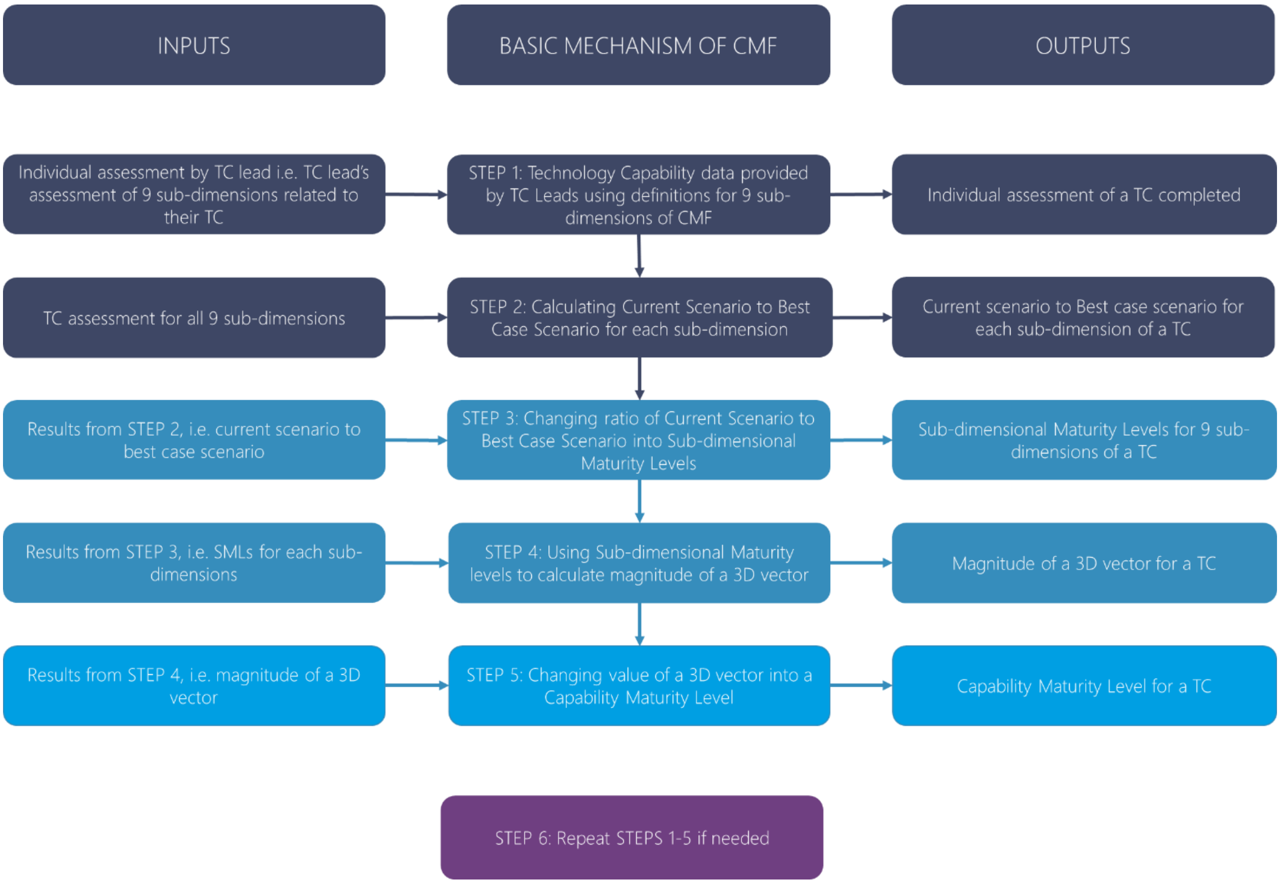


Figure 5.3: Step by step process of Capability Maturity Framework

Figure 5.3 presents the following steps:

- **Step 1:** Technology Capability data is collected and recorder into CMF. Assessment scores are provided by TC Leads using definitions for 9 sub-dimensions of CMF
- **Step 2:** Calculating ratio value of Current Scenario to Best Case Scenario for each sub-dimension, using outputs from Step 1
- **Step 3:** Using outputs from Step 2, Sub-dimensional Maturity Levels (SMLs) are calculated using upper and lower limits (for each SML) as presented in Table 5.13
- **Step 4:** Using outputs from Step 3, magnitude of a 3D vector is calculated
- **Step 5:** Using outputs from Step 4, a magnitude of a 3D vector is translated into Capability Maturity Level (using upper and lower limits for each CML, as presented in Table 5.14
- **Step 6:** Repetition of a process (i.e. Steps 1 to 5) if decision makers think that CMLs should be assessed again.

The visual representation of how each sub-dimension feeds into CML is shown in Figure 5.4 below. It shows that data collected at each sub-dimensional level influence the overall maturity of technology capability. In other words, assessment scores regarding each person, equipment and project have a direct impact on CML.

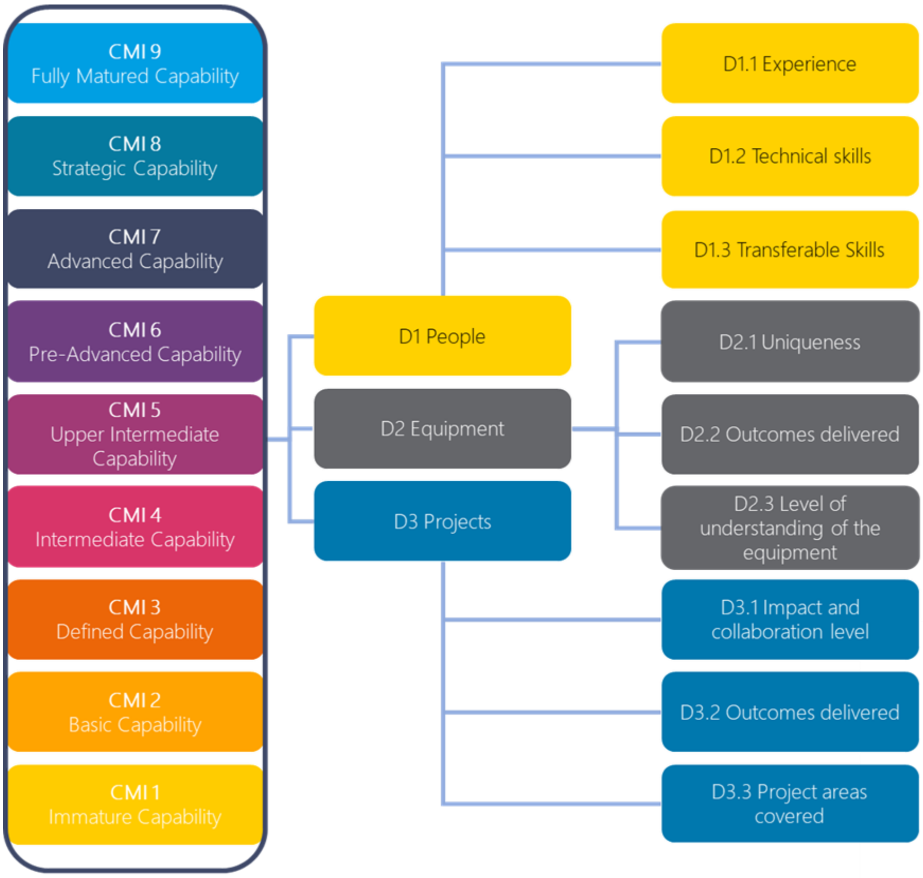


Figure 5.4: Visual representation of sub-dimensions of Capability Maturity Levels for Technology Capability in a research centre

As explained in Section 5.3 (and as it is visible in Figure 5.4 above), the three sub-dimensions contribute to the overall maturity level of Technology Capability. As each dimension consists of 3 sub-dimensions, there is a strong link between all sub-dimensions and the final Capability Maturity Level. Thus, the Capability Maturity Levels are also treated as 3-dimensional measurement that helps to visualise which dimension is weakest/strongest for each Technology Capability.

5.5 CMF Interface - Prototype

In order to familiarise participants (i.e. users) with CMF, an interface prototype was created. The interface was created in MS Excel, and various files were connected through hyperlinks to simplify data access. That way, users only had to open one file – CMF Dashboard (Figure 5.5 below). From there, users only had to click on the categories displayed in the CMF Dashboard to access files they were interested in.

Starting from the left hand side, there is a list of individual TCs from RC 1 that took part in data collection in 2019 (described in detail in section 5.6). In total, there are 15 TCs that can be accessed through CMF at the moment.

In the middle of the dashboard there are 6 programmes that started in 2019 at RC 1. Hence, by clicking on one of the programmes listed in the CMF dashboard, users can access information related to what TCs are involved in a specific programme, how mature each TC is and overview of all involved TC's maturity.

There are couple of different functions of the right hand side of the dashboard. First one is a bottom called 'Help with navigation' which takes a user to a page that looks exactly like CMF dashboards, except that each section has an explanation added next to it. Underneath that there is an option to go and see each definition for CMLs, and for sub-dimensional definitions used during data collection.

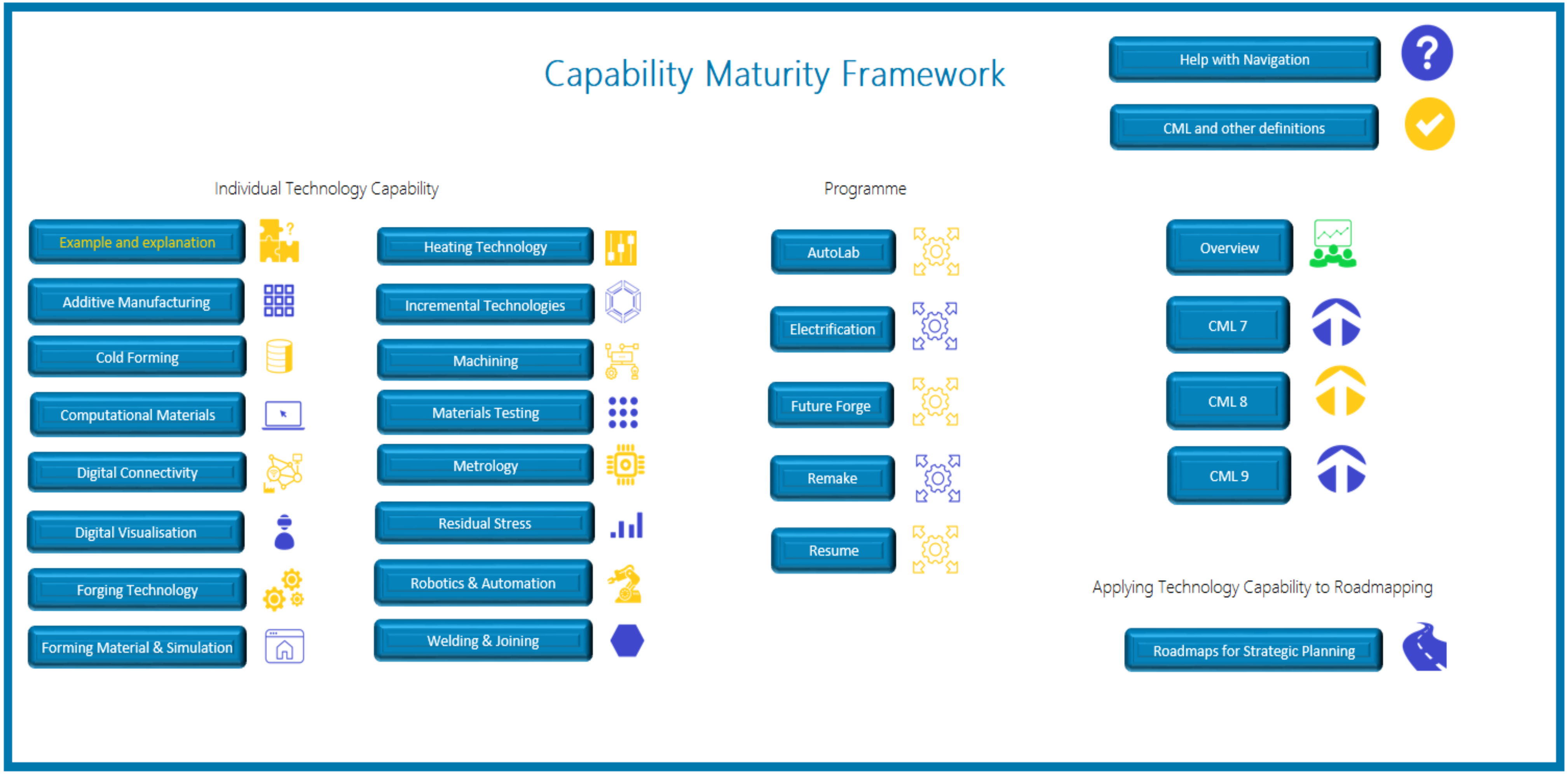


Figure 5.5: CMF Dashboard, created in MS Excel

By clicking on one of the TCs, user will be taken to a summary page that shows information about each sub-dimension illustrated in Figure 5.6 (a). It also includes a visual option that shows all sub-dimensional levels for a TC, shown in Figure 5.6 (b). Additionally, it includes potential risks and recommendations for each sub-dimension, and a current CML level (shown in Figure 5.6 (c) in Table A7, Appendix 18).There is also function that allows user to go back to the dashboard. Apart from that, users can select one of 9 tabs that will take them to a page dedicated to one of 9 sub-dimensions (Figure 5.7). Each tab shows data inputs that were provided by each TC lead and which are used as a basis for all the calculations during CMF process. It should be highlighted that when users go to tab D1.2, a visual representation of all the skills is included, so that TC can identify which skills are immature and which ones are mature. Also, a graphical representation for each team member was added that represents each person's skills level. If a team is quite big, a visual representation should help with gap identification so that TC do not need to spend a lot of time and effort to go through big datasheet (Figure 5.8 (a) and (b)).

Technology Capability

CML 6

Go back to Dashboard

Dimensions	Sub-dimension	Link to sub-dimensions	SML
People	D1.1 Experience	D1.1	5
	D1.2 Technical Skills	D1.2	4
	D1.3 Transferable Skills	D1.3	5
Equipment	D2.1 Uniqueness	D2.1	9
	D2.2 Outcome delivered	D2.2	6
	D2.3 Level of understanding of the equipment	D2.3	8
Projects	D3.1 Impact and collaboration level	D3.1	8
	D3.2 Outcomes delivered	D3.2	7
	D3.3 Project areas covered	D3.3	1

Figure 5.6 (a): Technology Capability view – Summary page (I)

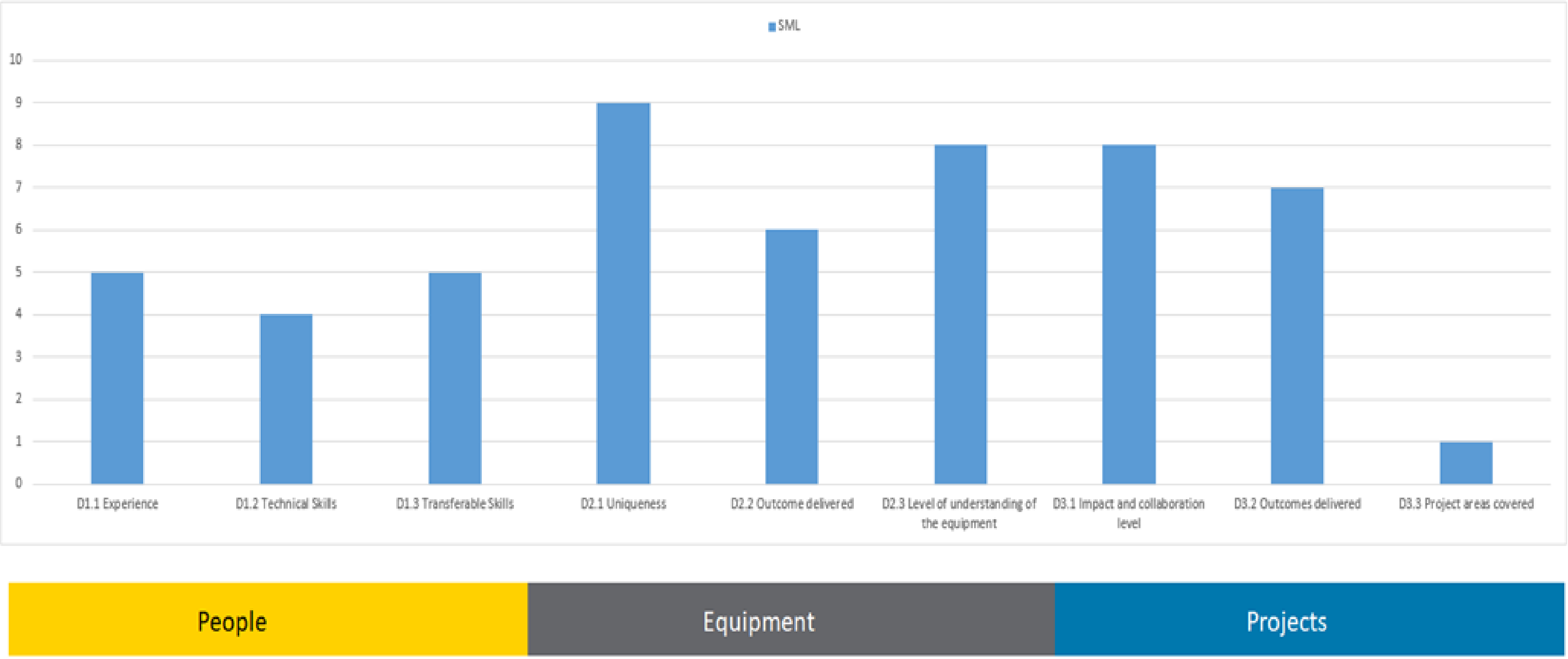


Figure 5.6 (b): Technology Capability view – Summary page (II)

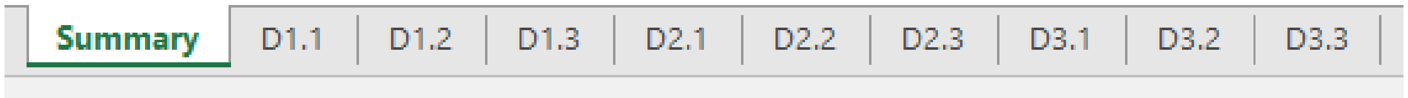


Figure 5.7: Tabs available in Technology Capability page

D1.2: Technical Skills

Category	Skills	Person ID: Person 84	Person 85	Person 86	Person 87	Person 88	Person 89	Person 90
Alloy Knowledge	Nickel superalloys -aerospace	6	4	4	4	4	4	6
	Titanium based	6	4	4	4	4	4	6
	Steel - regular / alloy	6	4	4	4	4	4	4
	Steel - stainless	6	5	4	4	4	4	4
	Aluminium	6	4	4	4	4	4	4
	Maraging / high strength	4	4	4	4	4	4	4
	Nickel - general non-aero	4	4	4	4	4	4	4
Practical Skills	Radial forge	1	1	1	1	1	1	1
	Heat Treatment	3	1	3	2	3	1	4
	Welding	2	2	2	2	2	2	2
	Ball milling	8	8	3	8	6	6	2
	Cold sheet forming	2	2	2	2	2	2	2
	Material Formability	2	2	2	2	2	2	2
	Tool Design	5	5	4	7	4	3	2
	Preform Design	5	5	4	7	4	3	2
	Mechanical testing	5	2	4	3	3	2	5
	Tooling selection	8	8	3	8	5	5	1
	Tool design (excluding FEA)	6	7	3	7	4	3	3

Figure 5.8 (a): Graphical representation of D1.2: Technical skills (I)

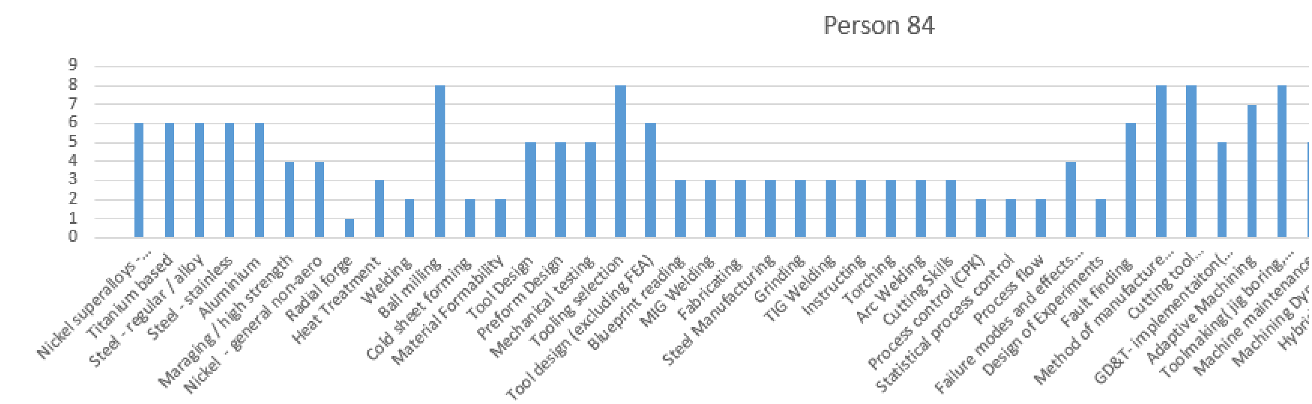


Figure 5.8 (b): Graphical representation of D1.2: Technical skills (II)

If user clicks on one of the programmes listed in the dashboard, a summary page (of a programme) will open. It includes a list of all TCs and their sub-dimensions considered for this programme (Figure 5.9). It will also show lowest. Next tab called 'Overview' will show a list of all sub-dimensions of all TCs listed from highest to lowest. The rest of the tabs will show a summary of each of TC considered for the programme, including summary of potential risks and recommendations. Each page dedicated to each TC has also a function to go to data inputs of that particular TC to see another level of detail if needed (e.g. by programme manager).

	Dimensions	Sub-dimensions/	TC 1	TC 2	TC 3	TC 4	TC 5	TC 6	TC 7
			SML						
PROGRAMME 2	People	D1.1 Experience	5	5	6	6	6	5	6
		D1.2 Technical Skills	3	7	4	4	3	6	4
		D1.3 Transferable Skills	5	5	7	7	5	5	6
	Equipment	D2.1 Uniqueness	4	3	5	5	3	6	4
		D2.2 Outcome delivered	3	6	7	6	4	6	5
		D2.3 Level of understanding of the equipment	3	5	7	7	6	6	4
	Projects	D3.1 Impact and collaboration level	6	6	5	5	5	5	5
		D3.2 Outcomes delivered	7	6	5	5	4	5	5
		D3.3 Project areas covered	8	7	6	4	8	4	8

Figure 5.9: Programme view - Summary page

Next, option 'Overview' takes users to a new file that includes information about all TCs. First tab called 'Process' explains the CMF process and steps needed to follow during that process. Second tab 'Sub-dimensions' includes a filter option, so that users can find information about any TC. Users can choose from the following options: TC, Sub-dimension, SML (Figure 5.10).

TC	Sub-dimension	SML
MT	D1.1 Experience	6
Comp Mat	D3.2 Outcomes delivered	7
W&J	D2.2 Outcome delivered	5
Comp Mat	D1.2 Technical Skills	3
MT	D3.1 Impact and collaboration level	5
MT	D3.2 Outcomes delivered	4
FM&S	D2.1 Uniqueness	3
Comp Mat	D1.3 Transferable Skills	5
W&J	D1.2 Technical Skills	4
RS	D3.2 Outcomes delivered	5
MT	D1.2 Technical Skills	3
Comp Mat	D2.2 Outcome delivered	3

Figure 5.10: Filter function in 'Sub-dimensions' tab

Third tab, included all TCs at RC 1 listed from highest CML to lowest one. Fourth tab includes all programmes and visually shows which TCs are needed for each Programme (Figure 5.11). That helps to observe which TCs are 'in demand,' i.e. they are needed in each programme and which are in only one programme. It should help programme managers help with understanding that more 'popular' TCs could be under pressure and there might be challenges (e.g. overload of work) that needs to be overcome first.

Last tab called 'Research Centre' is similar to 'Programme' tab, as it also shows which TCs 'belong' to which Team. That could be helpful view for new members of staff to help them familiarize themselves with a research centre structure. Again, CML levels are presented for each TC, so once TCs are grouped under one Team, it is easy for Team Leads to see were weakness could lie (Figure 5.12)

Roadmaps for Strategic planning is a link that takes a user to a SharpCloud website which is a roadmapping tool. The idea was that information from CMF could be also added to a roadmap, which would present a visual overview of a programme, team or TC (depending on the level of detail of a roadmap). That idea is discussed in Chapter 8 (section 8.6.3).

Technology Capability		TC 1	TC 2	TC 3	TC 4	TC 5	TC 6	TC 7	TC 8	TC 9	TC 10	TC 11	TC 12	TC13	TC 14
CML		6	5	4	4	4	6	6	6	5	5	5	5	4	5
Programme	Programme 1														
	Programme 2														
	Programme 3														
	Programme 4														
	Programme 5														

Figure 5.11: Distribution of various Technology Capabilities across Programmes

Technology Capability		TC 1	TC 2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12	TC13	TC14
CML		6	5	4	4	4	6	6	6	5	5	5	5	4	5
Teams	Team 1														
	Team 2														
	Team 3														
	Team 4														
	Team 5														

Figure 5.12: Distribution of various Technology Capabilities across Teams

5.6 Pilot Study: Data collection 2019

5.6.1. Overview of the pilot study

This section discussed the process of data collection in 2019. Data collected was 'processed' through CMF and results were implemented into Validation process in 2020 (in order to gather feedback from participants who participated in Validation process). Validation Design is described in Chapter 6 and Results from Validation process are discussed in Chapter 7.

This section explains who took part in pilot study, how data was collected and results obtained through this data collection. Next sections also discuss results obtain from the pilot study, as well as similarities and differences between various TCs (from the same research centre as well as different ones).

5.6.2. Participants

Participants from research centres were selected based on their knowledge and role at the research centres. All participants were (at the time) Technology Theme leads, i.e. they were responsible for a specific Technology Capability at the centre. It was important that Technology Theme Leads were the ones who fill in the data as several Technology Themes create a team at a research centre (as previously described in section 5.1). Hence, several Technology themes can support a development of a new programme or can be part of one team. Using this stature as well as selecting Technology Themes Leads (rather than Team Leads) as participants for this stage of the research was also intentional. By first collecting information about Technology Themes, the results could be later reviewed by Team Leads (during validation stage). Hence as Team leads are more senior then Technology Theme Leads, that also gives an opportunity to review the results by technical engineers who have broader view of teams' capabilities. Figure 5.13 shows a hierarchy of technological activities at a research centre (RC1).

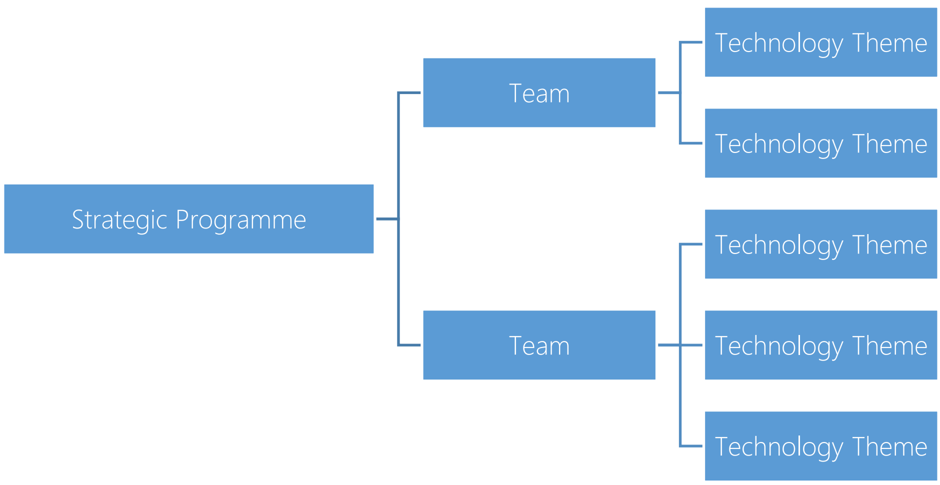


Figure 5.13: Hierarchy of technological activities at a research centre (RC 1)

Participants from other two research centres (RC 2 and RC 3), which are also part of HVMC network were contacted in order to increase 'data pool' and perform more detailed analysis. However, only three participants agreed to take part in this research. In total, there were 18 participants, 15 from

RC 1, 2 from RC 2, and 1 from RC 3. The summary of case studies used in at this stage of research is presented in Table 5.14 below.

Table 5.14: Summary of Technology Capabilities

Research Centre	Team	No of participants	Technology Capabilities within the team
RC 1	Machining	2	Additive Manufacturing, Machining
	Forging and Incremental Technologies	4	Forging, Heating Technology, Incremental Technology, Forming Modelling and Simulation
	Forming	1	Cold Forming
	Materials	4	Material Testing, Residual Stress, Computational Martials, Welding & Joining
	Digital & Metrology	4	Digital Connectivity, Digital Visualisation, Robotics & Automation, Metrology
RC 2	Materials	2	Material Testing, Composites
RC 3	Additive Manufacturing	1	Additive Manufacturing
	Total	18	

5.6.3. Process of data collection

Data was collected between August 2019 and January 2020. Majority of data collection took place at AFRC, those were face-to-face meetings, and it was possible to explain to participants the process. That part of the process took place between August and September 2020.

Next, the idea was to gather data from other HVM Catapults. Hence, the author started contacting the other 6 Catapults to take part in this research. Unfortunately, only 2 Catapults agree and from that only 5 people were interested.

The data collection from RC 2 where three participants, but in the end only two provided required information. That part of research took place in November 2019. The author had to travel to the research centre in order to meet participants face-to-face and to explain the whole process.

The last part of data collection that involved gathering information from last participant took place over the phone/Skype. That took place in January 2020, as there was a problem with availability of participants. The process was explained over the phone/Skype and afterwards participant filled in required information and send it back through e-mail. When the process was explained over the phone/Skype, two participants showed interested in this stage of the research. However, only one person returned the file with required information.

In order to gather data for CMF, participants had to use definitions for 9 sub-dimensions in order to provide numerical evaluation of People, Equipment and Projects. The rules for assigning specific numerical indicator for each sub-dimension were as follows:

- Participants need to answer 'yes' for all bullet points presented in the definition for each *n-th* level of CML (for each sub-dimension)
- If participants are not sure about some of the statements for *n-th* level of CML, then the *n-th* CML is potentially achievable but need to be marked as *(n-1)* CML
- If none of the bullet points/statements presented in the *n-th* CML, then participant should assign *(n-1)th* CML (if all statements from *(n-1)th* CML can be answered as 'yes')

Figure 5.14 below present the process of assigning numerical indicators using CML definitions for each sub-dimension.

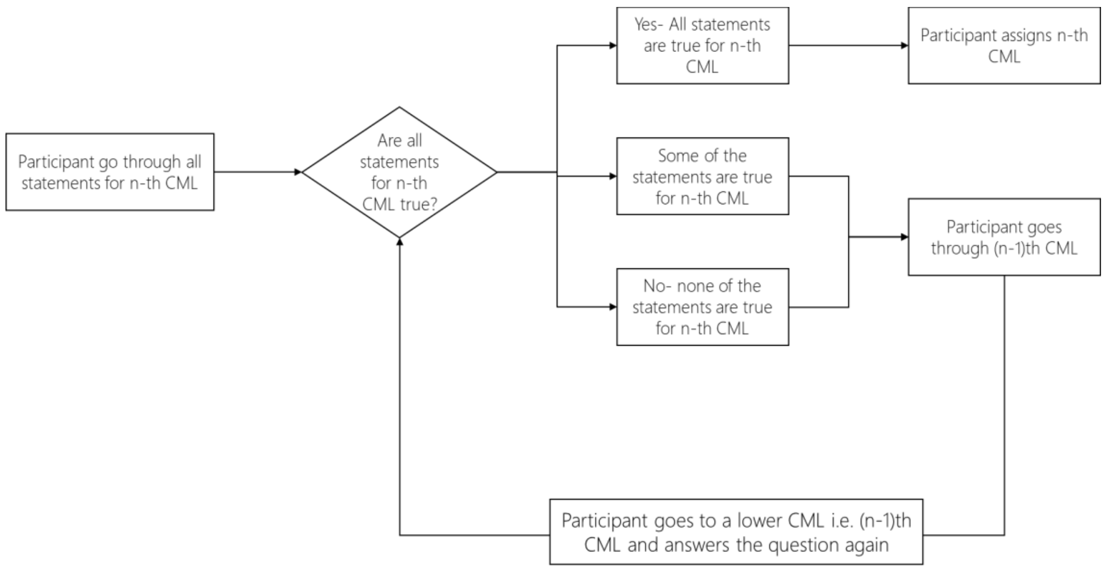


Figure 5.14: Process of assigning definitions for each data point by participants during data collection 2019

5.7 Pilot Study: CMF Results

This section presents the results from 15 participants from Research Centre 1 (RC 1), 2 participants from Research Centre 2 (RC 2), and 1 participant from Research Centre 3 (RC 3). The intention was to get more information from HVMC centres and compare them. However due to unavailability of participants it was no possible to get more data (which is also considered one of the main limitations of this research).

However, data collected in 2019 was used to calculate CMLs and SMLs for those TCs (and their representatives) that took part in this study. Detailed results delivered by CMF are discussed in next sections.

5.7.1. Results from Research Centre 1 (RC1)

Results from Research Centre 1 (RC 1) are presented below. Data was collected in August/September 2019. 15 participants agreed to take part in this research, and by using definitions introduced in section 5.2, they evaluated team members for each specific Technology Capability (all 15 TCs are presented in Table 5.15 below). Table 5.15 presents results for each sub-dimension, calculated vector magnitude (based in the 9 sub-dimensions) and the Capability Level based on the value of vector magnitude. The order of TCs in table 5.15 is alphabetical.

Table 5.15: Capability Maturity Levels for 15 Technology Capabilities (based on RC 1)

Technology Capability	D1.1	D1.2	D1.3	D2.1	D2.2	D2.3	D3.1	D3.2	D3.3	Vector Magnitude	CML
Additive Manufacturing	5	4	5	9	6	8	8	7	1	31.32	6
Cold Forming	6	3	7	1	4	4	5	7	6	25.71	5
Computational Materials	5	3	5	4	3	3	6	7	8	26.65	5
Digital Connectivity	5	2	5	3	4	5	6	5	3	22.00	4
Digital Visualisation	5	6	6	2	6	6	1	1	1	22.23	4
Forming Material and Simulation	5	7	5	3	6	5	6	6	7	29.09	6
Forging Tech	5	4	6	4	4	5	4	4	3	22.69	4
Heating Tech	5	4	6	5	7	7	5	5	6	29.02	6
Incremental Tech	6	4	7	5	6	7	5	5	4	28.44	6
Machining	5	3	6	3	7	6	4	4	5	24.92	5
Materials Testing	6	3	5	3	4	6	5	4	8	25.57	5
Metrology	6	3	6	3	5	6	5	5	3	24.29	5
Robotics & Automation	5	4	5	4	7	6	1	1	1	22.23	4
Residual Stress	5	6	5	6	6	6	5	5	4	27.86	5
Welding & Joining	6	4	6	4	5	4	5	5	8	27.37	5

5.7.2. Results from Research Centre 2 (RC 2) and Research Centre 3 (RC 3)

As mentioned before, the idea was to gather more information from other HVMCs. However only 3 participants from 2 other HVMCs took part in this study. Data from RC 2 was collected in November 2019, and data from RC 3 was collected in January 2020. Table 5.16 below shows the results from RC 2, and Table 5.17 shows results from RC 3. Both table shows results for each sub-dimension, vector magnitude and Capability Maturity Level for the Technology Capability they were evaluating.

Table 5.16: Capability Maturity Levels for 2 Technology Capabilities (based on RC 2)

Technology Capability	D1.1	D1.2	D1.3	D2.1	D2.2	D2.3	D3.1	D3.2	D3.3	Vector Magnitude	CML
Metrology	4	3	5	3	5	4	1	1	1	17.23	3
Composites	8	5	8	4	6	6	4	6	3	29.43	6

Table 5.17: Capability Maturity Levels for 1 Technology Capability (based on RC 3)

Technology Capability	D1.1	D1.2	D1.3	D2.1	D2.2	D2.3	D3.1	D3.2	D3.3	Vector Magnitude	CML
Additive Manufacturing	5	4	6	4	6	7	5	5	5	27.18	5

5.7.3. Comparing results from three HVM Catapults

The initial idea was that research centres will provide information on the TC that are 'shared' between centres, e.g. TC such as Metrology or Additive Manufacturing are performed at all 7 HVMCs (High Value Manufacturing Catapult , 2020). However only 3 participants agreed to take part in this stage of this study, and so the only comparison could be made between 2 TCs (see Table 5.18 below).

Table 5.18: List of Technology Capabilities from three HVMCs

Technology Capability	RC 1	RC 2	RC 3
Additive Manufacturing	6	-	5
Cold Forming	5	-	-
Computational Materials	5	-	-
Digital Connectivity	4	-	-
Digital Visualisation	4	-	-
Forming Material and Simulation	6	-	-
Forging Tech	4	-	-
Heating Tech	6	-	-
Incremental Tech	6	-	-
Machining	5	-	-
Materials Testing	5	3	-
Metrology	5	6	-
Robotics & Automation	4	-	-
Residual Stress	5	-	-
Welding & Joining	5	-	-

Although there was a potential to perform a more detailed comparison between centres, due to unavailability of participants, it is only possible to compare two/three TCs. In this case, the following comparison can be performed:

- Additive Manufacturing can be compared between RC 1 and RC 3
- Metrology between RC 1 and RC 2

Unfortunately, Composites TC could not be compared between different centres as only one centre provided data for that TC. By using structure of CMF, the comparison can be performed by first comparing sub-dimensions and then going into more details provided by participants. Those comparisons are discussed in the next section.

5.7.3.1. Comparing sub-dimensions between RCs

In this section, detailed data can be taken from pilot study and compared with data from another research centre. 2 TCs will be used for that comparison: Additive Manufacturing and Metrology. First, comparison between sub-dimensions highlights difference between TCs. If the difference is substantial (e.g. bigger than two levels), it is possible to 'dive into' data sheet of both RCs and investigate why one centre has much bigger score than other. For example Table 5.19, sub-dimension D2.1 (highlighted in yellow) shows the difference between sub-dimensional maturity levels is equal to 5 sub-dimensional maturity levels. Therefore, RC 1 must have excellent equipment and experience in using equipment for the Additive Manufacturing TC. This topic is discussed further in the next section 5.7.3.2.

Table 5.19: Comparing sub-dimensional results for TC Additive Manufacturing between two RCs

Additive Manufacturing	D1.1	D1.2	D1.3	D2.1	D2.2	D2.3	D3.1	D3.2	D3.3	Vector Magnitude	CML
RC 1	5	4	5	9	6	8	8	7	1	31.32	6
RC 3	5	4	6	4	6	7	5	5	5	27.18	5

On the other hand, Table 5.20 shows difference between sub-dimensional maturity levels related to Metrology in two different research centres. The difference in SMLs are equal 2 in D1.1: Experience, but there is no difference in D1.2: technical skills i.e. that was a good opportunity to compare aspects that achieved the same scores. Hence, D1.1 and D1.2 were selected for further analysis (which will be described in the next section).

Table 5.20 Comparing sub-dimensional results for TC Metrology between two RCs

Metrology	D1.1	D1.2	D1.3	D2.1	D2.2	D2.3	D3.1	D3.2	D3.3	Vector Magnitude	CML
RC 1	6	3	6	3	5	6	5	5	3	24.29	5
RC 2	4	3	5	3	5	4	1	1	1	17.23	3

Next level of analysis for all sub-dimensions mentioned above is described in the next section.

5.7.3.2. Comparing data provided by participants between RCs

Using information from previous section, it shows that RC 1 and RC 3 both concentrate on Additive Manufacturing, D2.1: Uniqueness. However, when more detailed analysis of input data was performed, it was found that participant from RC 1 who provided input data provided 9's or 8's for all equipment listed in the research centre (except for one machine which scored 2). On the other hand, person in RC 3 provided a variety of scores between 2's and 5's. It is hard to believe that all equipment for a specific TC can be defined as *Globally unique equipment/Equipment cannot be replicated elsewhere/ Highly important to manufacturing research centres* (i.e. 9) *or Nationally recognised demo function/Demonstration equipment for HVMC* (i.e. 8). Hence, a robust review process needs to be introduced in the future for reviewing scores provided by TC leads (which is discussed in Chapter 9).

High level view showed that in D2.1, RC 1 achieved CML 9, and RC 3- CML 4. Deeper analysis showed was that RC 1 has 68 pieces of equipment/software and RC 3 has 18. What is more interesting there was no correlation between equipment/software used between those two centres. It is interesting to see that Catapults with the same TC (and both part of HVMC) seem to use different equipment/software. It could confirm different strategic directions that drive those decisions (i.e. to which equipment research centres should invest in). On the other hand, both research centres could work on different areas (i.e. processes) of Additive Manufacturing which could explain why they use different equipment/software.

What it also showed, that another (i.e. more detailed) level of analysis is needed, i.e. analysis on technology processes levels. Technology processes are part of each TC, and are also important to understand areas of focus of TC and a research centre. Therefore, another layer that contributes into TC and understanding its CML, would add value. That aspect will be added to future work to understand in more detail which technology processes contribute to TC and how that additional layer could be added to calculations.

The lack of correlation could indicate what areas of TC both research centres concentrate on, hence it could help justify why they use that specific equipment and not the one that other centre is using. For that reason, CMF could help research centres to apply for specific funding as equipment in CMF could be grouped based on technological processes (which is part of future work, as described previously).

Secondly, we have results for Metrology TC for D1.1: Experience and D1.2: Technical skills. This time Metrology Tc was compared between RC 1 and RC 2 and the initial analysis showed that both TCs achieved the same sub-dimensional maturity level. Hence RC1's Metrology TC includes 4 people, and RC 2's – 3 people. Also participants from RC1 listed 17 technical skills during data collection, and participants from RC 2 listed 57 technical skills. Only one technical skill was shared between research centres. Again, as discussed previously – two research centres could concentrate on different aspects of technological capability, which could be a result of different strategic directions. Furthermore it also confirms the need for an independent review by a technical experts who could analyse data (and justifications) provided through CMF and recommend appropriate actions to research centres. However, because the skills used at the two research centres, there is no benefit to compare different skills.

That again shows, that the comparison between research centres should take place on more detailed level i.e. technological processes that belong to technological capabilities, i.e. another level of CMF should be introduced in the future.

On the other hand, when looking at results from D1.1: Experience between two centres, RC 1 achieved sub dimensional level 6 and RC 2- level 4. Hence, to compare individual scores between each person in that TC, Table 5.21 was introduced.

Table 5.21: Individual scores for each person in Metrology TC in RC 1 and RC 2 for D1.1

Metrology D1.1: Experience			
RC 1		RC 2	
Person ID	Score	Person ID	Score
Person 22	9	Person 1	5
Person 23	5	Person 2	5
Person 24	5	Person 3	1
Person 25	3		
Current scenario/Best case scenario	0.6111	Current scenario/Best case scenario	0.407
Sub-dimensional Maturity Level (SML)	6	Sub-dimensional Maturity Level (SML)	4

Therefore, Table 5.21 shows that in Metrology TC at RC1 there is a senior and very experienced person who scored 9 in D1.1. For that reason, RC1 achieved higher sub-dimensional maturity level. Hence, it shows, that RC 2 is missing a senior and experience person who could contribute to overall experience of Metrology TC at RC 2.

5.8 Capability Maturity Framework: Future Implementation

After definitions were created, and the process of calculating the Capability Maturity level was completed, it was important to explain to participants the whole process and steps included within the Capability Maturity Framework. Bullet points below describe steps of CMF that need to be taken to use it successfully. Figure 5.15 also illustrates the CMF process.

- Step 1: Technology Capability Leads are presented with an Excel file and definitions for each sub-dimension. This step could be taken parallel as TC leads can fill information in at the same time, as they all need to access specific file relevant to their TC. Definitions are presented to TC leads. They can evaluate each team member, equipment and completed project. At the same time they can also update the file by adding newly identified skills or equipment that has not been yet added to the database. At the same time, they can remove skills which they identified as no longer needed or outdate (the same applies to the equipment list).
- Step 2: Using approach explained in section 5.3 and data from Step 1, CMF is used to calculate Capability maturity level for each Technology Capability

- Step 3: Results mean that each Technology Capability is assigned Capability Maturity Level based on the information in Step 1 and calculations in Step 2. Results are presented to Technology Capability Lead, who can still change it if they think that something seems incorrect. Results of all Technology Capabilities are presented together.
- Step 4: Results are review by senior management in order to validate the results across the research centre. At this stage, senior manager have a chance to address issues related to Capability Maturity Level of any Technology Capability.
- Step 5: Ideally, if process was already used in the past, current result can be compared with past results and so the progress could be visualised. Therefore questions like 'which capabilities had improved in the last 6/12 months?' or 'where do we struggle?' could be answered. Progress could be easily visualised and presented to senior management and/or CTO/COO.
- Step 6: Understanding current Capability Maturity Levels is very important, as well as identifying causes of improvement or decline of maturity levels. That is why detailed database allows TC leads to look back and understand what have changed since last data collection took place. Understanding changes in Technology Capability allows to set up suitable corrective actions and avoid high risk actions in order to improve CML.
- Step 7: Once senior management and TC leads decide on what corrective actions should be taken, those actions are planned, implemented and monitored. If there is a clear indication that corrective actions are not helpful, TC lead should end those and consult with senior management what should be done instead. There is always more than one way to achieve progress, hence, TC leads might need to apply various actions before finding the one that is suitable to their team.
- Step 8: After agreed period of time, Steps 1-7 should be repeated. By keeping past data stored in an online database, it is possible to create comparison between past and current data, but also (as database growth and there's more data points), it allows projections to be calculated in included in the review process.

Potentially another activity could be added to the CMF Step 4, i.e. introducing target for each Technology Capability. As senior management has a wider view across research centre, they would understand that not all technology Capabilities improve with the same pace. Therefore targets could be adjusted depending on Technology Capability. Target would be set out by senior management and during review process it could be compared which Technology Capabilities are on target, who needs more help etc.

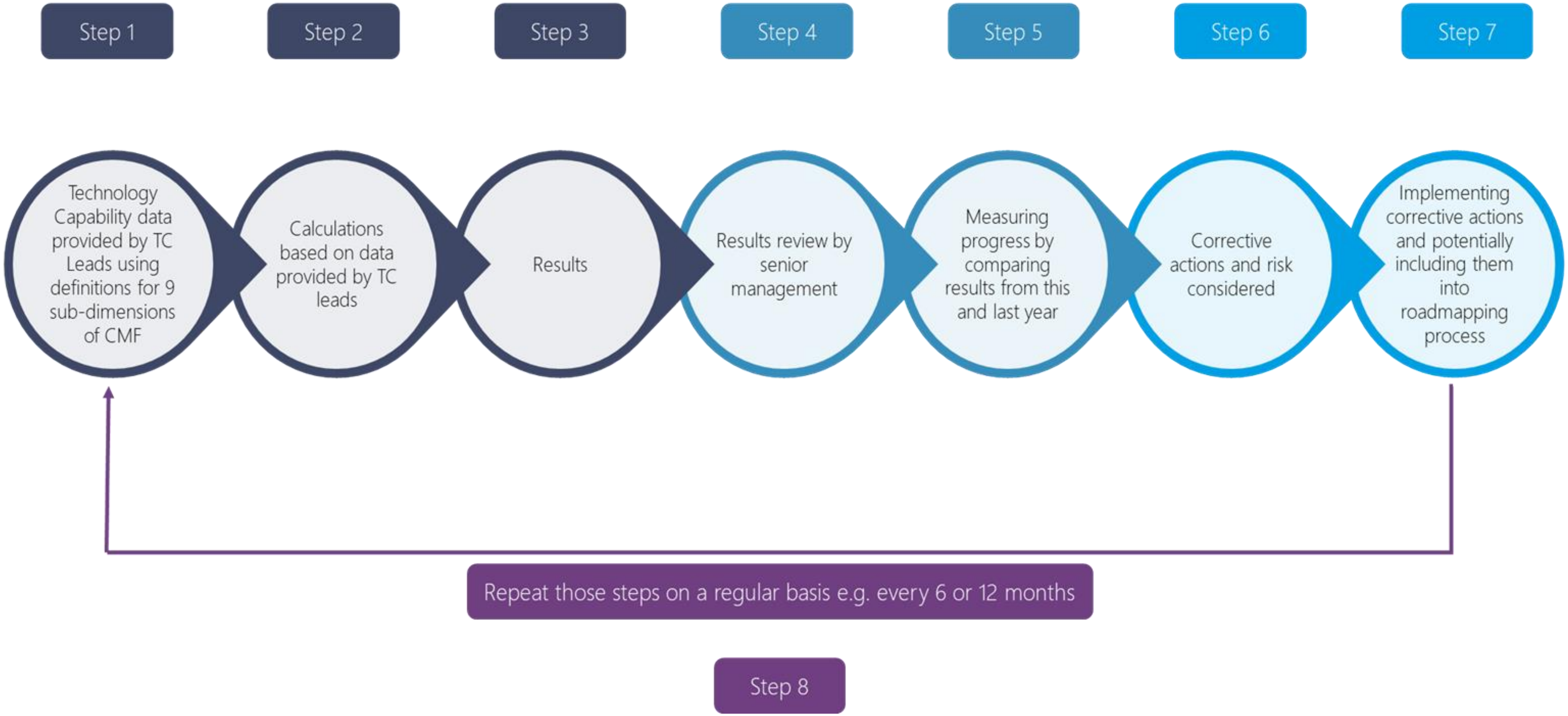


Figure 5.15: Capability Maturity Framework, step-by-step process

5.9 Summary

Even though information from other Catapults was limited, it was still interesting to see a potential comparison between research centres. Such comparison aims to ask questions like

- How mature we and other research centre are at a TC?
- What are our weakest (i.e. least mature) areas of a TC?
- What areas of TC (i.e. which sub-dimensions) can be improved?
- What can we learn from other Catapults with the same TC?
- Should a research centre 'catch up' to other Catapults (with the same TC) or should it concentrate on other TCs?
- Should a research centre look for a different technological niche in which it could excel?

Above questions are important if research centres want to evolve and advance their capabilities. Hence, the first step is to start gathering data, analyse data and understand what those results are showing. **Having a framework that will support and guide decision makers during that process, will provide data driven results and will help with highlighting gaps and strengths of research centres**.

The illustration of mechanism and details captured by Capability Maturity Framework are important as it shows how CMF could be used in the future. Depending on users' role at a research centre, CMF will provide different benefits, as illustrated by Table 5.22. However, regardless of who uses CMF, it offers a centralised place where different pieces of data (which are sometimes ignored or neglected) are put in one place. It means that users **have structured evaluation process to identify current capability–related challenges**.

Table 5.22: Benefits and importance of Capability Maturity Framework to various users

User's Role	Benefits & Importance to Users
Team member	• Understand progress of each team member and also how person contributes to overall team's skillset and experience • Understand how much progress team member had performed (had their skills improved/decreases, what is the reason for that? What can be done to change that)
Technology Capability Lead	• Identify strengths and weaknesses of a team • Put succession plan in place in case anyone decides to leave/retire • Understand how many people have specific skills, can operate equipment etc. • Identify how and wat projects equipment is used on (or not) • Determine impact and deliverables of projects and how those outcomes match with project requirements – help to answer the questions do we overpromise to clients? Can we deliver what we promised? What impact do we create? Do we need help with project management aspect? • Applying results to roadmapping and planning TC development accordingly
Programme Manager	• Identify gaps and strength of a programme • Set up corrective actions if certain capabilities as not matured as we would like to
Senior Manager	• Put succession plan in place in case anyone decides to leave/retire • Identify capability gaps and plan how team/research centre can address that • Understand what skills we are missing as a centre & avoiding hiring people with the same set of skills

	• Understanding cost and time needed to achieve new maturity level • Helps with analysing which dimension of Technology Capability is the strongest, and which one is the weakest, which leads to identifying reasons why that is, i.e. CMF offers transparency of data • Delivers standardised method for calculating each Capability maturity Level in the same manner
CTO/COO	• Understand research centres progress on a regular basis e.g. update it every 6 or 12 months • Identify strengths and gaps of centres capabilities • Does it mean that our capabilities allow us to work at low/middle/high TRL level? • Evaluate which capabilities are worth investing in • Identify partners and collaborators • Link capabilities with sector challenges and create new offerings

As it if first version of CMF, it has some limitations. One of them is the fact that comparing the same TC form different research centres would depend on the openness of those research centres (and individuals responsible for those research centres and TCs). It is not clear how open research centres would be if such situation happen, but this could investigated further in future work.

However, CMF is still helpful when indicating which sub-dimensions of TC are the lowest and where the gaps are (i.e. where future investment should go). Thus, CMF adds value to internal planning and strategy building, which will also affect **future improvements across research centre related to its technological offerings**. Even if CMF cannot be used in a comparative mode (between research centres) at this stage, it can certainly be applied as an inward facing tool for **driving internal improvements related to a TC**.

Additionally, having CMF will help industry understand research centres and their capabilities better. CMF will provide benefits by aligning market needs with capability maturity, i.e. mapping of capability maturity and industrial requirements, based on the results of CMF and current market needs.

It should be highlighted that **CMF was not created to replace TRL-based approaches but rather to support the stage before TRL is applied**. Having two frameworks that now support both side of the process, i.e. industry and research centres, will benefit everyone involved in the overall development process. Therefore, industry can also use CMF to have a clear picture of which research centres have capabilities to support their technological strategy. What is more, policy makers and senior managers responsible for research centres collaboration can also use CMF to identify where the weaknesses and strengths of the network are, and what could be done to address the immature capabilities.

Additionally, as TRL fits well with existing systems like UK Research and Innovation (UKRI), it means that CMF does not need to do that. The idea of creating CMF was not to create another solution that fits into the same systems as TRL-based approaches; but **to create a new approach that will fit well with research centres needs and challenges.**

While there has been much research on readiness aspect of technology, few researchers have taken maturity into consideration, or distinction between maturity and readiness. Hence, other existing frameworks might concentrate on different purposes (people/innovation/supply chain), but limited number of research concentrated on research centres perspective. Therefore, not many studies taken capability maturity at research centres into consideration. That is why this research is important as it introduces capability maturity framework created for research centres that has not been introduced in the literature before (i.e. addresses the knowledge gap).

In the meantime, the first version of CMF was validated through online surveys, and the results are discussed in Chapter 7. Chapter 6 describes how the validation process was design.

Chapter 6: Validation Design

6.1 Introduction

As discussed previously in Chapter 3, the empirical nature of this study requires validation of gathered findings. Because action research was applied in this study, it was important to assess the validity, reliability and generalisability of the CMF. In order to do so validation design for this study was supported by (Schmiedel, et al., 2014) and (Hong & Kim, 2004).

In addition, one of the beliefs associated with action research is that those who will be affected by changes (i.e. participants from research centres), should be involved in the process as much as possible (Saunders, et al., 2009) (section 3.8). That is why it was important that participants from all HVM Catapults were contacted and asked to participate in validation.

At first, validation was supposed to be organised as face-to-face meetings to explain the process of CMF and answer questions that participants might have. However, due to Covid-19 pandemic that approach was no longer possible and so an alternative solution was design. In order to give participants overview of how CMF was created, it was decided that **a pre-recorded presentation** would be best solution to this challenge, as it could be send to larger number of participants. At the beginning of this process, two pre-recorded presentations were created: Presentation No 1 explained the gap in the knowledge and origin of this research; Presentation No 2 - how the Capability Maturity Framework works.

The idea of creating a presentation and a short video that presents how the CMF works, was supported by motivation to reach as many participants as possible. Many participants have various responsibilities and it was often difficult to contact them, even by Skype or e-mail. Thus, it was decided that it would be best if participants could view all the information in their own time (either during working hours or in their free time).

Before presentations were distributed among participants they went through **two pilot studies** in order to make sure that presentations are understandable and clear. Therefore the validation process was divided into three steps (Schmiedel, et al., 2014), as presented in Figure 6.1 below. Moreover, Table 6.1 present overview of three steps taken in this validation process: Pre-Validation, Small-scale Validation and Final Validation. Next sections describe each step in detail, as well as what changes had been made based on the comments from participants.

It should be highlighted that the three steps and modifications that improved this validation process could not be possible without participants who agreed to take part in this study. They dedicated their time and went through the presentations and surveys. Afterwards they provided constructive feedback that was used to improve this process and to help me to explain the research to wider audience.

The process of collecting data for this stage of research **lasted around 6 weeks**. As the use of secondary data was not possible, the time and effort had to be dedicate to validate CMF.

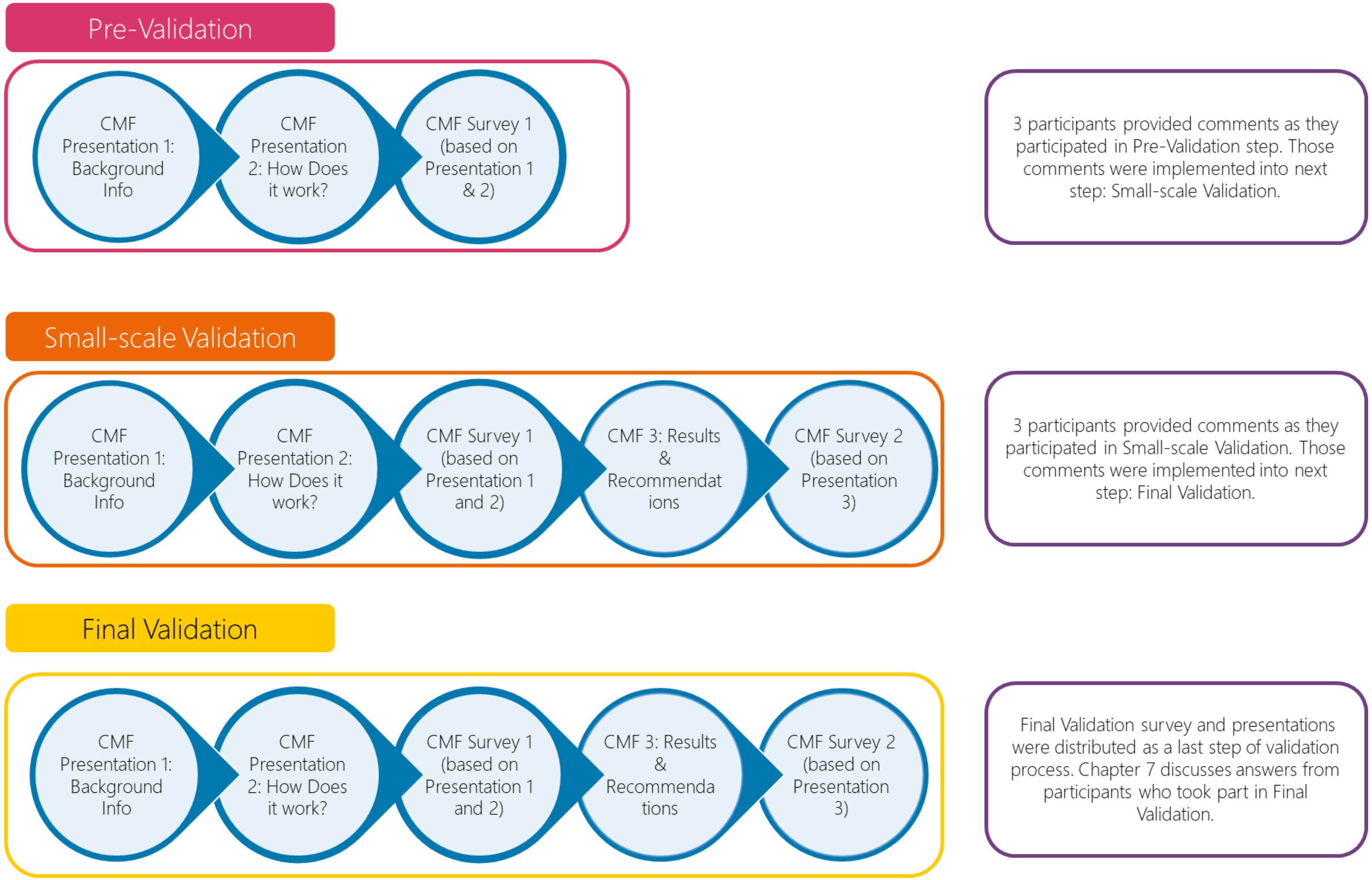


Figure 6.1: Validation process – Overview

Table 6.1: Validation process – Overview

Step	Overview
Pre-Validation	• Two presentations and a survey sent out to 3 participants • Each participant provided comments and suggestions on how to improve presentations and surveys • Comments were analyses and incorporated • Participants were not required to complete surveys at that point
Small-scale Validation	• Comments from Pre-Validation were incorporated • One more pre-recorded presentation was added • Additional questions added to the survey (based on the new presentation) • Survey was divided into 2 surveys at this point • 5 participants were asked to go through three presentations and to complete the surveys at this point • 3 participants watch the presentations and completed the surveys • Participants provided feedback regarding three presentations and two surveys • Each participant provided comments and suggestions on how to improve presentations and surveys • Comments were analyses and incorporated
Final Validation	• Comments from Small-scale Validation were incorporated • 60 participants in total were contacted and asked to take part in this research • 34 participants took part in Final Validation • Answers from participants were used to review CMF and understand what future users are concern about • Answers are analysed in Chapter 7 and discussed in Chapter 9 • Answers related to Future work are analysed in Chapter 9

Sections 6.2 and 6.3 discuss how the presentations and survey evolved through pilot studies, based on the feedback gathered from participants.

6.2 Pre-Validation

At first the validation process was supposed to include one presentation that described the most important aspects of the CMF. However, after several iterations and analysis of the presentation that will pre presented to participants, it was decided that more information should be added to the presentation so that participant's understand the whole process of creating the CMF and why it was designed in a specific structure.

Hence, one presentation was split into two, in which the first one was called 'Background Information' and the second one was called 'How does it work?'. After viewing those two presentations, participants were asked to go through a 37-question survey related to what was presented in the two presentations

3 participants took part in this Pre-Validation step by reviewing the presentations. Participants were asked about the format, technical aspects (if there were any issues while listening or completing survey), was the logic of CMF clear, etc. Participants were also encouraged to provide comments or suggestions about improving presentations and the survey (i.e. what would make them user-friendly).

Participants' general and specific comments are presented in Table 6.2 and 6.3 respectively.

Table 6.2: General comments from Pre-Validation Step

#	Comment
1	*Some grammar errors*
2	*It is more applied model*
3	*It reviews the current state of services and identifying areas of improvement*
4	*It helps identify areas of improvement but also gaps when people leave*
5	*I would consider ensuring that in whatever format people receive the information, it is really easily readable on the screen (the videos I had were very good but one or two slides I couldn't read the detail and most people who will answer this will want to understand the detail. (will advise in the email to watch it in full screen if possible)*

In general, Table 6.2 shows positive feedback. It provides evidence that there are clear benefits of implementing CMF, and it is applicable to manufacturing research centres. Detailed comments are presented in Table 6.3.

Table 6.3: Specific comments from Pre-Validation Step

#	Comment	Actions
1	CMF Presentation 2 Slide 9: *It is a very busy slide and although you're trying to illustrate a very complex problem, you could zoom in to the LHS when describing it in more detail in order to let people see what it includes (not very visible for me) and likewise when you describe through the rest it would be beneficial to zoom into that part of the screen*	Slide divided into 2 slides, modifications of visual presentation so that participants can have clearer view
2	CMF Presentation 2 Slide 10: *you have the scores, but I haven't seen you describe criteria for assessment. Are the criteria quite prescriptive? Like – in a risk review you would have L, M and H and you would normally have to determine for a particular project what you mean by low (could be a 3 day delay) M might be 2 weeks and high might be more than 1 month or something that has an effect… do you have something similar?*	Criteria were added, i.e. definitions used in data collection were added to Presentation 3
3	CMF Presentation 2 Slide 11: *This got answered in the other presentation after I watched it – so again, importance of order*	Added instructions so that participants will follow a specific order
4	CMF Presentation 2 Slide 11: *Are these real examples from people within AFRC? TL's / SPL's might get hung-up on how data was gathered and what it means. Looking at it, Additive manufacture is not more mature than some other areas but scores very highly – could also be a bias based on who you speak to (worth being aware of)*	Future Work: that is one of the questions in final survey, i.e. expectations of the participants
5	CMF Presentation 2 Slide 14: • *You have coloured and non-coloured boxes. The non-coloured ones have reached the target?* • *Maye they should be in the same colour as the target colour which I think is either blue or green?* • *Also – are the other colours always consistent? I noticed some difference in orange, yellow and white and found this most difficult to comprehend.*	Added a small text box mentioning that the white boxes are the ones that hit the target/ colours are always consistent)
6	CMF Presentation 2 Slide 20: *I think you are sometimes pointing at the screen when you narrate, however, this does not carry when someone is watching a static screen – just be mindful of this.*	Video was recorded again
7	CMF Presentation 1: *Very good – I wished I had watched this one first!*	Added instructions so that participants will follow a specific order
8	CMF Presentation 1: *some slides are very busy, and although you're trying to illustrate a very complex problem, you could zoom in to the LHS when describing*	Slide divided into 2 slides, modifications of visual

	it in more detail in order to let people see what it includes (not very visible for me)	presentation so that participants can have clearer view
9	Survey 1: *I think some people who perhaps have a limited attention span may find the presentations + questions a lot to digest*	Suggestion that the presentation and survey might take a bit of time included in the email, i.e. participants might want to block some time in their dairies or even divide it into two timeslots
10	Survey 1: *I would be able to answer the questions with no issues.*	No action required

Apart from modifications highlighted in Table 6.3, the following changes were made additionally:

- Presentation 3 including results and recommendations (from pilot study reported in Chapter 5) as added to receive comments from participants in regards to results obtained. The new presentation also included definitions, results, risk calculation, recommendations and link to Survey 2.
- Definition for each Capability Maturity Level were added to Presentation 3 to investigate if participants agree with the high level definitions
- Survey was divided into two parts: Survey 1 related to Presentations 1 and 2, and Survey 2, which relates to Presentation 3: Results and recommendations.
- The number of questions was changed, and Survey 1 contained 28 questions (instead of 37) and Survey 2 included 58 questions

6.3 Small-scale Validation

Using feedback from Pre-Validation, the presentations were updated. New presentation (i.e. Presentation 3) called Results and Recommendations (which included results from pilot study, discussed in Chapter 5) was added together with Survey 2. This new presentation focused on how each Technology Capability ended up with such results, i.e. results for sub-dimensional levels were also included. Recommendations were based on scores of each sub-dimensions for each Technology Capability. As new presentation were added, it was only reasonable to add more questions related to Presentation 3. Hence, Survey 2 was added. The link to online survey was added to the last slide of Presentation 3.

During Small-scale Validation, 3 participants (out of 5) managed to review the presentations and the survey. Those participants were different from those, who took part in Pre-Validation step. Also, because at that point participants completed 2 surveys, some preliminary results were obtained.

The participants are from technical background. All of them worked in one research centre and they have been working there for at least 4 years. Hence, they are familiar with daily operations. In addition, two participants are also involved strategic activities of research centre.

Table 6.4: Comments captured during Small-scale Validation and actions applied to address those comments

#	Comment	Actions
1	• *Definitions are very long- try to make them shorter and simpler and easier to digest* • *Definitions needs to be as quick and easy to digest*	A high level version of definitions was created for participants in Step 3; bullet points were added to simplify the definitions
2	*Change definitions into bullet points*	
3	*Break the sentences- make it easier for everyone*	
4	*I think the description could be tidied up to make it easier to use and differentiate*	
5	*Make it easier of all bullet points need to be 'hit' or just some to achieve CMI 4/5/6 etc.*	
6	*The CMI labels doesn't feel like continuum – maybe be easier to group them and label the group; make the name as clear as possible to indicate the order e.g. Basic (1-3)/Medium(4-6)/high(7-9) maturity*	New names for Each CML were added
7	*What is the difference between CMF and CMI*	The difference has been explained by adding extra slides to Presentation 3
8	*Risk (presentation 3) might be confusing – might need to add screen shot from CMT to show as example*	Slide that explains risk was modified and additional information was added
9	*The survey itself is well-developed, understandable, intuitive and the survey itself take a reasonable time to complete*	No action required
10	*CMT could be used for different purposes- but you need to make it clear what are those purposeless*	Added question to a survey that concentrates on purpose of CMF
11	*This is a complex process to explain- how much does the user needs to know?*	It was decided that user's need to have background information about the project in order to see 'the bigger picture. That is why there are 3 presentations that participants need to go through to get a better understanding of the topic
12	*I think the major issue is that your topic and your survey cover an extensive piece of information and it would have been prefect for a conference workshop*	
13	• *It takes a long time to go through everything* • *The whole process is too long* • *Looks very labour intensive to populate – can this be simplified?*	
13	*I get the impression that you will struggle to get participants to answer everything and I cannot find a way you could make it shorter*	Suggestion that the presentation and survey might take a bit of time added to an 'introduction' email, i.e. participants might want to block some time in their dairies or even divide it into two timeslots.
15	*Good to have the video in order to answer the survey*	No action required
16	*Very interesting topic*	

Actions listed in Table 6.4 were applied to CMF in order to improve Final Validation step. Apart from the comments presented in Table 6.4, Small-scale Validation also captured comments that could not be immediately fixed, but provided basis for future work. Therefore, Table 6.5 presents comments based on Small-scale Validation which will support future work (those comments are also included in Chapter 9).

Table 6.5: Comments from Small-scale Validation related to Future Work

#	Comment
1	*'Gameification' of the system*

	• *if it gets linked to funding- what technology is important for the future- someone will say that he needs that capability for the future and they might get more funding – and someone else will say that we are where we supposed to be- and will get less funding* • *People might score 'incorrectly' to get better results even if this is not necessarily true and they just want to downgrade the score for the funding*
2	*CMF development should be done in collaboration with quality team*
3	*The main purpose of CMF should be to set and assess capability project outcomes*
4	*Fewer dimensions/sub-dimensions would be better – do you need 3 sub-dimensions for all?*
5	*Maybe including a factor of probability about (e.g. technology become obsolete, personal skill being overtaken by automation, digitalisation etc. can provide better insight into risks)*
6	*It is very important to be able to capture how a staff member is able to maintain the skills over a long period and if that person changes roles and acquires new skills and leaves older skill then how this is captures and affect the CMF*
7	*I think it would be really good to see if the outside assessment and the bit about how people can maintain their skill level can be incorporated into the CMF, that way it'll be very robust*
8	*There needs to be a framework where people with particular skills (equipment, software trained etc.) are able to demonstrate regular experience of it. E.g. a person trained on a flow former let's say only spends 30 hours a week on the machine in a whole year, because there was only so much work for that, may not remain an expert user compared to someone in the industry who spends 30 hours a week on the machine; how can we incorporate a framework where the centre is funding internal 'practise' work to say manufacture demo parts or something so that the person can keep practising their skills and can maintain the level of expertise which results into a 'score; in the CMF*
9	*The structure of CMF (dimensions/sub-dimensions) are good but outside factors such as accreditations, REF etc. is crucial because it's not just internal framework that improves credit of a centre, it's internationally recognised assessment frameworks liked accreditations, REF score, research outputs, recommendations provided by industry partners (web interviews of experience of the companies working with us etc.) that really boost the credit and recognition of the centre*
10	*Agree that CML will help communicating our technological progress outside the research centre but again the outside world is going to 'judge' (if I can this word here) the centre based on their merit (decided by the know assessment frameworks i.e. accreditations, REF, KTP outcomes, feedback of customers etc.) not to say complete based on this but these things play a big role in outside world's perspective of how mature a research centre is*
11	*Probably a more intuitive interface built in a software*

6.4 Changes applied to presentations after Small-scale Validation

At the beginning of Small-scale Validation there were 28 questions in survey 1 (which is completed after participants go through presentations 1 & 2), and 58 questions in survey 2 (which is completed after participants go through presentation 3). Together there were 86 questions.

After going through each question, repetitions were removed. In addition, some questions were merged together in order to reduce number of questions in the surveys. For example, instead of asking participants 'How much do you agree with a statement CMF is a reliable tool' were the possible answers were Strongly Agree/Agree/I don't know/Disagree/Strongly Disagree/Other' – a question was replaced by CMF is a) reliable, b) objective c) easy to understand etc. were participants had to tick answers that they agreed with.

Moreover, some questions were added, based on the feedback from Small-scale Validation, e.g. questions regarding aim of CMF and aspects that it could help with, as well as questions regarding future review process of CMF. Those questions are included in Table 6.6.

Table 6.6: Questions added to the validation process based on comments from participants from Small-scale Validation

Category	Comments from participants from Small-scale Validation
questions regarding purpose of CMF and aspects that it could help with	*I think the Capability Maturity Index with clear definitions will be helpful when communicating our technological progress WITHIN the research centre*
	CMF could become a consistent approach among NMIS
	CMF provides clear understanding of capability maturity (i.e. research centre understands its own weaknesses and strengths) before taking on a project
	CMF will help with aligning Technological Capability with Industrial challenges/Cross-sector challenges
	I believe CMF provides information that could be used when discussing future projects with members/clients
	CMF process will be useful when guidance in CORE programme development is needed i.e. to understand how successful projects were and what new skills/methodologies were developed
	CMF process will be helpful when planning Catapult programme
	CMF process will be helpful when considering future investment/manpower decisions
	CMF could be used as diagnostics and capability evaluation tool at the research centre in the future (i.e. to identify weaknesses and areas of improvement e.g. limited understanding of a piece of software etc.)
questions regarding future review process of CMF	*Data in the Capability Maturity Framework can only be input by team leads or senior management personnel to protect results from any 'data manipulation'*
	In the future, results should be reviewed by senior management or technical director to ensure participants provided objective information

Moreover, the surveys' interface was improved. As the surveys were accessed online, it was suggested that questions should be made mandatory to gather as much information as possible from participants. Also, 'breaks' were added to break down surveys into 4-5 pages instead of one big page. Hence, participants saw 12-15 questions per page which seemed more doable and easy to go through when they were completing the surveys. In the end, final version of surveys used in Final Validation, section 6.6), included 37 questions (survey 1) and 43 questions (survey 2).

It is important to highlight that changes made to Final Validation design were made due to comments and suggestions of participants who took part in Pre-validation and Small-scale Validation. Their contribution helped to improve presentations and surveys by adding clarity and order. Pre-validation and Small-scale validation were important as they helped to incorporate participants' perspective.

However, it should be noted that if more participants agreed to take part in Pre-Validation or Small-scale Validation (as well as in Final Validation), the changes might have been different, and perhaps surveys would have included different kind of questions, e.g. focusing more on other Catapults perhaps. Unfortunately, that was something that was out of author's control. Nevertheless, the feedback and suggestions from participants who took part in this research were implemented and made the Final Validation design robust and highly relevant to the research.

6.5 Preliminary Results from Small-scale Validation

Apart from comments that helped improve Step 3, Step 2 also captured some preliminary results. 5 participants (4 at AFRC and 1 from industry) were contacted at first. However only 3 completed two surveys after watching/going through 3 presentations (2 participants from AFRC, 1 from industry). All answers are included in Appendix 19 and 20 (answers from survey 1 and survey 2, respectively). Some preliminary results are included below.

One of the first questions that participants were asked was about their knowledge (or awareness) the well-known tools/frameworks that could be used to manage readiness/maturity. They all answered that they know TRLs and MRLs. Participants also answered that they know MCRLs and 1 participant mentioned that "accreditations and other outer assessments should be considered." Results for this question (Q3, Survey 1) are presented in Figure 6.2 below.

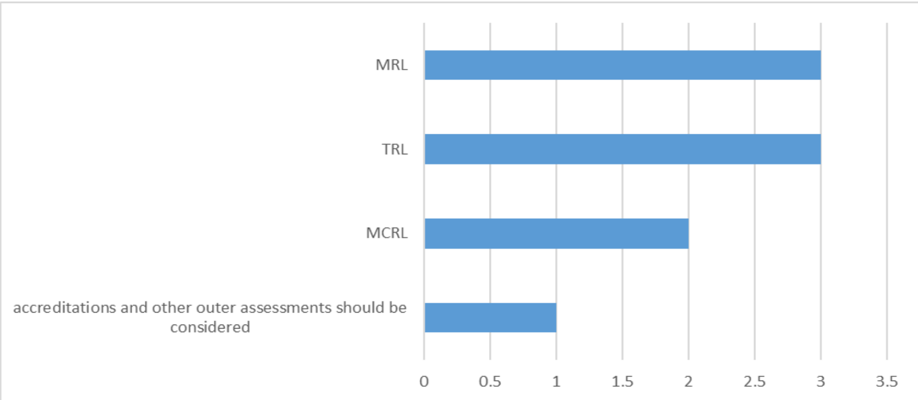


Figure 6.2: Could you list some of the well-known tools/frameworks that could be used to manage readiness/maturity?

Participants were also asked if they could list some of the tools/methods you are currently using (or used before) to manage readiness/maturity (Q4, Survey 1). They provided the following answers:

- *A variation of the technology readiness level which includes an extra level for technology pick.* Participant 1
- *I have contributed to MCRL preparation in the past for specific ManTech* Participant 2
- *None* Participant 3

Participants were also asked about their professional background and what their work was related to. Table 6.7 presents answers from 3 participants.

Table 6.7: Is your work related to

Participant	Professional background
Participant 1	Technological decision-making
Participant 2	Strategic decision-making
Participant 3	All of the above

The main purpose of pilot study was to test if the presentations explain clearly the logic and process of capturing Capability Maturity, and if the surveys capture the most important information. However, as participants answered questions in Survey 1 and Survey 2, preliminary analysis was performed. Sections 6.5.1 and 6.5.2 describe those preliminary results. Also Figure 6.2 shows the distribution of answers from 3 participants who took part in this pilot study.

6.5.1. Preliminary Results Survey 1

For this preliminary study, 12 questions (out of 37) were chosen. The idea of this preliminary analysis it to show the general overview of what participants' thoughts are about CMF. As the preliminary results will not be used in the final analysis, 12 questions that were considered most significant, were chosen for this preliminary analysis. Those 12 questions are listed below. Figure 6.3 below illustrates the results from first part of preliminary study.

- Q7. CMF will improve the research centre's understanding of its own TECHNOLOGICAL capabilities
- Q8. CMF will be useful to support my role
- Q9. CMF provides useful data for TECHNOLOGICAL road-mapping implementation
- Q10. The research centre needs tools like Capability Maturity Framework to improve their TECHNOLOGICAL capabilities
- Q11. I will use CMF when looking for an overview of strengths and weaknesses of technological capabilities at the research centre
- Q12. I think CMF will be a valuable addition to the research centre I work at/with
- Q13. The structure of CMF (3 dimensions: People, Equipment, Projects) and further 9 sub-dimension (3 sub-dimensions in each dimension) are a good representation of a research centre's capabilities
- Q14. I will be able to access useful and detailed information regarding individuals, equipment and projects through CMF to understand relevant challenges
- Q15. I think the Capability Maturity Index with clear definitions will be helpful when communicating our technological progress WITHIN the research centre
- Q16. I think the Capability Maturity Index with clear definitions will be helpful when communicating our technological progress OUTSIDE the research centre (e.g. with members or industrial partners)
- Q17. CMF makes us aware of our own (i.e. centre's) maturity
- Q23. In my opinion there is a need for a standard tool that captures data about research centre's Technological Capabilities

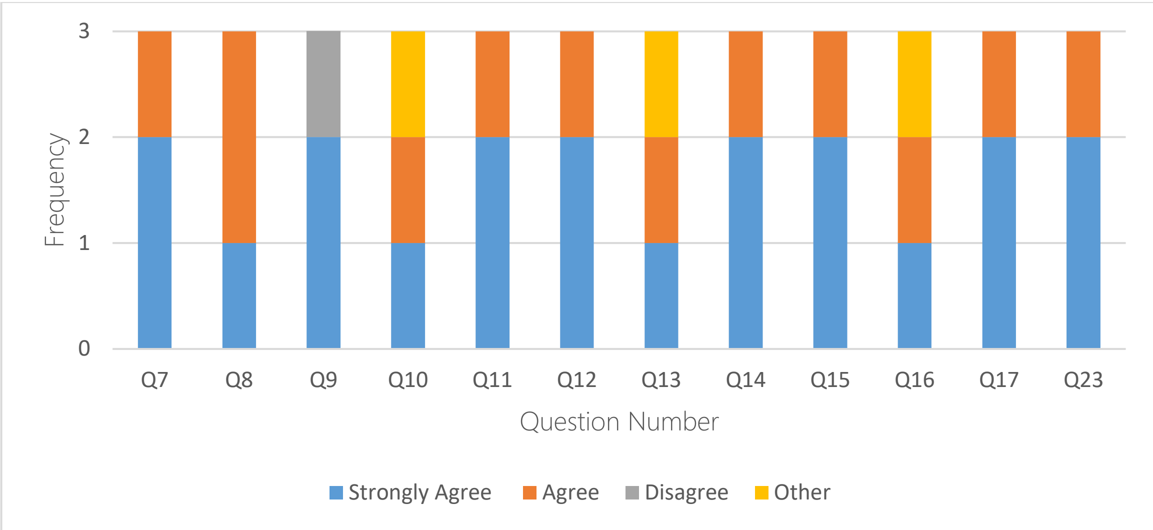


Figure 6.3: Preliminary Results Survey 1: Small-scale Validation July 2020

Figure 6.3 presents distribution of answers for 12 questions from Survey 1. It should be highlighted that participants ‘strongly agreed’ (blue colour) or ‘agreed’ (orange colour) with the questions listed above. Hence, overall feedback regarding CMF and its benefits was positive. Only one participants disagreed with Q9: ‘CMF provides useful data for TECHNOLOGICAL road-mapping implementation’, which is showed in Figure 6.4 by grey colour. In this case 2 participants ‘strongly agree’ and one ‘disagrees’ with the statement in Q9. Furthermore, one participants also selected ‘other’ as an answer to Q10: ‘The research centre needs tools like Capability Maturity Framework to improve their TECHNOLOGICAL capabilities’, Q13: ‘The structure of CMF (3 dimensions: People, Equipment, Projects) and further 9 sub-dimension (3 sub-dimensions in each dimension) are a good representation of a research centre's capabilities’ and Q16: ‘I think the Capability Maturity Index with clear definitions will be helpful when communicating our technological progress OUTSIDE the research centre (e.g. with members or industrial partners).’ However, those comments were captured already in comments and suggestions presented in Table 6.5, which refers to Future Work.

6.5.2 Preliminary Results Survey 2

7 questions (out of 58) were chosen. As the preliminary results will not be used in the final analysis, those 7 questions that were considered most significant, were chosen for this preliminary analysis. Those 7 questions are listed below. Figure 6.4~~5~~ below illustrates the results from first part of preliminary study.

- 5. CMF will improve the research centre’s understanding of its own TECHNOLOGICAL capabilities
- 6. CMF will provide valuable data and support regarding TECHNOLOGICAL decision making and/or planning
- 7. CMF contains valuable data and support regarding OPERATIONAL decision making and/or planning
- 8. CMF contains valuable data and support regarding STRATEGIC decision making and/or planning

- 15. CMF provides an appropriate amount of detail to identify capability related gaps
- 46. CMF could be used as diagnostics and capability evaluation tool at the research centre in the future
- 50. The transparency about data collection and interpretation has been demonstrated

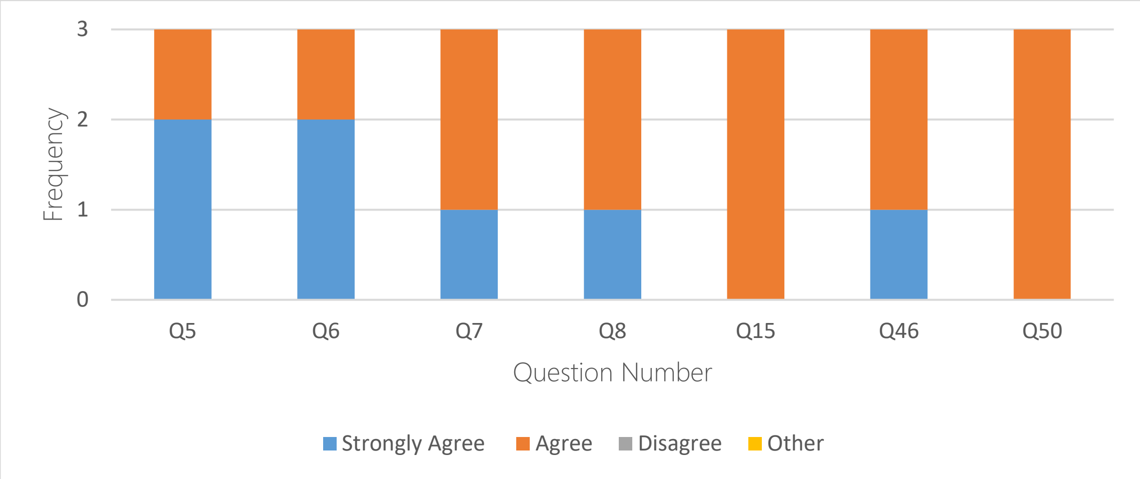


Figure 6.4: Preliminary Results Survey 2: Small-scale Validation July 2020

Figure 6.4 presents distribution of answers for 7 questions from Survey 2. It should be highlighted that participants 'strongly agreed' (blue colour) or 'agreed' (orange colour) with the questions listed above. Hence, overall feedback regarding CMF and its benefits was positive. Hence, preliminary results from Survey 2 show that participants see benefits of CMF e.g. support for technological, operational and strategic decision-making. The presentations also provided transparency about data collection process (which was very important from academic viewpoint). Furthermore, participants also agreed that CMF would improve the research centre's understanding of its own technological capabilities, and that it provides an appropriate amount of detail to identify capability related gaps, which are the aims of CMF. Therefore, this pilot study provided a positive feedback, and gave a positive indication that CMF could be used as diagnostics and capability evaluation tool at the research centre in the future.

After modifications were applied to presentations and surveys (comments from Table 6.4 and questions identified in Table 6.6), Final Validation process was implemented.

6.6 Final Validation

Once above modifications were made and online survey was improved, participants were contacted and ask if they would like to participate in this stage of my research. Final validation process took place between September and November 2020. Initially 3 weeks were dedicated to this step, however due to unavailability of some participants it had to be extended. By extending the deadline for completing surveys it was ensured that more participants would take part in this study. In the end Final Validation took about 6 weeks to gather information from participants. In total, 60 people were contacted. However, 34 participants completed the surveys.

The questions were divided in 15 categories. All questions were distributed amongst 2 surveys. The categories were based on previous comments (from 2 pilot studies) as well as literature sources related validation processes of management tools. Those literature sources are highlighted in Table 6.8 in relation to specific criteria.

Table 6.8 shows evaluation criteria in the following order:

- Participants background i.e. what readiness/maturity tools participants currently use and why, but also what participants expect from the new framework i.e. users' goals, users' expectations (highlighted in blue).
- Need for standardisation i.e. participants' perspective on the need for standardised approach, which aims to understand capability maturity across one research centre and/or across network of research centres (highlighted in orange).
- Feedback that can be applied easily to CMF i.e. aspects that can be modified when validation process is completed (highlighted in green).
- CMF and its importance to wider network i.e. to HVMC network (highlighted in yellow).
- Future work and changes that require more time and effort to be applied (i.e. future research work) (highlighted in grey).

Table 6.8: Evaluation criteria used during validation process

Evaluation Criteria	Definition	References
Participants background	Participants' role, experience, and work type (are they working at the research centre, industry etc.)	Research methodology (chapter 3, section 3.7)
Tools to measure readiness/maturity	Participants awareness of available solutions, and which solutions they currently use and why	Literature review (Chapter 2, section 2.5.3), Interviews (Chapter 4, section 4.2.5.1, 4.2.5.2, 4.2.5.3)
Users' goals (Technical vs Operational)	Participants' perspective on what aspects (technical or operational) could be completed with the help of CMF	Validation design (Chapter 6) (Hong & Kim, 2004), (Sun, et al., 2019)
Users' expectations	"A set of beliefs held by the targeted users of" CMF associated with the eventual performance of the CMF and with research centre's performance using the system	Feedback from pilot study, (Chapter 6, section 6.3), Validation design (Chapter 6) (DeLone & McLean, 1992), (Szajna & Scamell, 1993)
Need for standardisation	A need for a set of standards designed to help research centres navigate the complex process of capability development, "systematize their activities and enhance efficiency of its management" (Mir, et al., 2016)	Interviews (Chapter 4, section 4.2.5.4), (Literature review (Chapter 2, section 2.5), Validation design (Chapter 6)
Purpose and benefits of CMF	How could CMF be applied and what it is exact aim? Aspects that CMF will help with	Interviews, (chapter 4, section 4.2.5.5, section 4.4.5.1), Feedback from pilot study (Chapter 6, section 6.3, section 6.4)
Mechanism/Structure of CMF	Structure of how various elements of CMF are combined/linked together and how the process of calculating CML works	Interviews (Chapter 4, section 4.3.5.1), Development of CMF (Chapter 5, section 5.2, section 5.3), Feedback from pilot study (Chapter 6, section 6.4)

Practicality of CMF	Delivery of realistic information by the conceptual framework	Interviews (Chapter 4, section 4.4.5.5), Literature review (Chapter 2, section 2.6)
Transparency of CMF	Transparency, as the concept people know and use today, is defined as the extent to which one entity discloses relevant information about its own decision processes, procedures, performance, and functioning (Hosseini, et al., 2018)	Interviews (Chapter 4, section 4.2.5.6, section 4.3.5.2), Validation design (Chapter 6) (Hong & Kim, 2004), (Li, et al., 2005), (Zhu, et al., 2018), (Hosseini, et al., 2018)
Reliability of CMF	Quality of knowledge of various kinds, including its quality relevance, accuracy, timeliness, applicability, comprehensibility, presentation formats, extent of insight, availability of expertise (Kulkarni, et al., 2006)	Validation design (Chapter 6) (Li, et al., 2005), (Kulkarni, et al., 2006)
Strategic Importance	The long term decisions an organization makes about how it uses its data to take actions that satisfies its organizational vision and mission; specifically, the selection of analytic opportunities by an organization (Grossman, 2018)	Interviews (Chapter 4, section 4.3.5.2, 4.3.5.3), Literature review (Chapter 2, section 2.5.7)
Applicability to HVMC	Potential applicability of CMF in different HVM Catapults	Interviews (Chapter 4, section 4.2.5.7)
Future CMF Review	Further steps that will ensure reliability of the results	feedback from pilot study, literature (Hong & Kim, 2004)
Validation process	Validation. "Am I building the right product?" (Boehm, 1984)	Validation design (Chapter 6) (Boehm, 1984), (Lee & Kim, 1999), (Bouabidi, et al., 2012), (Ahmad, et al., 2017)
Future work & Additional comments	Critical feedback from participants; Elements/mechanisms that might be added to CMF in the future in order to improve overall applicability and meaningfulness of the framework; Elements and/or aspects that were captured in the follow up discussions	Validation design (Chapter 6) Feedback from pilot study (Liao & Cheung, 2001), (O'Brien & Toms, 2008), (Huyean, et al., 2020)

6.7 Summary

To sum up, participants' comments and feedback captured during Pre-validation and Small scale Validation were very important to validation design. Feedback and comments helped to incorporate participant's perspective and improve presentations as well as surveys. During Pre-validation and Small scale validation it was assumed that if something was not clear to one participant, it would probably confuse other participants too. Therefore, Pre-validation and Small-scale Validation provided an opportunity to improve validation design and review it, which led to Final Validation design becoming robust and relevant to this study.

The validation design process took several months to finalise. The biggest limitation during validation design was the availability of participants and lack of face-to-face meetings (due to Covid pandemic). However, once presentations and surveys for Final Validation step were improved, they were distributed to 60 new participants. Final surveys included 37 questions (survey 1) and 43 questions (survey 2). Questions included in survey 1 and 2 are presented in Appendix 21 and 22 (Table A8 and A9, respectively). Results from Final Validation are presented in Chapter 7.

Chapter 7: Validation Results

7.1 Introduction

This chapter discusses the results collected from 34 participants through two online surveys (using SoGoSurvey website). Survey 1 referred to Presentation 1:' Background Information' and Presentation 2: 'How does it work?'; Survey 2 referred to Presentation 3: 'Results & Recommendations'. Data was collected between September and November 2020. Initially 3 weeks were dedicated to this research stage. However due to unavailability of some participants it had to be extended. By extending the deadline for completing surveys it was ensured that more participants would take part in this study. In the end, it took about 6 weeks to gather information from participants. At the beginning of this process, 60 people were contacted, and a total of 34 participants completed the surveys. The response rate was 57%.

The questions were divided into 15 evaluation criteria, which were created based on participants' comments (from Pre-validation and Small-scale validation, section 6.2 and 6.3, Chapter 6) as well as literature sources. All the questions were distributed through two online surveys.

Table 7.1 below shows evaluation criteria discussed in this chapter as well as definition of each of the criteria. The criteria were divided in five categories (as described in Chapter 6), and are colour coded to highlight which criteria belong to specific category. The categories are:

- Participants background i.e. what readiness/maturity tools participants currently use and why, but also what participants expect from the new framework i.e. users' goals, users' expectations (highlighted in blue).
- Need for standardisation i.e. participants' perspective on the need for standardised approach, which aims to understand capability maturity across one research centre and/or across network of research centres (highlighted in orange).
- Feedback that can be applied easily to CMF i.e. aspects that can be modified when validation process is completed (highlighted in green).
- CMF and its importance to wider network i.e. to HVMC network (highlighted in yellow).
- Future work and changes that require more time and effort to be applied (i.e. future research work) (highlighted in grey).

Table 7.1 Evaluation criteria used in the Final validation

Section #	Evaluation Criteria	Definition	References/Based on
7.2	Participants background	Participants' role, experience, and work type (are they working at the research centre, industry etc.)	Research methodology (chapter 3, section 3.7)
7.3	Tools to measure readiness/ maturity	Participants awareness of available solutions, and which solutions they currently use and why	Literature review (Chapter 2, section 2.5.3), Interviews (Chapter 4, section 4.2.5.1, 4.2.5.2, 4.2.5.3)
7.4	Users' goals (Technical vs Operational)	Participants' perspective on what aspects (technical or operational) could be completed with the help of CMF	Validation design (Chapter 6) (Hong & Kim, 2004), (Sun, et al., 2019)

7.5	Users' expectations	"A set of beliefs held by the targeted users of" CMF associated with the eventual performance of the CMF and with research centre's performance using the system	Feedback from pilot study, (Chapter 6, section 6.3), Validation design (Chapter 6) (DeLone & McLean, 1992), (Szajna & Scamell, 1993)
7.6	Need for standardisation	A need for a set of standards designed to help research centres navigate the complex process of capability development, "systematize their activities and enhance efficiency of its management" (Mir et al., 2016)	Interviews (Chapter 4, section 4.2.5.4), Validation design (Chapter 6)
7.7	Purpose and benefits of CMF	How could CMF be applied and what it is exact aim? Aspects that CMF will help with	Interviews, (chapter 4, section 4.2.5.5, section 4.4.5.1), Feedback from pilot study (Chapter 6, section 6.3, section 6.4)
7.8	Mechanism/Structure of CMF	Structure of how various elements of CMF are combined/linked together and how the process of calculating CML works	Interviews (Chapter 4, section 4.3.5.1), Development of CMF (Chapter 5, section 5.2, section 5.3), Feedback from pilot study (Chapter 6, section 6.4)
7.9	Practicality of CMF	Delivery of realistic information by the conceptual framework	Interviews (Chapter 4, section 4.4.5.5), Literature review (Chapter 2, section 2.6)
7.10	Transparency of CMF	Transparency, as the concept people know and use today, is defined as the extent to which one entity discloses relevant information about its own decision processes, procedures, performance, and functioning (Hosseini et al., 2018)	Interviews (Chapter 4, section 4.2.5.6, section 4.3.5.2), Validation design (Chapter 6)
7.11	Reliability of CMF results	Quality of knowledge of various kinds, including its quality relevance, accuracy, timeliness, applicability, comprehensibility, presentation formats, extent of insight, availability of expertise (Kulkarni, et al., 2006)	Validation design (Chapter 6) (Li, et al., 2005), (Kulkarni, et al., 2006)
7.12	Strategic Importance	The long term decisions an organization makes about how it uses its data to take actions that satisfies its organizational vision and mission; specifically, the selection of analytic opportunities by an organization (Grossman, 2018)	Interviews (Chapter 4, section 4.3.5.2, 4.3.5.3), Literature review (Chapter 2, section 2.5.7)
7.13	Applicability to HVMC	Potential applicability of CMF in different HVM Catapults	Interviews (Chapter 4, section 4.2.5.7)

Sections 7.2-7.13 present a detailed review of questions aligned to each of the evaluation criteria. Each section will report the distribution of answers based on participants' background and responsibilities, as well as their comments. Section 7.14 includes summary of the key results from sections 7.2-7.13.

Some aspects cannot be fixed immediately and require more effort and time, thus need to be considered for Future work (e.g. future review of CMF, which is also related to reliability of the results delivered by CMF). Therefore, those aspects are discussed in Chapter 8 and Chapter 9.

7.2 Participants' background

The background of participants differ as the aim was to gather as much feedback not only from technical perspective but also from operational, strategic and project management perspective. Not only the feedback within AFRC and NMIS was collected, but also participants from various HVMC centres, Lightweighting Manufacturing Research Centre (LMC) (which is part of NMIS), as well as those from industrial companies who work regularly with manufacturing research centres were contacted. Going one step forward, even though the aim of this research was to create CMF for manufacturing research centres in the UK, participants from manufacturing research centres outside the UK were also contacted to increase the sample diversity.

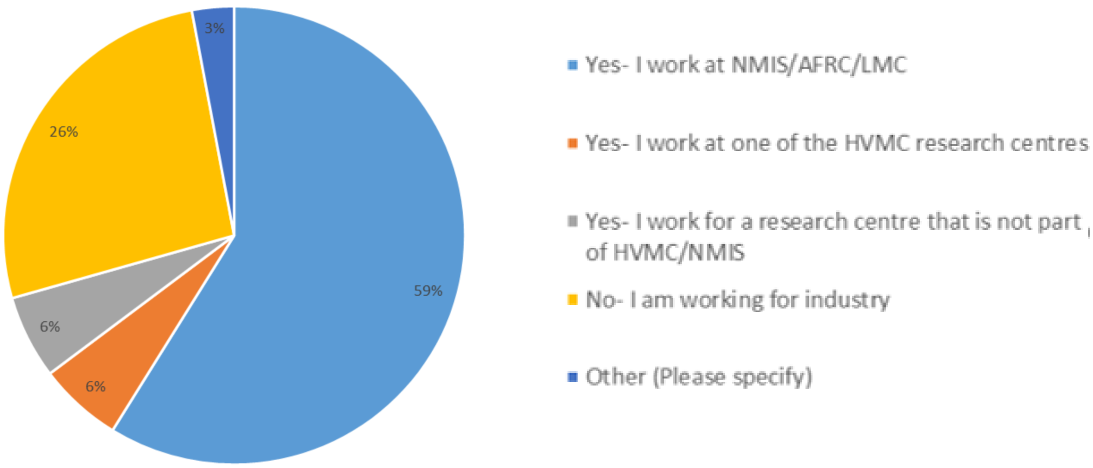


Figure 7.1: Participants' background – where do they work

Figure 7.1 shows that 59% of participants came from AFRC/LMC/NMIS centre. 26% of participants work for an industrial company that collaborate with research centres. 6% of participants work for other research centres that are part of the HVMC network, and the other two came from a manufacturing research centres that are not part of HVMC network. One participant came from a different background i.e. 'Other', which was explained as "work at University of Strathclyde in Engineering Faculty (previously worked at AFRC)."

It should be highlighted that potential participants from all HVMC were contacted in order to gather responses from a wider and more diverse group of experts. However, in the end, those potential participants did not take part in the study.

Figure 7.2 shows a variety of activities that participants are responsible for at their work. 32% of the participants mentioned that they are involved in technical, operational and strategic (TOS) activities. 21% of participants mentioned that they are only involved in technical activities, and 18% highlighted that they are involved in operational and strategic activities. 3% mentioned that at he/she is involved in operational activities, and another 3% is involved in strategic activities only.

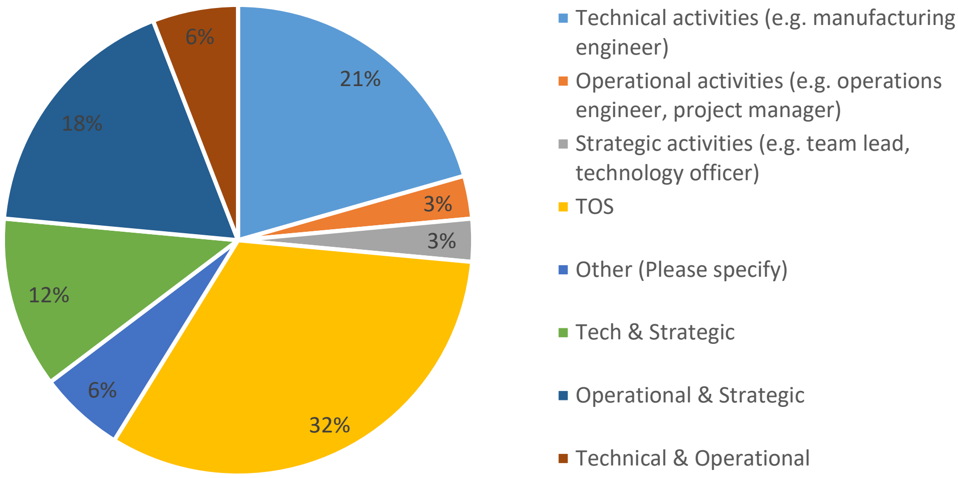


Figure 7.2: Participants' background – responsibility

Table 7.2 below shows the summary of participants who took part in the Final validation stage, and was created using information presented in Figure 7.1 and 7.2. Table 7.2 shows that 7 participants who are involved in technical, operational and strategic activities came from NMIS/AFRC/LMC, one came from a research centre that is not part of HVMC, and two came from industry.

Table 7.2: Participants' background

Background	NMIS	HVMC network	RC - not part of HVMC	Industrial company	Other	Total	%
Technical activities	2			5		7	21%
Operational activities				1		1	3%
Strategic activities	1					1	3%
TOS*	8			2		11	32%
Other	1			1		2	6%
Technical & Strategic activities	2	1	1			4	12%
Operational & Strategic activities	5	1				6	18%
Technical & Operational activities	1				1	2	6%
Total	20	2	2	9	1	34	100%
%	59%	6%	6%	26%	3%	100%	

*TOS=Technical, operational & strategic activities

Two participants who selected 'Other' as their answer, explained that their background could be describe as follows:

- *"All the above can affect my work. However, using data for developing best engagement practice methods is probably most applicable"*
- *"Research"*

Table 7.3 below shows participants' role. It shows that 26% of participants were from technical theme/team lead background. The second biggest category, 21%, was business development/Industry engagement (BD/IE) background. The third biggest group was participants with leadership background and with industrial engineering background (equally 15%). 3% of participants came from management background, and another 3% from project & programme management.

Table 7.3: Participants' roles and experience

Role	Frequency	Percentage	Combined experience (in years)	Average experience (in years)
Technical Leads (technical programme leads, technical theme leads & team leads)	9	26%	54.5	6
Business Development/Industry Engagement (BD/IE)	7	21%	73	10.4
Leadership	5	15%	42.5	8.5
Industry-Engineer	5	15%	18	3.6
Senior Manufacturing Engineer	4	12%	46	11.5
Industry-Manager	2	6%	10	5
Management	1	3%	10	10
Project & Programme Management	1	3%	10	10
Total	34	100%	264	

Table 7.3 presents average experience for each group of participants based on their roles. Group of participants assigned to Industry- Engineer role has the shortest average experience (3.6 years). On the other hand, Senior Manufacturing Engineer group has the longest average experience (11.5 years). Moreover, participants from industry (Industry-Engineer and Industry-Manager group) have the shortest average experience from all the groups in Table 7.6. Using total number of participants (34) and the total number of years of all participants (264 years) (from Table 7.6), mean, median and standard deviation were calculated for that dataset and are presented below:

- Mean: 7.76
- Median: 4
- Standard Deviation: 8.91

In addition, those who selected 6 months as their time in the particular position, have much longer prior experience of working at research centres (e.g. 15-20 years). It means that at the particular role (that they had included as their answer), they have been for (at least) 6 months. However, due to their prior experience, they do understand the work and dynamics of research centres.

Figure 7.3 shows distribution of years of experience based on participants' answers. It shows that experience of participants in their current roles differ from 6 months to 33 years. As mentioned before, mean of participants' experience is equal to 7.76, i.e. almost 8 years of experience, which is a significant amount of time and can provide insightful contribution to this research.

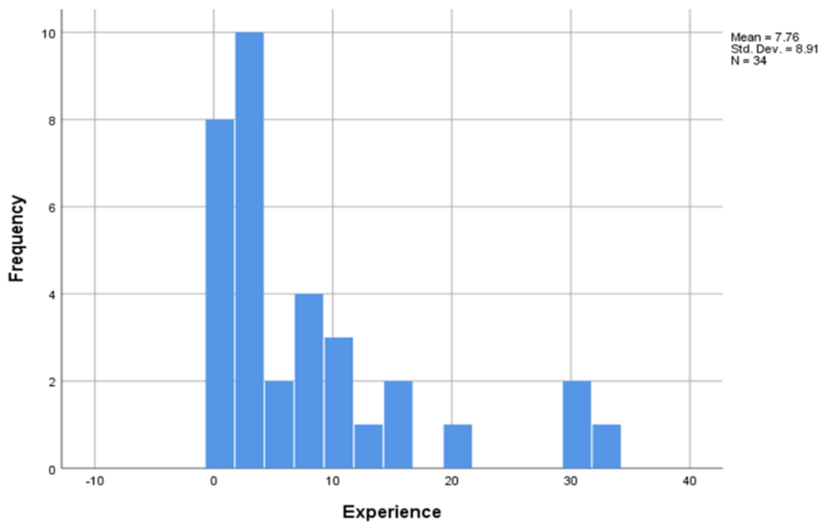


Figure 7.3: Histogram showing years of experiences of participants (created using SPSS software)

Overall, the biggest group of participants (i.e. 9) belongs to technical leads (either they lead technical team, technical programme or technology capability theme). Even though technical leads mostly manage technical projects, they are also responsible for a range of activities: operational, strategic or combined. Therefore, those participants do not only concentrate on completing technical trials, but also on delivering products/services to industry, planning on future goals (i.e. how to implement vision etc.). Also, average experience (among 34 participants) was 8 years. That is an important information as it shows that participants involved in this research have a good level of knowledge regarding research centre environment, decision-making process but also capability maturity process.

7.3 Tools to measure readiness/maturity

Participants were asked if they were aware of any tools/methods for measuring readiness or maturity (Q4, Survey 1 and 2). Figure 7.4 below shows a number of different tools/methods that participants mentioned, and the frequency (i.e. number of people who are aware of mentioned tools/methods). Figure 7.4 clearly shows that TRL was the tool/method that participants mentioned the most.

The second mostly mentioned tool/method were MRL (manufacturing and material readiness levels) involving 11% of participants. Hence, these results confirmed that participants are aware of various tools and methods. Therefore,, the next question showed how many of those methods participants are actually using in their daily responsibilities. Figure 7.5 shows answers to (Q5, Survey 1 and 2), i.e. Could you list some of the tools/methods you are currently using (or used before) to manage readiness/maturity?

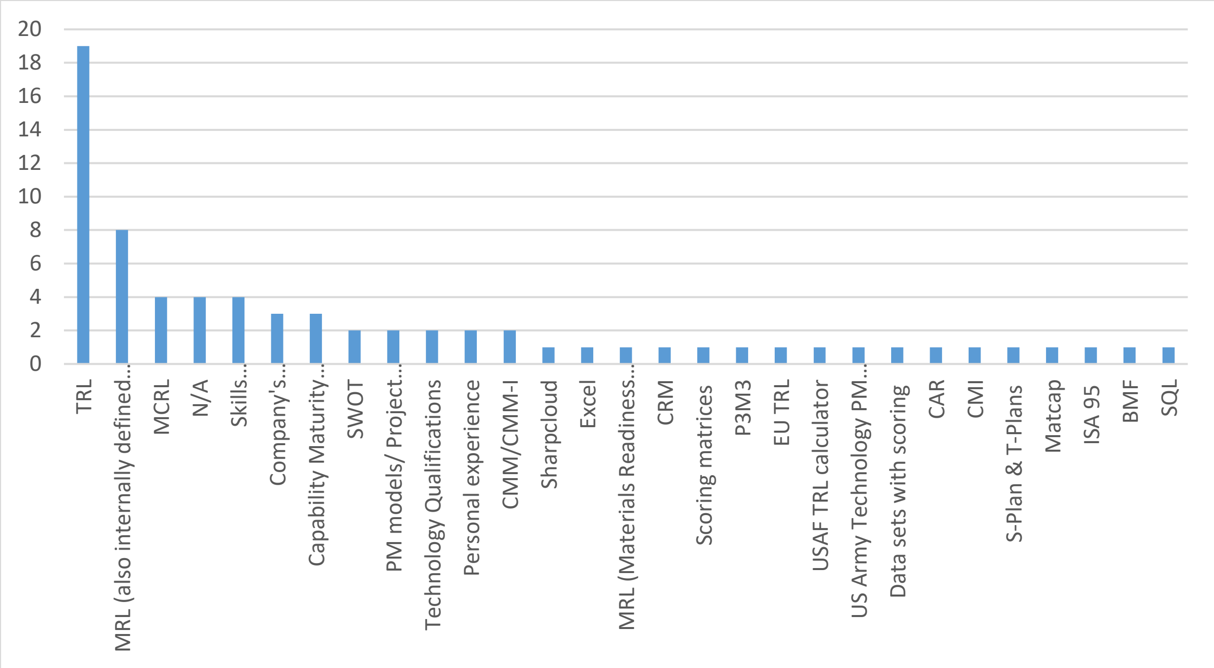


Figure 7.4: Tools/frameworks that you are aware of that could be used to manage readiness/maturity

Again, most participants (30%) indicated that they use TRLs. Second solution that received most votes was MRLs (12%). However, the biggest difference between answers to Q4 and Q5 is that in Q4, the total number of answers was 72 and in Q5 – 50. It means that some of the tools/methods mentioned in Q4 (i.e. solutions that participants are aware of) are not the ones that participants are using at work. Hence, these results suggested that there might not be a direct relationship between awareness and actual implementation regarding the management of readiness/maturity.

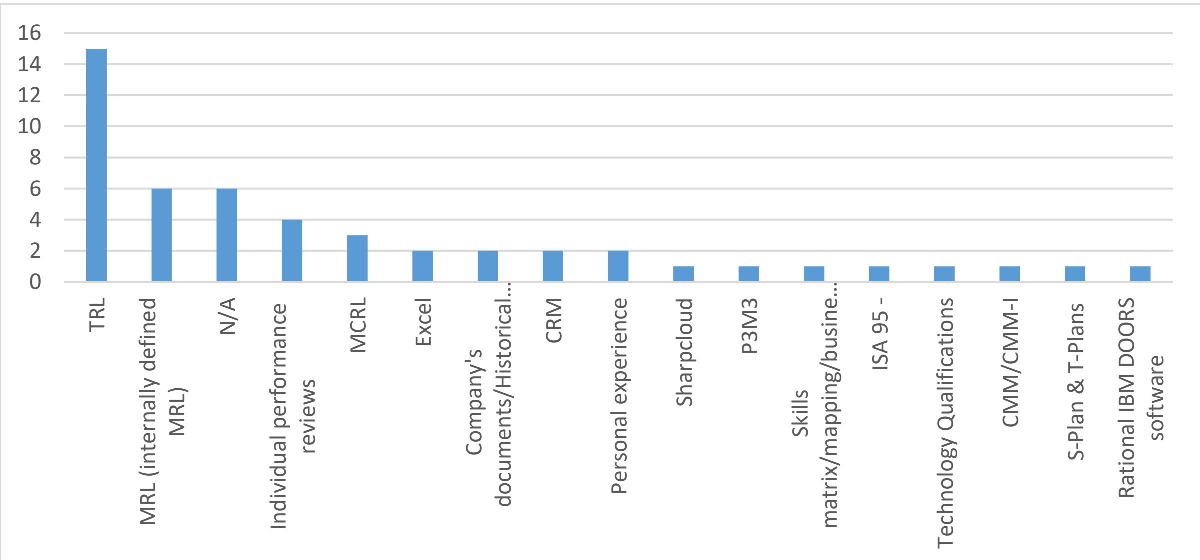


Figure 7.5: Tools/methods you are currently using (or used before) to manage readiness/maturity

Once participants mentioned tools/methods they use/used before, the next question (Q6, Survey2) concentrated on reasons why participants are using those particular tools, as presented in Figure 7.6 below. 16 participants (78%) did not provide any answer or explanation. However, it should be mentioned that 6 participants did not complete Survey 2, hence 10 participants (30%) did not provide any answer to Q6. 4 participants (12%) answered that they used previously mentioned tools because of the familiarity and availability of those tools. Another 4 participants (12%) answered that the tools they are using are the official standards. 3 participants mentioned that they use the tools in order to "get better understating of the maturity of technology and product." 2 participants (6%) need tools that combine funding data, and another 2 participants (6%) highlighted that there is "no active measurement undertaken," i.e. no tools are used at the moment. One participant (3%) mentioned that they use their tools for tracing requirements, and another participants (3%) answered that "Other solutions are not fit for purpose." Additionally one person mentioned that they 'don't know any other methods" (P127).

Hence, most participants provided the following three reasons for using specific tools for measuring readiness/maturity:

- These tools/methods are being used as a current practice (i.e. no specific explanation)
- Good familiarity and availability of the tools/methods
- The tools/methods they are using are of official standards

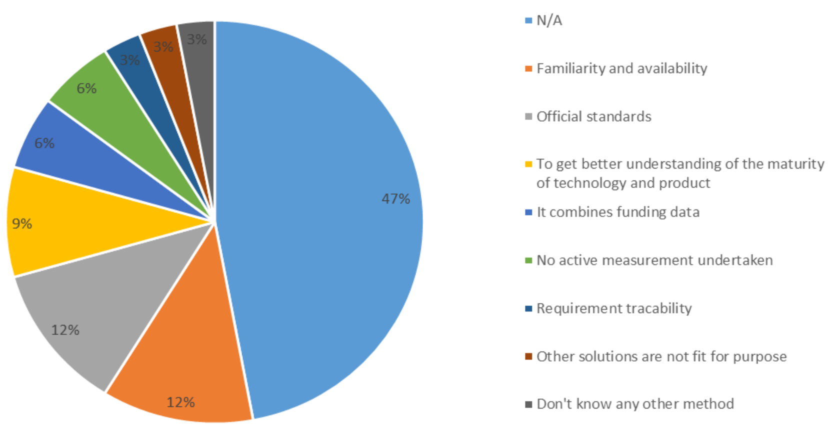


Figure 7.6: Distribution of answers to Q6: Why do you use those particular tools/methods?

Considering those three reasons, the next step was to investigate how useful the information included in the CMF is for users.

To summarize this section Figure 7.7 and Figure 7.8 below shows the use of previously discussed tools based on participants' role and responsibilities, respectively.

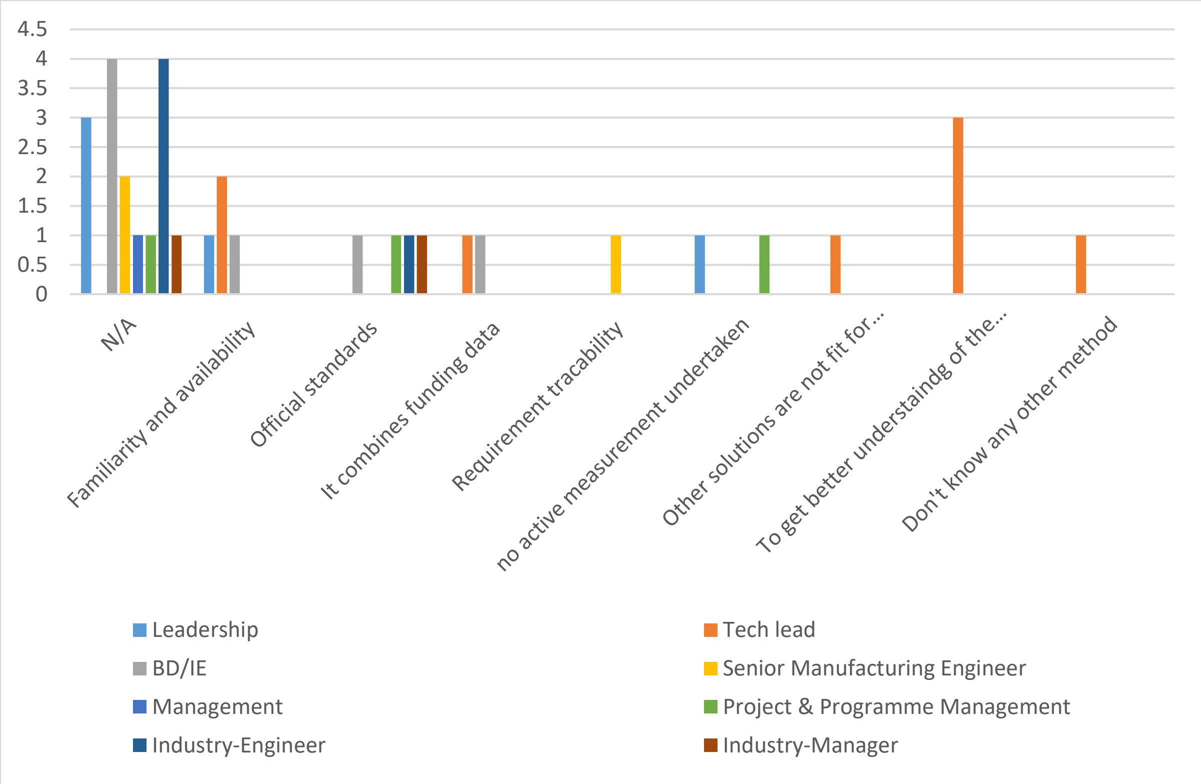


Figure 7.7: Answers to Q6 why you use specific solutions based on participants' roles

Figure 7.7 shows that majority of participants (from various groups) did not provide any answer. Therefore, substantial number of participants was not able to explain why they use certain tools (or they did not want to provide an explanation). It could be also possible that they do not use any of those solutions in their day-to-day activities, i.e. in that case the question is irrelevant. On the other hand, familiarity and availability seems to be one of the reasons why certain tools are used. It could also mean that tools/methods that are official standards in industry or specific companies, also bring that level of familiarity and availability (as companies make them available or create their own standards).

People usually become more familiar with certain tools/software/approaches that make available to them. Hence, they often (even if they take longer) use those tools simply because of ease of access and it does not necessarily mean that those tools are the best. Once organisations adapt something that works for them, it is difficult to change. Therefore, a well-thought-through implementation plan would need to be devised to outline the change step-by-step. It could be a good idea to involve a change management expert to overlook the change process. This expert will be able to identify resistances that are stopping the implementation of new tool, and will be able to lead the transition. That will help increase the acceptance of new tool and expedite its implementation.

Also Figure 7.7 shows that majority of technical leads selected (apart from availability and familiarity), the following answers

- Combines funding data
- Other solutions are not fit for purpose

- To better understand maturity of technology and product
- Don't know any other method

Hence, Figure 7.8 below shows which tools are used by participants who provided the above explanation. Legend underneath the figure explains reasons why certain tools were selected (i.e. the y-axis shows the mixture of tools used by participants).

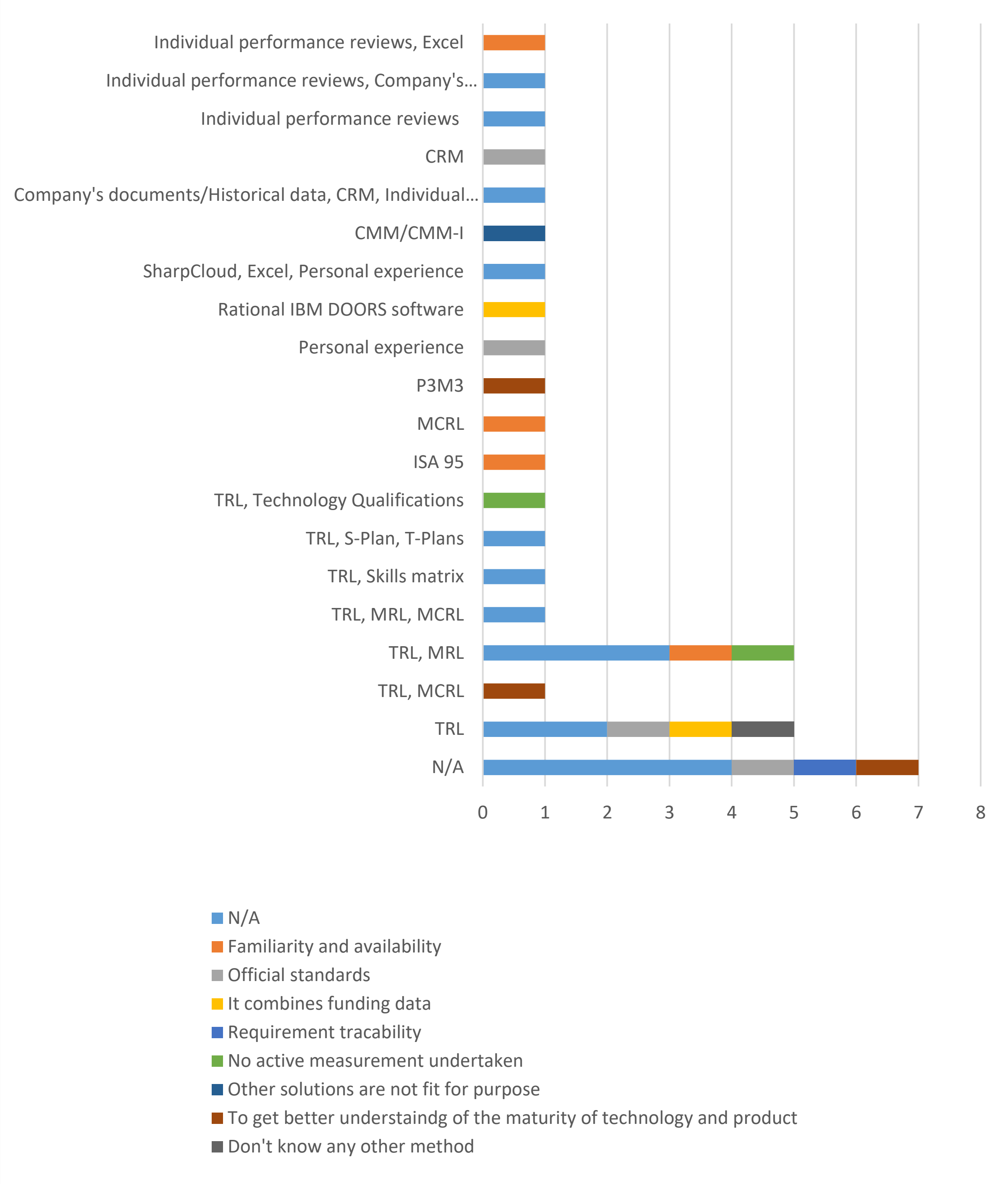


Figure 7.8 Distribution of answers to Q6 and Q5

Thus, to present the correlation between explanations provided by technical leads, the explanations and tools selected by the same participants (who provided specific explanation) are presented in Table 7.4 below.

Table 7.4: Explanations provided by technical leads correlation to solutions they currently use

Explanation	Tools used
Familiarity & availability	TRL, MRL, Skills Matrix
Combines funding data	TRL
Official standards	TRL, S-Plan, T-Plan
Other solutions are not fit for purpose	Individual Performance Reviews, Excel
To better understand maturity of technology and product	Company's documents, Historical data, Individual Performance Reviews, TRL, Technology Qualifications
Don't know any other method	TRL

Hence, majority of technical leads selected TRL as the tools that they use. Apart from familiarity and availability, the reason why participants use TRL (and other solutions mentioned in Table 7.4) is to better understand maturity of technology and product (which is the goal of TRL). On the other hand, one participant mentioned that they are not aware of any other method, and another participant said that 'other solutions are not fit for purpose'. Therefore, it is concluded that participants use certain solutions out of habit and because there is nothing else available to them.

7.4 Users' goals (Technical vs Operational)

This sub-section highlights questions about users' goals and the applicability of CMF to support those goals. Table 7.5 includes questions from two online surveys that were part of this category. Tables 7.6 and 7.7 shows results to those questions.

Table 7.5 Questions related to Technical vs Operational (User goals/Goal relevance)

Survey	Question
S1	Q8. Research centre needs tools like Capability Maturity Framework to understand and improve their TECHNOLOGICAL capabilities
S1	Q20. CMF will provide valuable data and support regarding TECHNOLOGICAL decision making and/or planning
S1	Q22. CMF contains valuable data and support regarding OPERATIONAL decision making and/or planning
S1	Q23. CMF supports identification and management of technological gaps in the research centre

Table 7.6 presents results in regards to Q8 and Q23 from Survey 1.

Table 7.6: Answers to Q8 and Q23 from Survey 1

	Q8 S1*		Q23 S1**	
Answer	Frequency	%	Frequency	%
Strongly Agree	13	38%	9	26%
Agree	17	50%	22	65%
Disagree	1	3%	0	0%
Don't Know	1	3%	1	3%
Other	1	3%	1	3%
No answer	1	3%	1	3%

*Q8 S1: Research centre needs tools like Capability Maturity Framework to understand and improve their TECHNOLOGICAL capabilities

**Q23 S1: CMF supports identification and management of technological gaps in the research centre

88% either **strongly agreed or agreed** with Q8 S1, i.e. **a research centre needs tools like Capability Maturity Framework to understand and improve their TECHNOLOGICAL capabilities.** On the other hand, 3% disagreed and another 3% provided no answer. Also, 3% selected 'Don't Know' and another 3% selected 'Other' saying *This needs to work along with a clearly articulated strategy to set the boundaries of the framework (P118).*

Figure 7.9 below shows distribution of responses to Q8 based on participants responsibilities. Fig 7.9 clearly shows that **participants with technical, operational, strategic, technical & operational and other responsibilities– all responded positively to Q8**. One participant with TOS responsibilities disagreed with Q8, and another one with TOS responsibilities provided no answer. One participant with operational & strategic responsibilities selected 'Other', and another one from the same group selected 'Don't Know'. Hence, the variety of responsibilities show that not only participants with technical responsibilities see the need for CMF in order to improve technological capabilities.

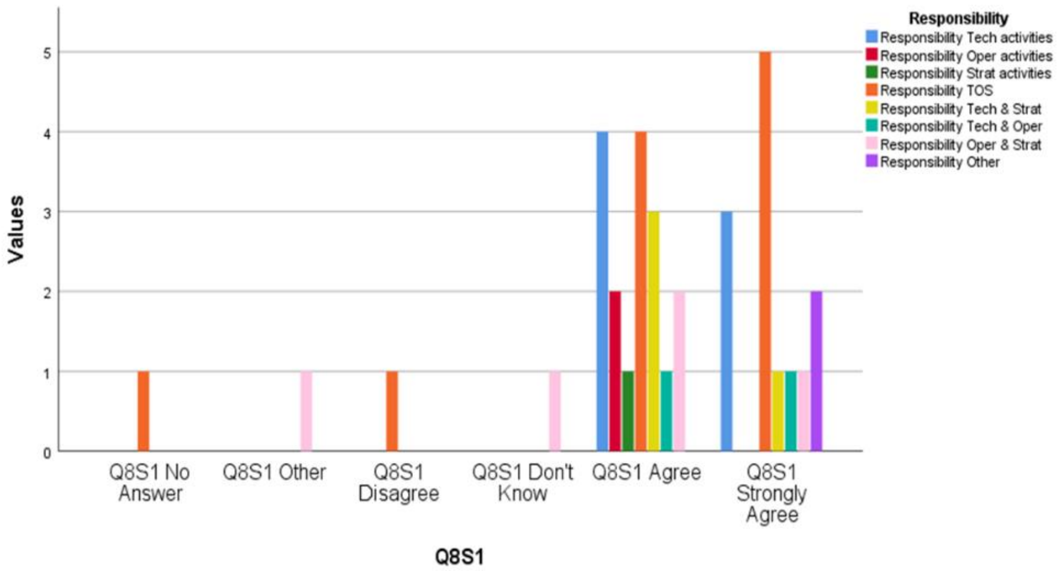


Figure 7.9: Distribution of answers to Q8 based on participants responsibilities

Furthermore, **91%** of participants either **strongly agreed or agreed** with Q23, i.e. **CMF supports identification and management of technological gaps in the research centre**. What is more, **no one disagreed** and only 3% selected 'Don't Know', while another 3% did not provide any answer.

Figure 7.10 below shows distribution of answers to Q23 based on participants' responsibilities. It shows that **almost all participants across different responsibility groups provided positive responses.** Only one participant with operational responsibilities selected 'Don't Know' as an answer. One participant with TOS responsibilities, selected 'Other' and another one provided no answer. P111 who selected 'Other' mentioned in comments section that they agree with Q23 saying '*Yes, but with a degree of subjectivity. There is also a potential need for weighting at the dimensional level dependent on the question being asked of the framework*'. It means that some aspects (sub-dimensions or level of experience) of CMF could have assigned weight. This however was left out of scope of this research as it is believed it is up to decision makers to decide if and how the weight is assigned. However, the responses to Q23 show **a solid evidence that majority of participants understand that the goal of CMF is to support identification and management of technological gaps in the research centre.**

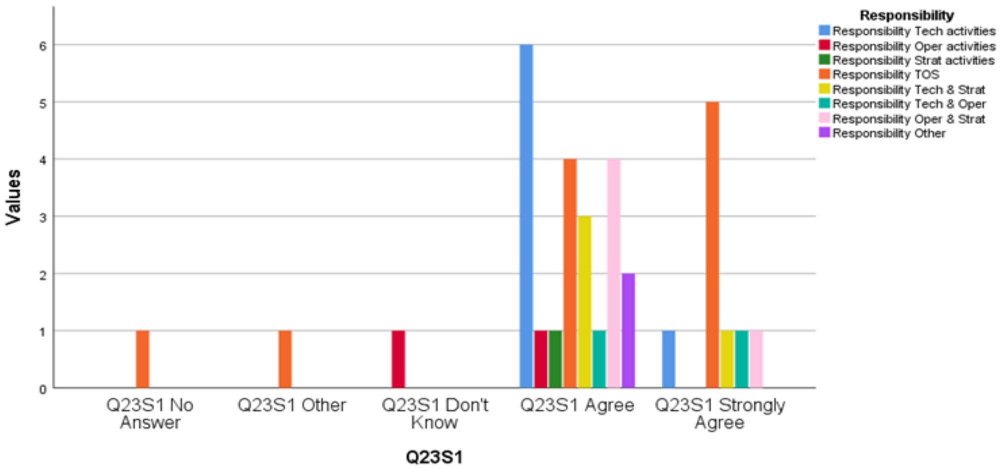


Figure 7.10: Distribution of answers to Q23, S1 based on participants' responsibilities

Next, Table 7.7 presents results in regards to Q20 and Q22 from survey 1.

Table 7.7: Answers to Q20 and Q22 from Survey 1

	Q20 S1*		Q22 S1**	
Answer	Frequency	%	Frequency	%
Strongly Agree	8	24%	6	18%
Agree	19	56%	16	47%
Disagree	0	0%	7	21%
Don't Know	3	9%	3	9%
Other	4	12%	2	6%
No answer	0	0%	0	0%

*Q20 S1: CMF will provide valuable data and support regarding TECHNOLOGICAL decision making and/or planning
**Q22 S1: CMF contains valuable data and support regarding OPERATIONAL decision making and/or planning

80% either **strongly agreed or agreed** with Q20 S1, i.e. **CMF will provide valuable data and support regarding TECHNOLOGICAL decision making and/or planning**. In addition, **no one disagreed**. However, 9% selected 'Don't Know', and another 12% selected 'Other'. The following comments were collected from people who selected 'Other' as their answer:

- *Potentially - yes, but strongly depends on the quality of data P106*
- *It 'could', but that's not to say it 'will' P108*
- *Not convinced of this yet P118*
- *If the question was 'could support', then 'yes' P122*

Moreover, **65%** of participants **either strongly agreed or agreed** with Q22 S1. However, seven participants (21%) disagreed and three participants selected 'Don't Know.' In addition, two participants selected 'Other'. The following comments were collected from people who selected 'Other' as their answer: *(1) It 'could', but that's not to say it 'will' (P108)* and *(2) If applied properly then it could (P118).*

7.5 Users' expectations

This sub-section highlights questions about users' expectations of the CMF and results provided through the process, i.e. this sub-section investigate if users' expectations of the process and results were met by the CMF. Table 7.8 includes questions from two online surveys that were part of this category. Tables 7.9 to 7.12 show results to those questions.

Table 7.8: Questions related to users' expectations

Survey	Question
S2	Q18. Results showed in Presentation 3 Show a good indication of capability maturity at the research centre
S2	Q31. I am satisfied with the Capability Maturity Framework at this point and would like to see it developed further
S2	Q32. Why do you think some Technology Capabilities scored better than others?
S2	Q34. Presented results are close to your expectations
S2	Q35. If you had different expectations regarding results presented, could you explain what you were expecting to see (if there isn't enough space below, please e-mail me directly)

Table 7.9 shows answers to Q18 from survey 2 regarding results showed in Presentation 3. As before, participants were able to select more than one answer.

Table 7.9: S2 Q18. I believe results presented in the presentations

Answer	Frequency (total=34)	%
Show a good indication of capability maturity at the research centre	18	53%
Show transparency of how different Technology Capabilities are used in different Programmes/Teams	13	38%

Show distribution of various Technology Capabilities (e.g. some Technology Capabilities are used only in one Programme and some are used in 3 or 4 Programmes)	10	29%
Other	7	21%

Hence, 53% of participants thought that the results presented in the presentations 'Show a good indication of capability maturity at the research centre.' 38% though that the results 'Show transparency of how different Technology Capabilities are used in different Programmes/Teams', and 29% agreed that the results 'Show distribution of various Technology Capabilities (e.g. some Technology Capabilities are used only in one Programme and some are used in 3 or 4 Programmes)'. In addition, 21% selected 'Other,' saying:

- *Show that assessment data accuracy is critical - see previous comments P100*
- *I was quite surprised by how much I agreed with the overall view of things, though I think some of the definitions need to be changed P107*
- *contradict my knowledge about the capabilities of teams P106*
- *Not sufficiently involved with AFRC to comment (about accuracy) P103*
- *Not in position to comment - think this should be tested with leadership at AFRC. (about accuracy) P116*

Next, Table 7.10 shows answers to Q31 and Q34 from survey 2.

Table 7.10: Answers to Q31 and Q34 from Survey 2

	Q31 S2*		Q34 S2**	
Answer	Frequency	%	Frequency	%
Strongly Agree	7	21%	1	3%
Agree	14	41%	17	50%
Disagree	2	6%	4	12%
Don't Know	0	0%	6	18%
Other	1	3%	0	0%
No answer	10	29%	6	18%

*Q31 S2: I am satisfied with the Capability Maturity Framework at this point and would like to see it developed further
**Q34 S2: Presented results are close to your expectations

In regards to Q31 S2, one participant (P110) mentioned that they will be able to provide some comments in the follow up chat. However, 62% of participants agreed/strongly agreed with current status of CMF and would like to see it being developed further. Those results are also shown by Figure 7.11 below, based on participants' role. Only 3% of participants from technical leads group, and another 3% from industrial engineering disagreed with Q31 S2. On the other hand, 8 out of 9 technical leads agreed/strongly agreed with Q31. Some participants expressed their view that CMF *"is a good starting point"* (P100) and a research centre needs a tool like that (P109). What is more, senior engineers from research centres also expressed positive viewpoints, as well as majority of BD/IE participants.

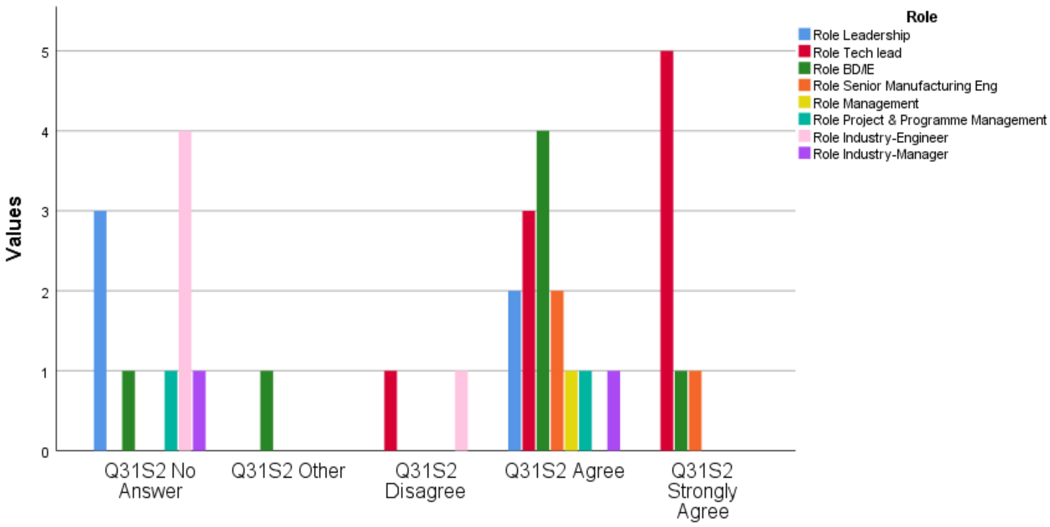


Figure 7.11: Distribution of answers to Q31, S2 based on participants' role

Additionally, **53% of participants strongly agreed/agreed with Q34: Presented results are close to your expectations,** and only 12% disagreed. Further 18% did not provide any answer, and another 18% selected 'Don't Know'. Figure 7.12 below presents results to Q34 based on participants' responsibilities. It shows that 3 participants, who are involved in technical activities, operational activities and TOS activities, disagreed with Q34. On the other hand, majority of participants involved in technical activities and TOS activities agreed with Q34. In addition, those involved in tech & strategic activities selected agreed or strongly agreed. Those with tech & operational responsibilities and 'Other' also provided positive responses. Participants involved in operational activities seem to provide most mixed responses, i.e. it is not easy to confirm if that group's expectations were met.

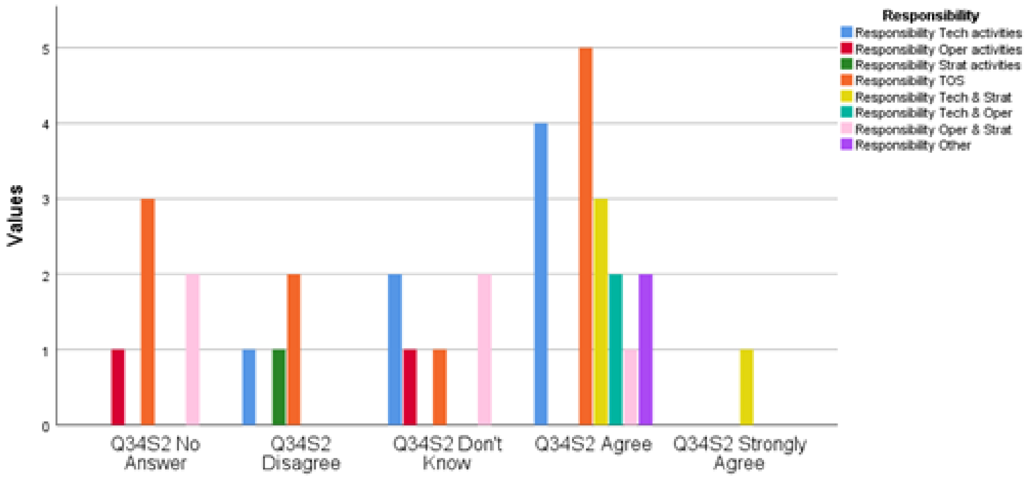


Figure 7.12: Distribution of answers to Q34, S2 based on participants' responsibility

Furthermore, majority of participants did not provide any comments in answer to Q35, survey 2. However, a few people provided some high-level comments, which are now included in Table 7.11.

In addition, some follow-up discussions were arranged with some participants to find out more information.

Table 7.11: S2 Q35. If you had different expectations regarding results presented, could you explain what you were expecting to see (if there isn't enough space below, please e-mail me directly)

Participant	Comments
P109	*See example given earlier for Additive and Materials Testing for example of expectations.*
P115	*I'm not sure how electrification was scored. NMIS capability is lower than scored IMO.*
P117	*Additive too high, RS & machining not high enough, welding too high for new technology*
P103	*Just not involved enough in all AFRC activities to have a detailed understanding*
P104	*Forging was shown as a low CML, surprising considering the focus of the AFRC*
P114	*Did not have expectations*
P125	*The 1-9 number system is good and the criteria for each one is clear but the process is hard to follow*
P127	*with my current knowledge, I probably would see the technologies and TB (testbeds) differently rated*

Table 7.12 shows answers to Q32 from survey 2: 'Why do you think some Technology Capabilities scored better than others?' As before, participants were able to select more than one answer.

Table 7.12: S2 Q32. Why do you think some Technology Capabilities scored better than others?

Answer	Frequency (total=34)	%
Some Technology Capabilities are used only in one Programme i.e. scored higher as fewer Programmes depend on them)	9	26%
Participants had too much confidence in their teams	12	35%
Technology Capabilities with lower scores were new at the time of data collection	7	21%
I think results show good reflection of Maturity levels of Technology Capabilities in 2019 (as data collection took place in 2019)	4	12%
I agree with the results but if data was collected in 2020- the results would have been different	7	21%
I think data should be collected every year to show progression of maturity of Technology Capability	15	44%
Other	6	18%
No Answer	10	29%

Table 7.12 shows that **44% of participants answered that 'data should be collected every year to show progression of maturity of Technology Capability'**. Also, 35% of participants though that people who provided data 'had too much confidence in their teams.'

26% thought that 'Some Technology Capabilities are used only in one Programme i.e. scored higher as fewer Programmes depend on them)', and 21% replied that 'Technology Capabilities with lower scores were new at the time of data collection.' What is more, 21% agree with presented results but if data was collected in 2020- the results would have been different. Another 12% thought that 'results show good reflection of maturity levels of Technology Capabilities in 2019 (as data collection took place in 2019)'. Also, 29% did not provide any answer, and another 18% selected 'Other,' saying:

- *Scoring is open to an individual's interpretation. Needs to be constrained more, too subjective. Options need to be better bound P100*
- *Dependency on the assessment of an individual P109*
- *From presentations if appeared to be a judgement decision by team, so it is teams' perception of themselves P13*
- *Opinions of individuals are always biased P106*
- *Variations in staff, skillset/experience/education differences P125*
- *I can't answer this as not close enough to the data capture exercise P121*

7.6 Need for standardisation

This sub-section highlights the need for standardisation of capability maturity process for research centres. This section is considered as the most important one as the rest of this chapter (i.e. sections 7.7 - 7.13) are linked to the need for a standardised approach. Thus, Table 7.13 presents questions from two online surveys that aimed to seek participants' agreement over the need of standardisation. Tables 7.14 and 7.15 show participants' responses to each of the five questions respectively.

Table 7.13: Questions related to need for standardisation of capability maturity process

Survey	Question
S1	Q15. In my opinion there is A NEED for a standard tool that captures data about research centre's Technological Capabilities
S1	Q16. In my opinion, CMF could become a standard tool for capturing maturity of Technological Capabilities AT A RESEARCH CENTRE
S1	Q30. CMF could become a consistent approach among NMIS
S2	Q23. CMF and CML offer (select all answers that you agree with) Standardised mechanism to determine Maturity of Technology Capability

Table 7.6 presents results regarding a need for a standardised tool for capturing technology capabilities.

Table 7.14: Answers to Q15, Q16 and Q 30 from Survey 1

	Q15 S1*		Q16 S1**		Q30 S1***	
Answer	Frequency	%	Frequency	%	Frequency	%
Strongly Agree	13	38%	7	21%	6	18%
Agree	15	44%	18	53%	15	44%
Disagree	0	0%	1	3%	0	0%
Don't Know	3	9%	2	6%	8	24%
Other	2	6%	5	15%	1	3%
No answer	1	3%	1	3%	4	12%

*Q15 S1: In my opinion there is A NEED for a standard tool that captures data about research centre's Technological Capabilities

**Q16 S1: In my opinion, CMF could become a standard tool for capturing maturity of Technological Capabilities AT A RESEARCH CENTRE

***Q30 S1: CMF could become a consistent approach among NMIS

82% either strongly agreed or agreed with Q15 S1. **None of the participants disagreed**, and one person did not provide any answer. Also, three participants (9%) selected 'Don't Know' as an answer, and two participants (6%) chose 'Other' as their answer, saying *(1) There needs to be a robust skills matrix measure in place first and Dynamics is the place this is being developed (P108)* and *(2) I can see value if all the HVMC centres adopted the same tool and we have a peer group to benchmark ourselves against (P118).*

Moreover, Figure 7.13 below shows how participants with different background answered Q15, S1. One person with industrial engineering (IE) background provided no answer. Also, one person from leadership and one from team lead background selected 'Other' as their answer. Additionally, one person from leadership, one from BD/IE and one from project & programme management selected 'Don't Know' as their answer. On the other hand, **participants from Industrial management background, management background at a research centre, senior manufacturing engineers and majority of leadership and team leads agreed that there is a need for a standardised tool that captures technology capability at research centres.**

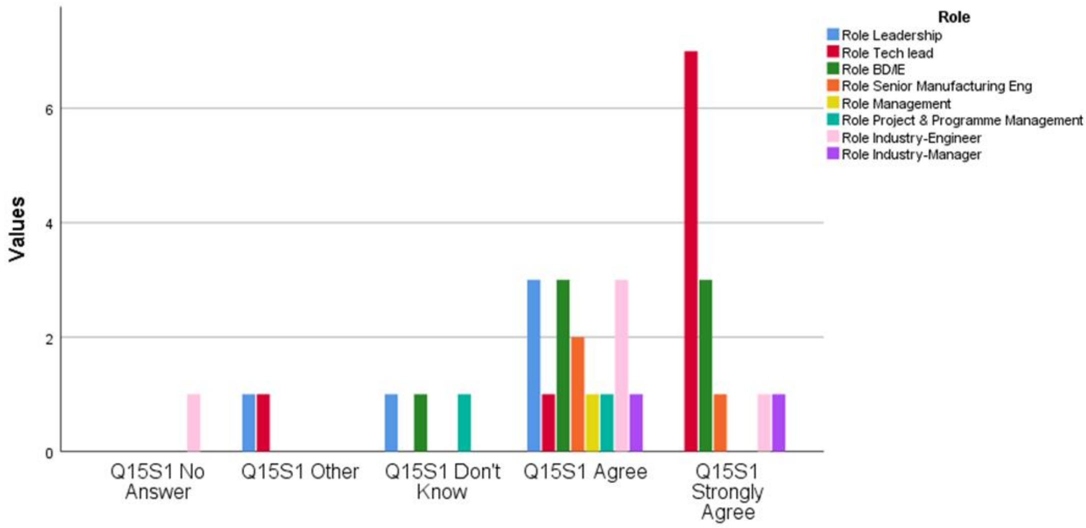


Figure 7.13: Distribution of answers to Q15, S1 based on participants' background

Hence, Fig. 7.13 shows that **everyone from leadership, senior management, and technical lead background agreed/strongly agreed with Q15**. One person with industrial engineering role provided no answer, and 2 participants (1 from leadership and one from technical theme/team lead background) selected 'other'. Hence, majority of people who see the need for a standardised approach provided positive responses, even though those participants come from various backgrounds.

Regarding Q16 S1, **74% either strongly agreed or agreed** with it. However, one participant disagreed. Another one provided no answer, and two participants selected 'Don't Know'. Also, five participants (15%) chose 'Other' as their answer, saying

- *I agree, however they need refined. In some areas (P119)*
- *agree but is only one of the many tools required (P115)*

- *Depends on how well it will be technically done to guarantee the objectiveness of information (P106)*
- *Yes but a web based version which is easier to manage and navigate would help rather than excel (P105)*
- *I would agree but would add that further work would need conducted - it is an ideal tool to benchmark your own capabilities but each research centre is slightly different so using it as a standardised tool across multiple centres would require more work… how do you standardise a capability? Does a technology mean something slightly different at a different centre? Who fills the CMF out to prevent bias? (P103)*

Moreover, Fig. 7.14 and shows distribution of answers to Q16 based on participants' role and responsibilities. Fig. 7.14 shows **all participants from leadership background agreed with Q16**. Hence, leaders who participated in this study thought that CMF is the right tool for research centres for capturing maturity of technological capabilities. Also, Fig. 7.14 shows that participants with senior management and tech theme/team lead background also provided positive responses. It is encouraging as the CMF is mainly created for those participants who need to know high and low level of what is happening/changing in regards to technological capabilities at the research centre, and those groups of participants also expressed positive responses to Q15 i.e. meaning that there is a need for a tool like CMF at research centres.

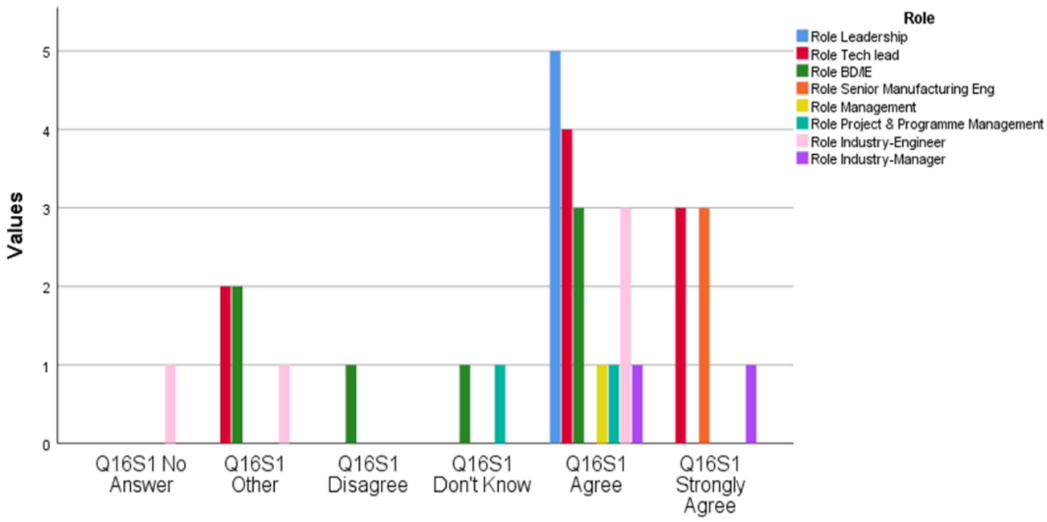


Figure 7.14: Distribution of answers to Q16, S1 based on participants' background

In regards to Q30 S1, **62%** of participants **either strongly agreed or agreed** with it. In addition, none of the participants disagreed with that statement. However, 12% provided no answer, and 24% of participants selected 'Don't Know'. In addition, 3% selected 'Other' as their answer, saying *Maybe. This answer is not among the list, but it's the answer to majority of questions here (P106)*. Hence, participant highlighted aspect related to validation process that will be improved in the future (discussed in Chapter 9).

What is more, Fig. 7.15 below shows distribution of answers from participants based on their responsibilities. Hence, **majority of participants who have TOS responsibilities provided positive responses to Q30, as well as majority of participants with operational & strategic responsibilities, strategic responsibilities, tech & operational responsibilities and 'other'**. Even though 4 participants provided 'no answer', 3 of them being from a technical responsibilities only. The reason for that could be the fact that some participants who took part in this study do not work at NMIS, i.e. work at industry or at different research centres.

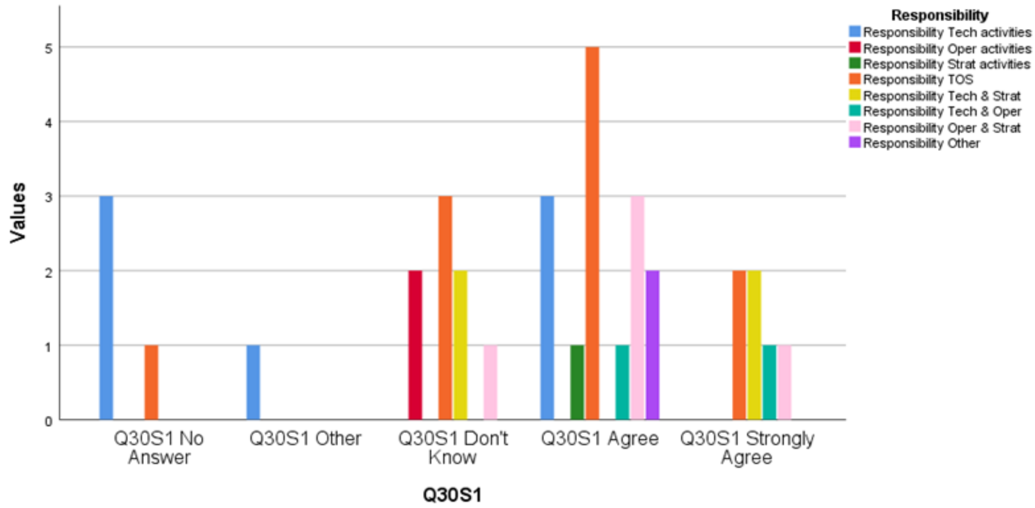


Figure 7.15: Distribution of answers to Q30, S1 based on participants' responsibility

Table 7.15 shows answers to Q23 from survey 2 in regards to offerings/benefits of CMF and CMLs. As this section concentrates on standardisation aspect, other answers from Q23 were removed and are analysed in relevant sections. In this case participants were able to select more than one answer.

Table 7.15: S2 Q23. CMF and CMLs offer (select all answers that you agree with)

Answer	Frequency (total=34)	%
Standardised mechanism to determine Maturity of Technology Capability	21	62%
Consistent approach for a research centre	19	56%
Good foundation for communicating our technological progress	22	65%
Other	7	21%

Thus, Table 7.15 shows that **62%** participants thought that CMF and CML offer '**Standardised mechanism to determine Maturity of Technology Capability**,' as well as **65%** agreed that CMF and CMLs offer **'Good foundation for communicating our technological progress.'** Moreover, 56% of participants thought that CMF and CML offer 'Consistent approach for a research centre.' Also, 21% selected 'Other,' and left the following comments:

- *This is only one tool in the tool box - an important one I agree (P100)*

- *Highly dependent on initial assessment process (P109)*
- *To confirm consistency of approach we would need to expand the use cases outside of just AFRC? (P121)*
- *There may be need to guide people until they are used to framework. But thought into data capture (optimistic vs pessimistic scorer) may be needed? (P116)*
- *CMF will improve the research centre's understanding of its own TECHNOLOGICAL capabilities (P103, P104, P116, P120)*

7.7 Purpose and benefits of CMF

This sub-section highlights questions about CMF purpose i.e. which decisions CMF should be able to support in the future. Table 7.16 includes questions from two online surveys that were part of this category. Tables 7.17 and 7.18 show results to those questions.

Table 7.16: Questions related to purpose of CMF

Survey	Question
S1	Q13. A research centre will benefit from using CMF by understanding gaps and strengths/weaknesses of a research centre (e.g. in relation to skills, experience, application of various machines/software etc.)
S1	Q24. CMF provides clear understanding of capability maturity (i.e. research centre understands its own weaknesses and strengths) before taking on a project
S1	Q25. I believe CMF provides information that could be used when discussing future projects with members/clients
S1	Q26. CMF process will be useful when guidance in CORE programme development is needed i.e. to understand how successful projects were and what new skills/methodologies were developed
S1	Q28. CMF could be used as diagnostics and capability evaluation tool at the research centre in the future (i.e. to identify weaknesses and areas of improvement e.g. limited undertaking of a piece of software etc.)

Table 7.17 presents results in regards to Q13 and Q24 from survey 1. **Almost everyone (97%) either strongly agreed or agreed that a research centre will benefit from using CMF by understanding gaps and strengths/weaknesses of a research centre (Q13)**. Only 3% of participants (i.e. one person) provided no answer.

Table 7.17: Answers to Q13, and Q24 from Survey 1

	Q13 S1*		Q24 S1**	
Answer	Frequency	%	Frequency	%
Strongly Agree	13	38%	8	24%
Agree	20	59%	17	50%
Disagree	0	0%	4	12%
Don't Know	0	0%	0	0%
Other	0	0%	4	12%
No answer	1	3%	1	3%

*Q13 S1: A research centre will benefit from using CMF by understanding gaps and strengths/weaknesses of a research centre (e.g. in relation to skills, experience, application of various machines/software etc.)

**Q24 S1: CMF provides clear understanding of capability maturity (i.e. research centre understands its own weaknesses and strengths) before taking on a project

Figure 7.16 shows that only one participant from industrial engineering background did not select any answer to Q13. Everyone else either agreed or strongly agreed regardless of their background, which is a positive and encouraging response. That provides a clear evidence that participants from different background see CMF being implement at a research centre and helping with identifying internal capability gaps.

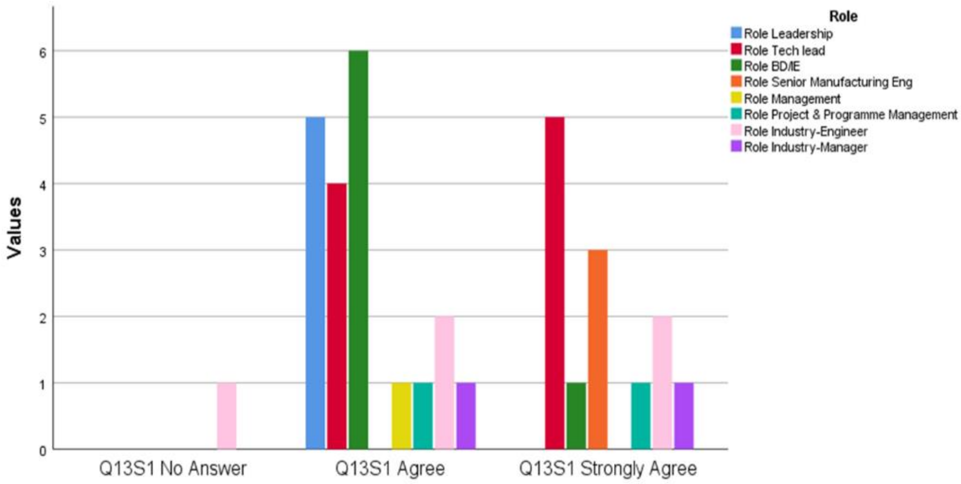


Figure 7.16: Distribution of answers to Q13, S1 based on participants' role

What is more, 74% of participants either strongly agreed or agreed with Q24, i.e. CMF provides clear understanding of capability maturity (i.e. research centre understands its own weaknesses and strengths) before taking on a project. On the other hand, only four participants disagreed with that statement, and one provided no answer. In addition, four participants selected 'Other' using the following comments

- *The user experience in our raw data form not allow this extra work is needed to add more data points and then refine the user experience to allow for a simplistic view of complex data P119*
- *Maybe, but me personally would trust more to my own experience and knowledge of people, equipment, etc. P106*
- *Think it will be hard to evaluate weakness and strengths in digital context which CMF won't be able to provide P105*
- *sometimes you have to take on the project to get the budget and experience to develop the capability, it's not always planned P108*

In response to first and third comment, the version of CMF presented to participants is only a starting point, and so future work will certainly require going through the same process again (i.e. validation process) and to wider the 'data pool' and gather more data from other Catapults. Again, this is discussed in Chapter 9.

Next, in response to second comment (i.e. trusting their own experience), (P109) mentioned: '*I had my expectations for the results but it doesn't mean that my expectations were right – that's why we need review process.*' What is more, (P110) participant said that '*It would be good to have a database* *like that, so I can see high level; and if I disagree I go into deeper level an see more detailed version and then I understand where those numbers come from, as I see the whole process*.' Hence, even though some participants trust their experience, it does not mean that everyone has the same level of knowledge/awareness of capabilities in the research centres, and/or they simply prefer to have a database that they could access when needed.

Last comment mentioned that some projects are taken on to develop capability, which is true. However, there should be a process in place to show which capabilities are currently under development and which capabilities are more matured (e.g. by using CMF and Capability Maturity Levels). Having a process that evaluates that and database which shows capabilities in early development will increase transparency and encourage collaboration between teams. In addition, current strategy teams work to develop capability alignment between current projects and capabilities, and they need to know what capabilities are being developed in order to plan future research priorities.

What is more, Fig. 7.17 below shows distribution of answers to Q24 based on participants responsibilities. It shows that one participants with TOS provided no answer. Also, it shows that out of 4 participants who selected 'Other', 2 are involved in technical activities, one is involved in TOS, and one in 'other responsibilities). Additionally, those who disagreed had the following responsibilities: operational (1 person), strategic (1 person) and TOS (2 people). Hence, Fig. 7.17 shows that participants involved in operational and strategic activities are unsure about CMF and its benefits before taking on a project. On the other hand, participants from leadership, senior manufacturers, managers, project & programme managers and industrial managers either agreed or strongly agreed with Q24. Therefore, it seems that people involved in management aspects of work see the benefits of CMF, which is very encouraging.

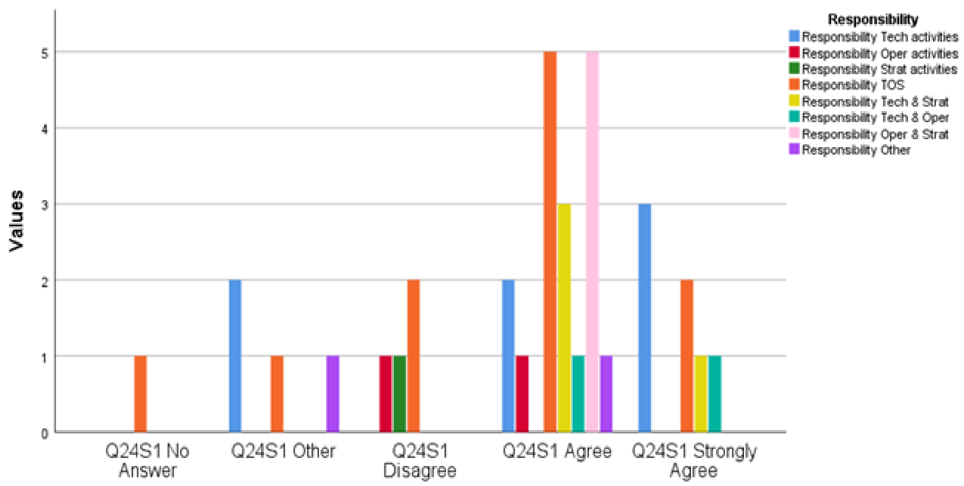


Figure 7.17: Distribution of answers to Q24, S1 based on participants' responsibilities

Next, Table 7.18 presents results in regards to Q25 and Q26 from survey 1.

Table 7.18: Answers to Q25 and Q26 from Survey 1

	Q25 S1*		Q26 S1**		Q28 S1***	
Answer	Frequency	%	Frequency	%	Frequency	%
Strongly Agree	7	21%	8	24%	7	21%
Agree	18	53%	14	41%	20	59%
Disagree	1	3%	2	6%	3	9%
Strongly Disagree	1	3%	0	0%	0	0%
Don't Know	3	9%	6	18%	2	6%
Other	3	9%	4	12%	2	6%
No answer	1	3%	0	0%	0	0%

*Q25 S1: I believe CMF provides information that could be used when discussing future projects with members/clients
**Q26 S1: CMF process will be useful when guidance in CORE programme development is needed i.e. to understand how successful projects were and what new skills/methodologies were developed
***Q28 S1: CMF could be used as diagnostics and capability evaluation tool at the research centre in the future (i.e. to identify weaknesses and areas of improvement e.g. limited undertaking of a piece of software etc.)

74% of participants either strongly agreed or agreed with Q25, i.e. **CMF provides information that could be used when discussing future projects with members/clients**. On the other hand, one participant (3%) disagreed with that and another strongly disagreed (3%). What is more, one person did not provide any answers, three participants selected 'Don't Know' and another three selected 'Other'.

Fig 7.18 below shows distribution of answers to Q25 based on participants' roles. It shows that one participant with industrial management background did not provide any answer. Moreover two participants from leadership group selected 'Other' as well as one person from BD/IE group. Those who selected 'Other' provided the following comments:

- *Potentially, but I would be cautious about using the output as authoritative without some validation. Have you tested the CMF outputs against past projects that struggled with capability or went well, to test whether it would have flagged strengths and weaknesses appropriately? P111*
- *It could, however, explanation of the overall framework to get people up to speed with what it is and how it works could be an issue P107*
- *not sure how useful this would be P123*

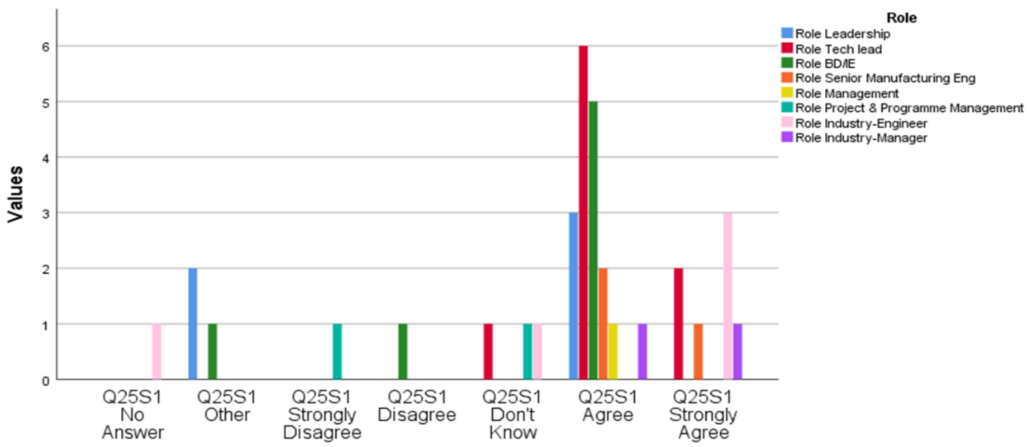


Figure 7.18: Distribution of answers to Q25, S1 based on participants' responsibilities

Hence, participants are worried about a) future validation/review process (i.e. control mechanism, which is an aspects that is described in Future Work, Chapter 9), b) measuring outputs against outputs from past projects and c) usefulness of CMF when discussing projects with members/clients.

Comment a) was mentioned before in other sections, and it is discussed in detailed in Chapter 9, hence it will not be discussed here again. Comment b) cannot be checked as this is a first time a framework like that has been introduced to research centre, i.e. up until now, results presented by CMF were not captured before. In addition, when asking about past projects, there is not much feedback from members/clients (which was already identified as an issue in Chapter 4, Interviews Phase 3). Hence, it is very difficult to measure something that was never measured before. However, if senior management is satisfied with CMF and sees its potential, future data can be compared with results presented in this research and so results could be compared on regular basis. Comment c) was mentioned as CMF would not bring benefits when discussing future projects with members/clients. Nevertheless, by considering other positive results to Q25, Fig 7.18 shows that **majority of participants found benefits of CMF when discussing future projects with members/clients.**

In addition, **65% of participants either strongly agreed or agreed** with Q26, i.e. **CMF process will be useful when guidance in CORE programme development is needed.** On the Other hand, two participants (6%) disagreed with that, and another 6 selected 'Don't Know'. Moreover, four participants (12%) selected 'Other'. The following comments were used by those who selected 'Other'

- *It 'could', but that's not to say it 'will' P108*
- *Back to strategy again - what does the strategy say we should be doing in the Core Programme with CMF as a tool to aid that P118*
- *Often the added value comes from learning with both client and research centre. CMF process should not inhibit this, e.g., showing as a centre gap may discourage client engagement and therefore centre development P124*
- *Not sure - again would need to see examples of the framework in context of core research people, equipment and projects P121*

Furthermore, **80% either strongly agreed or agreed** with Q28, i.e. **CMF could be used as diagnostics and capability evaluation tool at the research centre in the future**. Also, only three participants (9%) disagreed with that statement, and another two (6%) selected 'Don't Know.' Two more (6%) selected 'Other' as their answer.

Moreover, Fig. 7.25 below shows distribution of answer to Q28 based on participants' roles. Hence, two people who selected 'Other' are from leadership and tech lead group. Those two participants who selected 'Other' also provided the following comments: *(1) Yes, but only as part of a broader analysis framework (P111)* and *(2) It could, you will get a lot of resistance though if it is not done with sufficient support as the current structure means people are very busy and won't have time or motivation to learn it (P108*).

The comments are useful, especially the second one which highlights the issue concerning time and effort needed to add correct information to CMF. However, that is explained in Chapter 9.

What is more, 3 participants disagreed with Q28. Those participants come from tech lead, Project & programme management and industrial engineering groups. Additionally, only two people who are from industrial management background selected 'Don't Know'. On the other hand, it seems that **participants from BD/IE, senior manufacturers, managers and majority of leadership agreed with Q28: CMF could be used as diagnostics and capability evaluation tool at the research centre in the future (i.e. to identify weaknesses and areas of improvement e.g. limited undertaking of a piece of software etc.).**

7.8 Mechanism and structure of CMF

This sub-section highlights questions about mechanism/structure of CMF. Table 7.19 includes questions from two online surveys that were part of this category. Table 7.20 shows results to those questions.

Table 7.19: Questions related to mechanism/structure of CMF

Survey	Question
S1	Q11. The structure of CMF (3 dimensions: People, Equipment, Projects) and further 9 sub-dimension (3 sub-dimensions in each dimension) are a good representation of a research centre's capabilities
S1	Q14. CMF provides an appropriate amount of detail to identify capability related gaps
S1	Q35. CMF should include more dimensions/sub-dimensions

Table 7.20 presents results regarding Q11, Q14 and Q35 from Survey 1.

Table 7.20: Answers from Q11, Q14 and Q35 from Survey 1

	Q11 S1*		Q14 S1**		Q35 S1***	
Answer	Frequency	%	Frequency	%	Frequency	%
Strongly Agree	7	21%	5	15%	3	3%
Agree	21	62%	18	53%	4	12%
Disagree	2	6%	4	12%	7	21%
Strongly Disagree	0	0%	0	0%	4	12%
Don't Know	1	3%	4	12%	9	26%
Other	2	6%	2	6%	7	21%
No answer	1	3%	1	3%	0	0%

*Q11 S1: The structure of CMF (3 dimensions: People, Equipment, Projects) and further 9 sub-dimension (3 sub-dimensions in each dimension) are a good representation of a research centre's capabilities
**Q14 S1: CMF provides an appropriate amount of detail to identify capability related gaps
***Q35 S1: CMF should include more dimensions/sub-dimensions

83% strongly agreed or agreed with Q11 S1, i.e. **CMF structure is a good representation of a research centre's capabilities.** Two participants (6%) disagreed and one selected 'Don't Know' as their answer. Also, one person (3%) did not provide any answer and two participants (6%) selected 'Other.'

What is more, Fig. 7.19 below shows distributions of answers to Q11 based on participants' responsibilities. Hence, one participant involved in TOS provided no answer, while one person involved in operational & strategic activities selected 'Don't Know'. Also, two participants, one responsible for technical activities, and one responsible for other activities, selected 'Other' as their answer. They also left the following comments: *(1) The volume of data points is too small, you need more data points to allow for more accurate analytics P119)* and (2) *Agree but would also note that from an industrial perspective there are other softer elements that play an important role - communication, costs and value of the deliverables would also be important. But from a technology perspective then yes, the CMF is a good indicator (P103).*

Comment (1) was already described and explained the reason why this study did not involve more examples of technological capabilities. Comment (2) highlights that if its aim is only to focus on technological capabilities, which is a good indicator. Participant also mentioned there are other aspects that perhaps could be added to CMF in the future. However those aspects were out of the scope of the study.

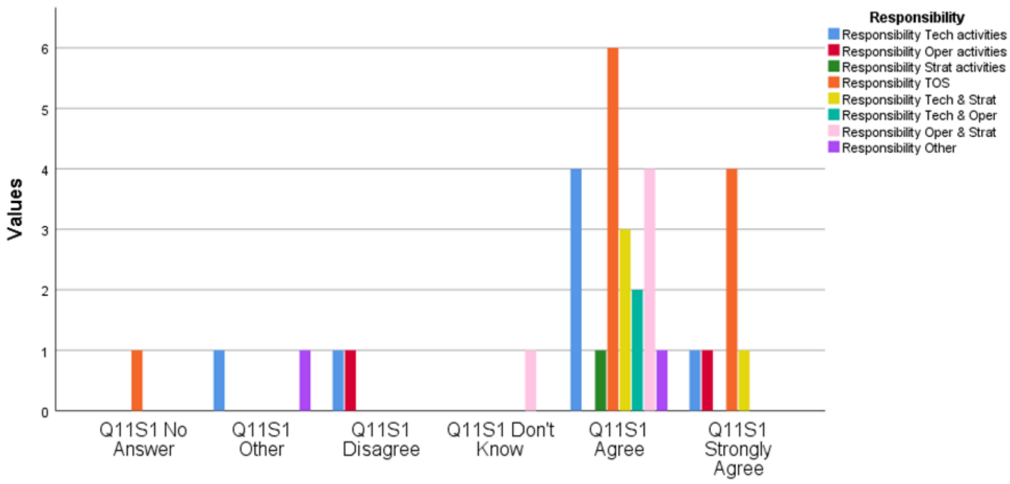


Figure 7.19: Distribution of answers to Q11, S1 based on participants' responsibilities

Fig. 7.19 also shows that 2 participants disagreed with Q11. Those participants provided comments in the follow up discussions which are included in Chapter 9 were suggestions about structure of CMF are added. On the other hand, **majority of participants involved in different activities agreed or strongly agreed with Q11, i.e. the structure of CMF (3 dimensions: People, Equipment, Projects) and further 9 sub-dimensions (3 sub-dimensions in each dimension) are a good representation of a research centre's capabilities.**

Furthermore, **68% of participants agreed/strongly agreed** with Q14 S1, i.e. **CMF provides an appropriate amount of detail to identify capability related gaps.** However, 12% disagreed and another 12% selected ‘Don’t Know’ as their answer. In addition, 3% did not provide any answer and 6% selected ‘Other.’

Moreover, Fig 7.20 below shows distribution of answers based on participants responsibilities. One person involved in TOS provided no answer. 2 participants (1 involved in technical activities and 1 in operational & strategic activities) selected ‘Other.’ They also left the following comments: *(1) Not sure it does, one element missing is what will be done to close gaps (P118); and (2) To some degree - we use a similar process but assess people and technology individually. However we have different people who assess at a technology level and at a higher strategic level. They wouldn't use the same framework but a flow through of data would definitely be helpful (P103).*

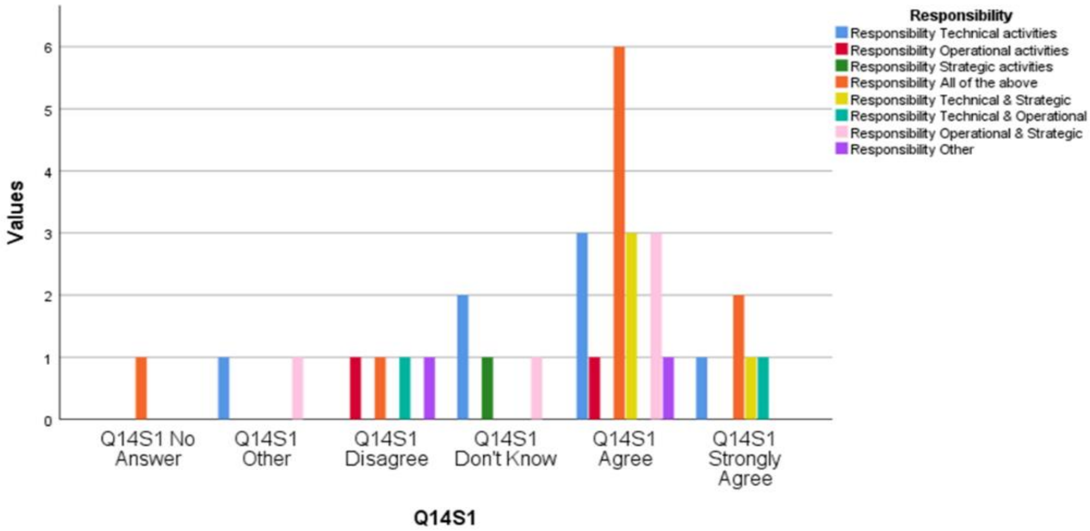


Figure 7.20: Distribution of answers to Q14, S1 based on participants’ responsibility

However, Fig. 7.20 also shows that majority (8 out of 9) of participants with TOS responsibilities agreed or strongly agreed with Q14. In addition, those with technical and strategic responsibilities as well as majority of those with technical responsibilities also agreed/strongly agreed that CMF provides an appropriate amount of detail to identify capability related gaps.

Additionally, 33% of participants either disagreed or strongly disagreed with Q35 S1, i.e. they thought that the current structure has enough dimensions/sub-dimensions. On the other hand, 15% of participants agreed/strongly agreed i.e. they would like to see more dimensions/sub-dimensions added to the CMF structure. 26% selected ‘Don’t Know’ as their answer and 21% selected ‘Other’. The following comments were included as part of those answers:

- *I think it is sufficient, but could usefully have a weighting factor applied at both dimensional and sub-dimensional level as certain capabilities rely more on people while Others rely more on equipment for example. The application of this tool must be conducted in an informed manner as must the interpretation of the results, hence the importance of transparency at each stage the process P111*
- *Not at the moment, but may evolve to include more in the future P109*
- *There can be different ways to rectify this structure further P106*

- *I think it shows a good level of data currently without being too overwhelming P103*
- *No - I think it is already very detailed P104*
- *3 x 3 seems adequate P120*
- *Not at first - once big gaps are closed you could consider P116*

7.9 Practicality of CMF

This sub-section highlights questions about practicality of CMF. Table 7.21 includes questions from two online surveys that were part of this category. Tables 7.22 to 7.23 shows results to those questions.

Table 7.21: Questions related to practicality of CMF

Survey	Question
S2	Q9. CMF will be useful to support my role
S2	Q10. CMF is informative as it provides current capability levels and gaps
S2	Q11. I will be able to access useful information through CMF in regards to PROGRAMME challenges
S2	Q12. I will be able to access useful information through CMF in regards to TEAM challenges
S2	Q14. CMF and TRL-like processes could complement each Other (CMF covering what research centre can do, and TRL what product/service needs to be delivered)

Table 7.22 focused on answers regarding Q9 and Q10 form survey 2.

Table 7.22: Answers to questions 9 and 10 from Survey 2

	Q9 S2*		Q10 S2**	
Answer	Frequency	%	Frequency	%
Strongly Agree	5	15%	7	21%
Agree	14	41%	19	56%
Disagree	3	9%	0	0%
Don't Know	4	12%	1	3%
Other	1	3%	1	3%
No answer	7	21%	6	18%

*Q9 S2: CMF will be useful to support my role
**Q10 S2: CMF is informative as it provides current capability levels and gaps

56% agreed/strongly agreed with Q9 S2, i.e. **CMF would support their role**. 9% of participants disagreed with that. In addition, 12% answered 'Don't Know', 21% of participants did not provide any answer and another 3% selected 'Other'. One participant who selected 'Other' mentioned *"No - I will have to use my company's framework"* (P125). That participant comes from industrial background and uses internal industrial framework that was set up specifically for the company. However, it should be highlighted that this is the ultimate goal of CMF: to become the internal 'go-to' framework for RCs.

Furthermore, **77% either agreed or strongly agreed** with Q10 S2: **CMF is informative as it provides current capability levels and gaps**. Also, **no one disagreed**, which gives a supportive evidence that CMF is informative. 18% did not provide any answer, 3% answered 'Don't Know' and another 3% selected 'Other'.

Fig. 7.21 shows distribution of answers based on participants responsibilities. The only one participant who selected 'Other' is involved in technical activities, and provided the following comment: '*Yes, it gives some results but I have doubts how objective they are' (P106)*. This comments refers to reliability of inputs collected during data collection, which is discussed in Chapter 9. However, it should be highlighted that **participants involved in technical activities provided positive responses, as well as participants involve in strategic activities**, as presented by Fig. 7.21.

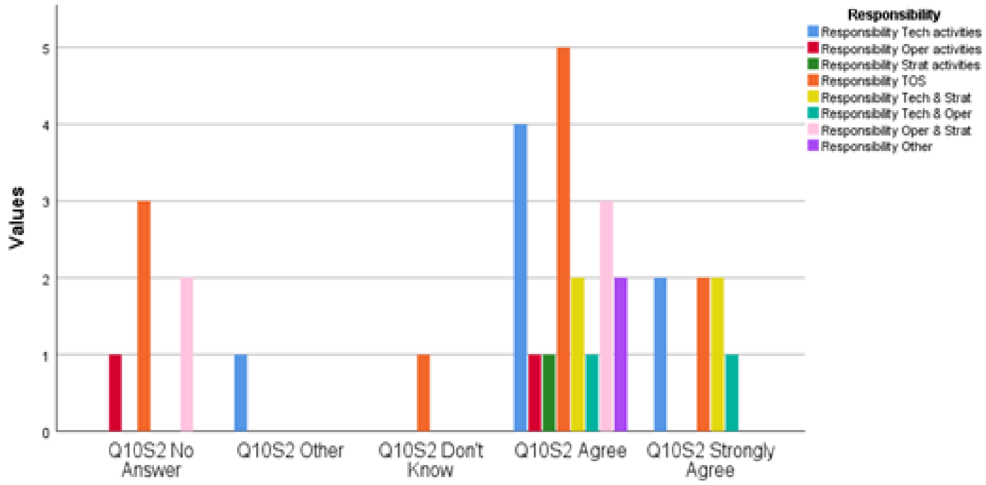


Figure 7.21: Distribution of answers to Q10, S2 based on participants' responsibility

Answers to Q11 and Q12 from survey 2 are presented in Table 7.23 below. Q11 S2 focused on **usefulness of information provided through CMF in regards to programme challenges**. In this case a programme can include several Technology Capabilities, some of which will belong to various teams. Therefore, when considering 'kick-off' of a programme, decision makers are able to evaluate which Technology Capabilities are the most developed (i.e. the most matured) and which Technology Capabilities have not reached required/expected maturity. Q12 S2 asked about **usefulness of information provided through CMF in regards to team's challenges**, assuming that teams are combination of several TCs managed under one team lead.

Table 7.23: Answers to Q11 and Q12 from Survey 2

	Q11 S2*		Q12 S2**	
Answer	Frequency	%	Frequency	%
Strongly Agree	4	12%	5	15%
Agree	15	44%	18	53%
Disagree	2	6%	1	3%

Don't Know	2	6%	1	3%
Other	5	15%	3	9%
No answer	6	18%	6	18%

*Q11 S2: I will be able to access useful information through CMF in regards to PROGRAMME challenges
**Q12 S2: I will be able to access useful information through CMF in regards to TEAM challenges

56% agreed or strongly agreed with Q11 S2, i.e. CMF function and found it useful in regards to PROGRAMME challenges. 6% of participants disagreed and another 6% answered 'Don't know.' 18% did not select any answer. 15% selected 'Other' leaving the following comments:

- *CML is only one aspect of defining and managing a programme, so care needs to be taken that it does not become the forcing function in decision P111*
- *Perhaps - depends how it is generated (how accurate the baseline information is) and applied P109*
- *Yes, if it will be fed with trustable information, otherwise it can strongly mislead P106*
- *Only if available to members P104*

The first three comments relate to trust generated by the CMF and its results, which is related to reliability of data inputs; that is discussed in Chapter 9. . Last comment refers to the aspect of availability of the results to industrial members. However, that decision should be made by senior management (of a RC or HVMC). Also, it depends what level of detail would be shown to members. Hence, it depends on senior management and if they allow to share CMF results with external audience.. It should also be highlighted that this aspect is out of the scope of this study.

Moreover, Figure 7.22 below shows how participants from different background chose their answers regarding Q11 S2. It shows that Technical Leads agreed with Q11. One participant from a leadership background agreed, one chose 'Other' and three provided no answer. On the other hand, participants from industrial engineering background distributed their votes equally across different answers, and those from industrial managerial background either chose no answer or they agreed.

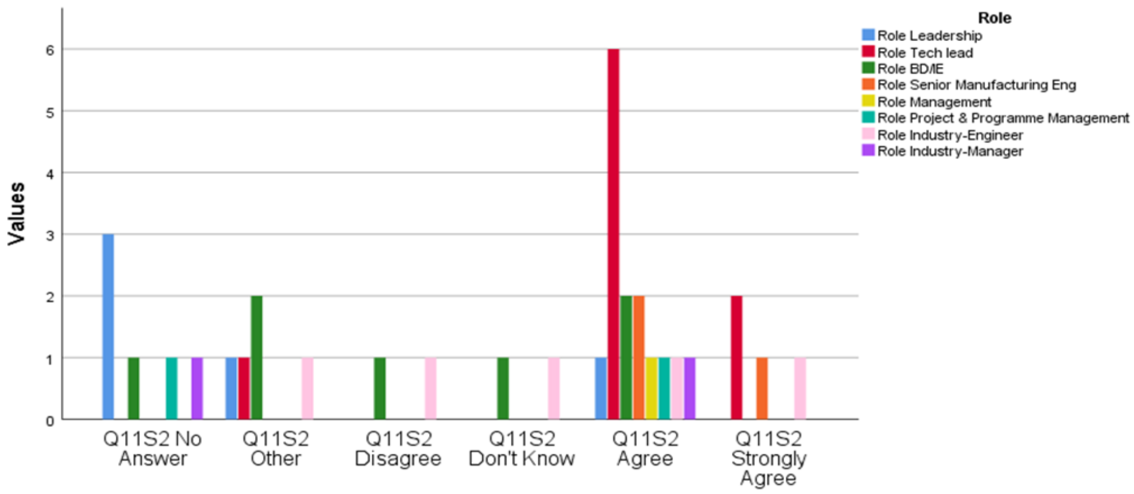


Figure 7.22: Distribution of answers to Q11, S2 based on participants' responsibility

Next, **68% of participants either agreed or strongly agreed** with Q12 S2, i.e. **being able to access useful information through CMF in regards to TEAM challenges.** One person disagreed with the statement and six participants did not select any answers. Also, one person selected 'Don't Know as an answer, while 3 participants selected 'Other'. Those three participants who selected 'Other' also provided the following comments:

- *This is highly dependent on generation and application. Done well, i have no doubt that it will be useful P109*
- *Theoretically - definitely yes, practically depends on people P106*
- *Only if available to members P104*

Figure 7.23 shows distribution of answers to Q12 S2 based on the background of participants. Participants with **senior manufacturing engineering background, management background, project and programme management background and majority of technical leads background agreed or strongly agreed with Q12**. 2 participant from leadership agreed with the statement while, 3 participants from the same background provided no answer. Also, majority of participants with BD/IE background (4) agreed with the statement. Hence, Figure 7.23 shows that for **participants who are managing teams' challenges on a regular basis, they found CMF useful.** Therefore, this confirms one of the benefits of CMF when applied to research centres.

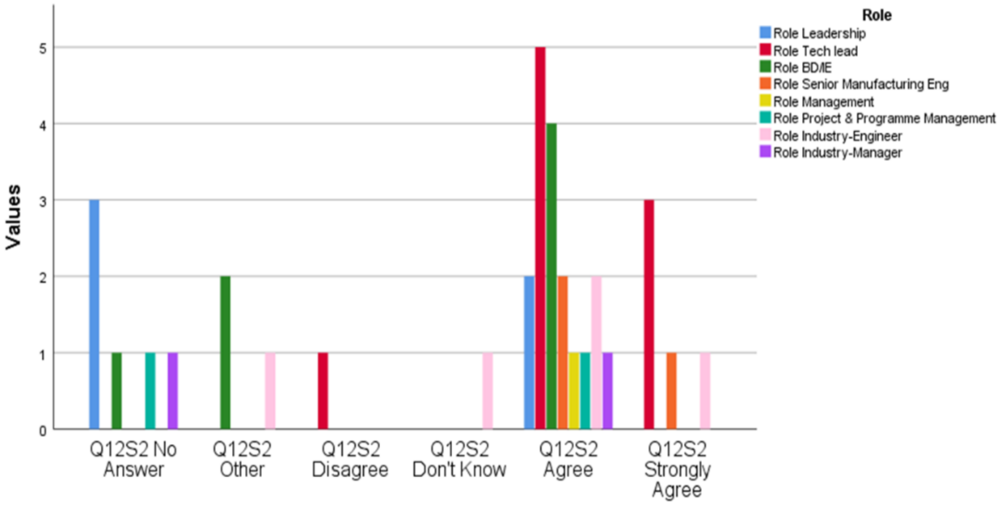


Figure 7.23: Distribution of answers to Q12, S2 based on the background of participants

Moreover, Q14 S2 asks about the possibility of **using both CMF and TRL frameworks as tools to provide information about technology capability maturity level but also about products' readiness levels.** The question was asked as CMF and TRL were created for different purposes, but they could still be used together, i.e. the results from both frameworks could be used to plan development of capabilities and how they can support development of a product. Therefore, CMF and TRL are not supposed to be 'competing' frameworks, but they should be used together to achieve higher levels of maturity and readiness, by concentrating on capabilities and products/services. Answers to Q14 S2 are presented in Table 7.24 below.

Table 7.24: S2 Q14. CMF and TRL-like processes could complement each other (CMF covering what research centre can do, and TRL what product/service needs to be delivered)

Answer	Frequency	%
Strongly Agree	9	26%
Agree	18	53%
Disagree	0	0%
Don't Know	1	3%
Other	0	0%
No answer	6	18%

79% agreed/strongly agreed with Q14 S2: **CMF and TRL-like processes could complement each other (CMF covering what RC can do, and TRL what product/service needs to be delivered)**. **None of the participants disagreed,** which shows the practicality of the CMF. Also, **none of the participants selected 'Other'** as an answer. One person selected 'Don't Know', and 6 participants provided no answer.

Figure 7.24 below shows distribution of answers to Q14 based on responsibilities of participants. 1 participant who selected 'Don't Know' is involved in operational & strategic activities, while another 2 participants from the same group selected no answers. Additionally, 1 participant from operational activities group did not select any answer, as well as 3 participant who are involved in TOS activities. However, **participants involved in any technical activities (individual or combined with other responsibilities), agreed or strongly agreed with Q14: CMF and TRL-like processes could complement each other.** That is a **strong evidence from technical community** that not only there is **a need for a tool like CMF** but also it could **bring extra benefits when combined** with already existing readiness tools that concentrate on readiness of a product/service.

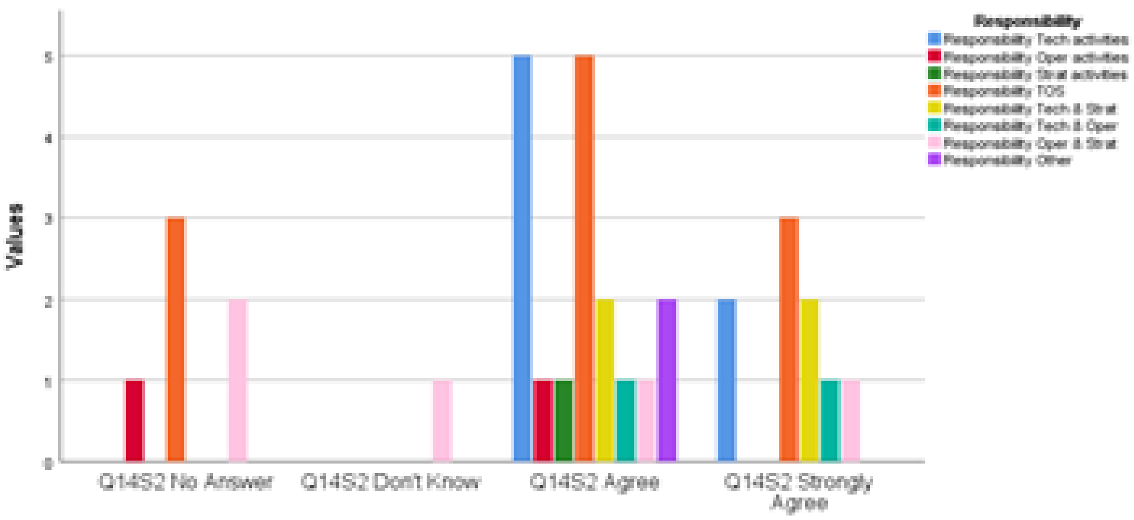


Figure 7.24: Distribution of answers to Q14, S2 based on participants' responsibility

7.10 Transparency of CMF

This sub-section highlights questions about transparency/clarity of the CMF process. Table 7.25 includes questions from two online surveys that were part of this category. Tables 7.26 to 7.13 shows results to those questions.

Table 7.25: Questions related to transparency/clarity of the process

Survey	Question
S2	Q19. In my opinion the process how each CML level is assigned (select all answers that you agree with)
S2	Q20. The CML definitions are
S2	Q21. There is a clear difference between CML levels and their definitions and I will have no issue distinguishing between them
S2	Q23. CMF and CML offer (select all answers that you agree with) Transparency

Table 7.26 shows answers to Q19 from survey 2 in regards to process of assigning CMLs. In this case participants were able to select more than one answer.

Table 7.26: S2 Q19. In my opinion the process how each CML is assigned (select all answers that you agree with)

Answer	Frequency (total=34)	%
Logical	16	47%
Accurate	4	12%
Relevant	13	38%
Practical	11	32%
Clear	9	26%
All of the above	2	6%
Other	8	24%
No Answer	6	18%

Table 7.26 shows that 6 participants (18%) did not provide any answer. Two participants thought that all answers listed above were true. 16 participants (47%) though that the process was logical and 13 thought that it was relevant. 11 participants (32%) answered that the process of assigning CMLs is practical, and 8 answered that it is clear. Only four participants though that the process of assigning CMLs was accurate. In addition, eight people (24%) selected 'Other.' The following comments come from participants who selected 'Other' as their answer:

- *I feel they need to be reduced from 9 to 5. Too much choice, also subjective (P100)*
- *Some make sense, but not all, so worth further discussion I think (P107)*
- *risks being time consuming / laborious to maintain (P108)*
- *I do think initially the process is tricky to grasp and I needed to review a number of times. I guess I may have benefitted from asking questions. You just need to be careful that the process is a clear and simple as possible for the end user, i.e. do not show them unnecessary detail if not needed (P121)*
- *The process of creating CML definitions is clear and understandable (P103, P104, P116, P120)*

Next, Table 7.27 presents results regarding definitions for CMLs, and how easy it is to distinguish between them.

Table 7.27: S2 Q21. There is a clear difference between CMLs and their definitions and I will have no issue distinguishing between them

Answer	Frequency	%
Strongly Agree	1	3%
Agree	15	44%
Disagree	3	9%
Don't Know	4	12%
Other	5	15%
No answer	6	18%

47% of participants either strongly agreed or agreed. On the other hand, 3 participants (9%) disagreed. Four participants selected 'Don't Know' as an answer, and six participants provided no answer. Also five participants (15%) chose 'Other' as their answer, saying that

- *It is not a simple toolset, but I would anticipate with training and use, it would become sufficiently familiar (P109)*
- *Yes in future after applying CML to explain projects to customers or members (P105)*
- *Not sure if definition refers to the brief name under each CML level number or the 3 different sets of criteria so not sure how to answer, as stated earlier then brief names are confusing and open to interpretation e.g. 'upper immediate capability' (P108)*
- *There may be need to guide people until they are used to framework (P116)*
- *I wonder whether level 1 should actually be no capability/knowledge at all rather than how it is described as low or little. It may be useful to have a simple statement that describes the basic difference between each level (as well as the embedded criteria at each level) - we have examples of that in MCRL and it is very useful (P121)*

Table 7.28 shows answers to Q23 from survey 2 in regards to offerings/benefits of CMF and CMLs. As this section concentrates on transparency and clarity, other answers from Q23 were removed and analysed in relevant sections. In this case participants were able to select more than one answer.

Table 7.28: S2 Q23. CMF and CML offer (select all answers that you agree with)

Answer	Frequency (total=34)	%
Transparency	17	50%
Identification of skills gaps	21	62%
No Answer	6	18%

Thus, Table 7.28 shows that 6 participants (18%) did not provide any answer. Majority of participants thought that CMF and CML offer transparency, which also links to 'Identification of skills gaps'- which 62% of participants agreed with.

7.11 Reliability of CMF results

Some participants expressed their concerns regarding reliability and accuracy of results delivered by CMF. Four questions captured that concern. Table 7.29 below shows responses to Q13 and Q17, and Table 8.6 shows responses to Q18 and Q21. All the questions come from survey 2.

Table 7.29: Answers to Q13 and Q17 from survey 2

	Q13 S2*		Q17 S2**	
Answer	Frequency	%	Frequency	%
Strongly Agree	4	12%	1	3%
Agree	14	41%	18	53%
Disagree	3	9%	3	9%
Don't Know	2	6%	6	6%
Other	4	12%	4	12%
No answer	7	21%	6	18%

*Q13 S2: CMF provides a clear and accurate high-level overview of the centre

**Q17 S2: Recommendations for Team and Programmes are objective and show accurate overview of improvements needed ACROSS the research centre

53% strongly agreed or agreed with that Q13. 9% disagreed and another 6% selected 'Don't Know' as their answer. In addition, 21% did not provide any answer and 12% selected 'Other.' Those who selected that answer also provided comments, which are included in Table 7.30 below.

On the other hand, Q17 asked about asked if recommendations highlighted accurate overview of improvements needed across the research centre (i.e. across different teams and programmes). 56% of participants strongly agreed/agreed with Q17. 9% disagreed. 6% selected 'Don't Know' and 18% provided no answer. 12% selected 'Other' and provided comments.

Table A10 (Appendix 23) includes not only comments related to Q13 and Q17 from survey 2, but also comments from other questions were participants commented on data input. However, comments from Table A2, were divided into five categories as presented in Table 7.30.

Table 7.30: Participants' concerns related to data input and reliability of results

Category	Frequency	Discussed in
Bias/Subjectivity of data	10	Chapter 9, section 9.2: Definitions
Reliability	4	Chapter 7, section 7.11
Future review process	3	Chapter 8, section 8.5: Future control/review mechanism.
Data collection process	2	Chapter 9, section 9.4: Validation process
Not enough data	2	Chapter 9, section 9.4: Validation process

As other aspects mentioned in participants' comments are discussed in Chapter 8 and 9, this section focused on reliability aspect which led to another question: who should provide data in the future. Relevant comments are presented in Table 7.31.

Table 7.31: Who should provide input data?

Participant	Quote
P111	*Senior management/management needs to control the input*
P110	*there are also conflicts between supervisor and team members, so team lead have a conflict with someone and might score them lower – for that reason we need independent review*
P117	*You know the approach UoS is taking with Engineering 360 degrees- we could do something like that so in CMF it would require everyone filling out the form – so everyone would need to fill in your datasheet and then you would take a sort of average from all data*
P116	*In general, how do you guard against pessimistic/optimistic scorers? What if the Additive focal is really positive and it's not a true reflection? Is it just one person responsible for scoring?*
Q37 S1P114	*If the assessment is done by in-house staff, the data will not be objective*

Some participants do not agree that it should be only TC/team leads who provide input data. Another participant suggested that everyone could provide data about themselves, and someone else suggested that management would need to control those inputs.

One participant actually suggested that process introduced by CMF should be part of ADR process: "*fill it up once or twice a year and it would always get updated, because everyone has to fill it in- and it could be also automated so it gets updated automatically*" (P100). Thus, it would mean that CMF is updated on regular basis, it does not require one person to upload all the data, but everyone does it in their own time (as it happens already for ADR), senior management can look at the results from past years and analyse what changes took place (or if there were no changes) regarding particular technology capabilities.

Eliminating vagueness and introducing improved version of definitions, as well as providing data on a regular basis in the same way as existing processes will eliminate bias and subjectiveness but will also increase reliability of results delivered by CMF. Another way to eliminate bias is **to introduce a control/review mechanism that will require checking the results and making sure any concerns are addressed.** Section 8.6 discusses that aspect.

Next, Q18 and Q23 from survey 2 also asked about accuracy of results and if the results, as well as CMF, offer good foundation for technological progress. Table 7.32 shows results to those questions.

Table 7.32: Answers to Q18 and Q23 from survey 2

Q18 S2: I believe results presented in the presentation		
Answer	Frequency (total=34)	%
Are accurate	6	18%
Are relevant	12	35%
Show a good indication of capability maturity at the research centre	18	53%
Other	7	21%
No Answer	6	18%
Q23 S2: CMF and CML offer		
Answer	Frequency (total=34)	%
Accuracy of measurement	6	18%

Good foundation for communicating our technological progress	22	65%
Other	7	21%
No Answer	6	18%

53% of participants said that results 'Show a good indication of capability maturity at the research centre.' In addition, Q23 showed that 65% of participants see CMF and CMLs as 'Good foundation for communicating our technological progress,' which could also mean that that the CMF and CML offer good level of reliability in order to communicate that.

On the other hand, answers to both questions showed that only 18% of participants thought that the results were accurate, and that CMF offers accuracy of measurement. It links back to concerns about Bias/Subjectivity and Reliability that were discussed before.

However, reliability of the CMF results will rely on data input, hence definitions (provided by CMF) need to eliminate vagueness and subjectivity. In addition, a review process (or a control mechanism) could eliminate any misalignment. Those two improvements are discussed in Chapter 9.

7.12 Strategic Importance

This sub-section highlights questions about strategic importance and if CMF could support strategic activities at a research centre. Table 7.33 includes questions from two online surveys that were part of this category. Tables 7.34 and 7.35 shows results to those questions.

Table 7.33: Questions related to strategic importance

Survey	Question
S1	Q12. I will be able to access useful and detailed information regarding individuals, equipment and projects through CMF to understand relevant challenges
S1	Q27. CMF process will be helpful when considering future investment/manpower decisions
S2	Q23. CMF and CML offer (select all answers that you agree with) Connection between technology capabilities and strategic planning
S2	Q24. Results from CMF provide a strong foundation for strategy building at the research centre
S2	Q26. CMF will support STRATEGIC decision making and/or planning
S2	Q27. CMF will help with identifying gaps when aligning Technological Capability with Industrial challenges/Cross-sector challenges

Table 7.34 presents results in regards to Q12 and Q27 from Survey 1.

Table 7.34: Answers to questions 12 and 27 from Survey 1

	Q12 S1*		Q27 S1**	
Answer	Frequency	%	Frequency	%
Strongly Agree	4	12%	11	32%
Agree	19	56%	19	56%
Disagree	5	15%	1	3%

Don't Know	3	9%	0	0%
Other	2	6%	3	9%
No answer	1	3%	0	0%

*Q12 S1: I will be able to access useful and detailed information regarding individuals, equipment and projects through CMF to understand relevant challenges

**Q27 S1: CMF process will be helpful when considering future investment/manpower decisions

68% of participants either **strongly agreed or agreed** with Q12 S1. However, 15% disagreed and 9% selected 'Don't Know', while 3% did not provide any answer. Additionally, only 6% selected 'Other,' saying:

- *I have some concerns regarding using the tool to make decisions around people and skills. It appears to give an objective measure of capability, but it is only quantified, in my view. Would it highlight one of the main issues with the centre, which is that the expertise is often vested in single individuals. How could the tool be used to help teams better plan to be resilient to staff leaving or being promoted to new roles in different teams, for instance? How can it be used to provide pathways for careers? (P107)*
- *I will need some training and other question is how much time is required to maintain CMF every year. I can imagine substantial effort in first year to capture capability but what input is required to maintain it and validate it (P105)*

What is more, Fig. 7.25 shows distribution of answers to Q12 based on participants' responsibilities. **Majority of participants who manage TOS activities, as well as those who manage technical activities, tech & strategic activities, operational activities agreed/strongly agreed with Q12**. Therefore, it shows that participants with various responsibilities agreed that CMF will provide access useful and detailed information regarding individuals, equipment and projects through CMF to understand relevant challenges.

On the other hand, some individuals did not provide answer, selected 'Other' or disagreed with Q12. 2 participants with technical, TOS and operational & strategic activities disagreed that CMF could provide useful and detailed information.

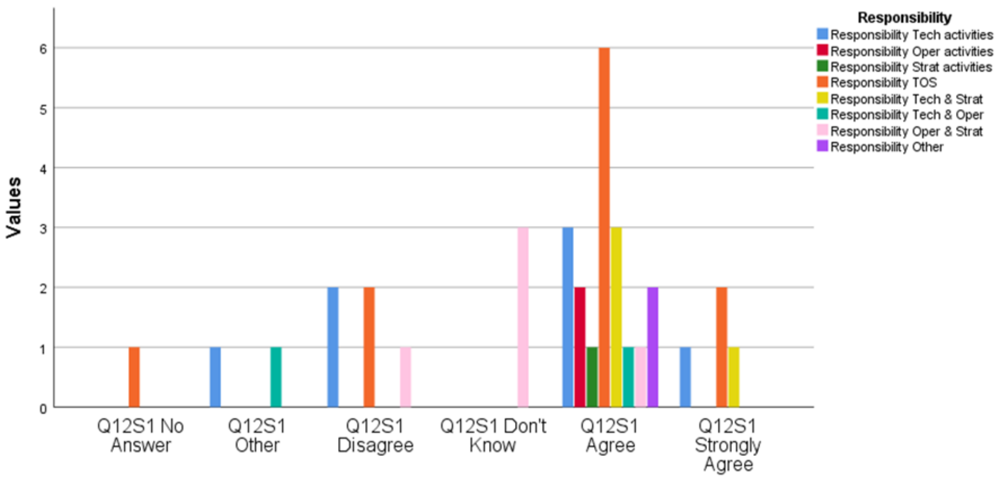


Figure 7.25: Distribution of answers to Q12, S1 based on participants responsibilities

In regards to Q27 S1, **impressive 88% of participants either strongly agreed or agreed that CMF process will be helpful when considering future investment/manpower decisions**. However, 3% disagreed with that statement, and 9% selected 'Other' saying:

- *If it will be possible to prove that this data is reliable (P106)*
- *It 'could', but that's not to say it 'will' (P108)*
- *I think it will help identify skill sets we need to recruit and/or develop within the teams (P118)*

Fig. 7.26 shows distribution of answers to Q27 based on participants' role and responsibilities, respectively. It shows that only one person from BD/IE background did not agree with Q27, and that 3 participants (1 from BD/IE, 1 from technical leads, 1 from leadership) selected 'other' as their answers. Comments from those who selected other are listed above. They were positive answers, however they did mention the concern about reliability of inputs, which was already highlighted in different sections of this chapter. This concern is also discussed in detail in Chapter 9.

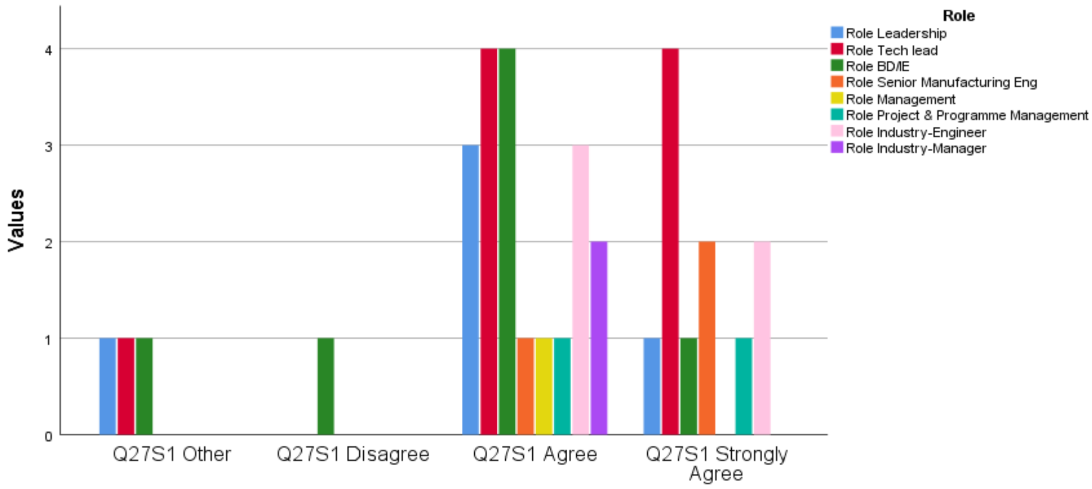


Figure. 7.26: Distribution of answers to Q27, S1 based on participants' role

Furthermore, Table 7.35 shows answers to Q23 from survey 2 regarding strategic benefits of CMF and CMLs. As this section concentrates on strategic importance, other answers from Q23 were removed and are analysed in relevant sections. In this case participants were able to select more than one answer.

Table 7.35: S2 Q23. CMF and CMLs offer (select all answers that you agree with)

Answer	Frequency (total=34)	%
Good approach for building resilience	7	21%
Identification of skills gaps	21	62%
Support for decision-making	19	56%
Connection between technology capabilities and strategic planning	16	47%

Table 7.35 shows that **62%** thought that **CMF and CML offer 'Identification of skills gaps,' which is good for succession building and planning for the future**. Also **56% thought that CMF and CMLs can support decision making process.** Additionally, **47%** thought that CMF and CML offer **'Connection between technology capabilities and strategic planning**.' Also **21%** answered that CMF and CML offer '**Good approach for building resilience.'**

Next, Table 7.36 presents results in regards to Q24, Q26 and Q27 from survey 2.

Table 7.36: Answers to questions 24, 26 and 27 from Survey 2

	Q24 S2*		Q26 S2**		Q27 S2***	
Answer	Frequency	%	Frequency	%	Frequency	%
Strongly Agree	7	21%	6	18%	4	12%
Agree	17	50%	18	53%	18	53%
Disagree	1	3%	0	0%	0	0%
Don't Know	1	3%	1	3%	0	0%
Other	2	6%	3	9%	2	6%
No answer	6	18%	6	18%	10	29%

*Q24 S2: Results from CMF provide a strong foundation for strategy building at the research centre

**Q26 S2: CMF will support STRATEGIC decision making and/or planning

***Q27 S2: CMF will help with identifying gaps when aligning Technological Capability with Industrial challenges/Cross-sector challenges

71% either strongly agreed or agreed with Q24 S2 i.e. **results presented through CMF provide a strong foundation for strategy building at the research centre**. However, 3% disagreed and another 3% selected 'Don't Know', while 18% did not provide any answer. Additionally, 6% selected 'Other,' saying

- *Not applicable - I don't think this tool has anything to do with strategy building - that comes from listening to industry and responding to that P100*
- *strategy is not and should not just be considered to be technical P108*
- *CMF is a great tool to show where the investment should go P117*

Fig. 7.27 below shows distribution of answers to Q24. **Almost every participant with technical responsibilities provided positive response**. Also, participant with technical & operational and other responsibilities, as well as majority of those with TOS, tech & strategic responsibilities agreed/strongly agreed that CMF provide a strong foundation for strategy building at the research centre. One participants from technical & strategic responsibilities disagreed. It could mean that information captured through CMF were not properly explained during validation process and the strategic importance was not highlighted properly during validation process. That is another aspect that is discussed in detail in Chapter 9.

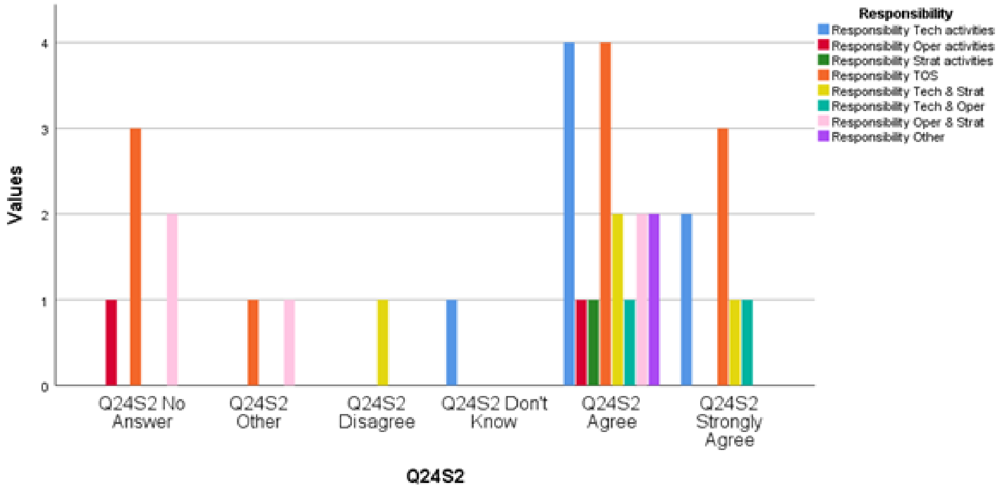


Figure 7.27: Distribution of responses to Q24, S2 based on participants responsibilities

In addition, two participants who selected 'Other', mentioned that CMF '*has anything to do with strategy building - that comes from listening to industry and responding to that*'. That of course is true, but in order to build strategy and response to industry, decision makers need to know how they can respond and if they have technological capabilities to do so. On the other hand, a different participant mentioned that '*CMF is a great tool to show where the investment should go*' P117.
Furthermore, 71% either strongly agreed or agreed with Q26 i.e., CMF will support STRATEGIC decision making and/or planning. Also, no one disagreed and only 3% selected 'Don't Know', while 18% did not provide any answer. Additionally, 9% selected 'Other,' saying

- *If used beyond a single centre, there needs to be a moderation of data to ensure that strategic decision making is consistent and appropriately weighted. P111*
- *I find it quite risky if we are not sure in reliability of data P106*
- *it may P108*

Additionally, 65% of participants either strongly agreed or agreed with Q27 S2, i.e. CMF will help with identifying gaps when aligning Technological Capability with Industrial challenges/Cross-sector challenges. Moreover, no one disagreed nor selected 'Don't Know.' However, 29% did not provide any answer. Additionally, 6% selected 'Other,' saying *Only if industry are bought into the methodology (P111) and It may help (P108).*

Figure 7.28 shows distribution of answers to Q27 S2 based on participants' responsibilities. It shows that even though participants focus on different day-to-day activities (i.e. mixed responsibilities), they agreed that CMF will help with identifying gaps when aligning Technological Capability with Industrial challenges/Cross-sector challenges.

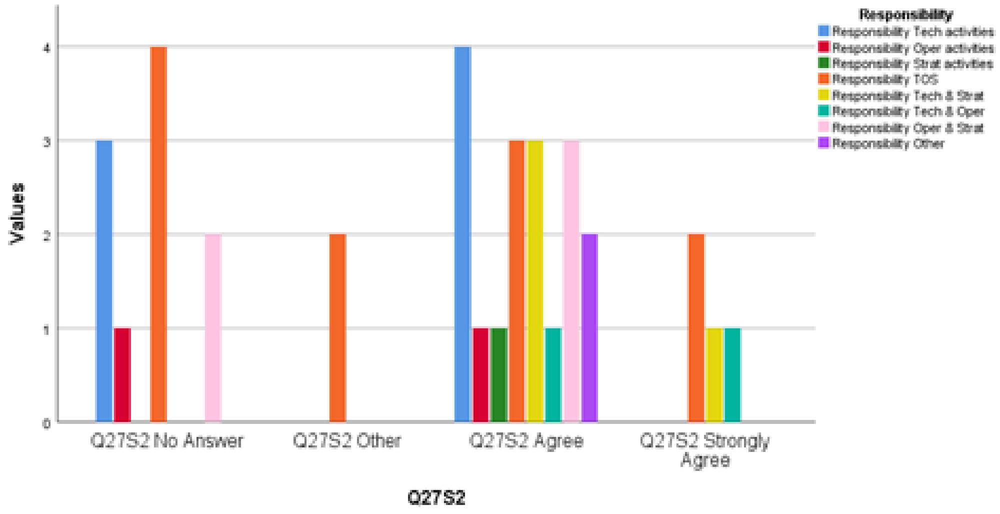


Figure 7.28: Distribution of answers to Q27, S2 based on participants responsibilities

7.13 Applicability to HVMC

This sub-section highlights questions about implementation of CMF across HVMC network. Table 7.37 includes questions from two online surveys that were part of this category. Table 7.38 shows results to those questions. Answers to all three questions are presented in Table 7.38 below.

Table 7.37: Questions related to applicability of CMF across HVMC

Survey	Question
S1	17. CMF could become a standard tool to manage capability maturity across HVMC
S1	18. CMF will help with improving transparency between HVM Catapults
S1	19. I think CMF could help with transferring knowledge and building common strategy between HVM Catapults

Table 7.38: S1 Q18. CMF will help with improving transparency between HVM Catapults

	Q17 S1*		Q18 S1**		Q19 S1***	
Answer	Frequency	%	Frequency	%	Frequency	%
Strongly Agree	6	18%	6	18%	7	21%
Agree	18	53%	13	38%	17	50%
Disagree	0	0%	2	6%	0	0%
Don't Know	5	15%	8	24%	4	12%
Other	4	12%	4	12%	2	6%
No answer	1	3%	1	3%	4	12%

Firstly, 71% either strongly agreed or agreed with Q17, i.e. CMF could become a standard tool to manage capability maturity across HVMC. In addition, none of the participants disagreed with that statement. However, 3% provided no answer, and 15% selected ‘Don’t Know’. Also, 11% selected ‘Other’ as their answer, leaving the following comments:

- *Only if there is a data moderation step at the input stage. Key comment here is that the underpinning data is gathered via a subject process and so quantitative conclusions need to be treated with caution absent data validation (P111)*
- *If data can be backed up with evidence to support it. I have concerns that this would lead to comparisons which would not necessarily help the centres work together, however. Aspirational, rather than evidentiary data will skew the results and some centre leads could manipulate the data to enable them to drive their agendas forward (P107)*
- *Same comment as above as in Q16: I would agree but would add that further work would need conducted - it is an ideal tool to benchmark your own capabilities but each research centre is slightly different so using it as a standardised tool across multiple centres would require more work… how do you standardise a capability? Does a technology mean something slightly different at a different centre? Who fills the CMF out to prevent bias?) (P103)*

Fig. 7.29 on below shows distribution of answers to Q17 based on participants' role. Again, participants with technical leads, senior manufacturing engineers, management and majority of leadership agreed/strongly agreed that CMF could become a standard tool to manage capability maturity across HVMC. What is more, majority of participants with TOS responsibilities and technical & strategic also provided positive responses. In addition, participants with operational responsibilities, strategic responsibilities, and operational & strategic, also provided positive responses. Hence, they confirmed that CMF could become a standard tool to manage capability maturity across HVMC. It also means that the benefits of CMF are not only understood by one group of participants, but by many participants with different responsibilities. It shows that even though participants' roles and responsibilities differ, they all see the benefits of having a standardised approach and for choosing CM as a standardised approach for research centres and/or HVMC.

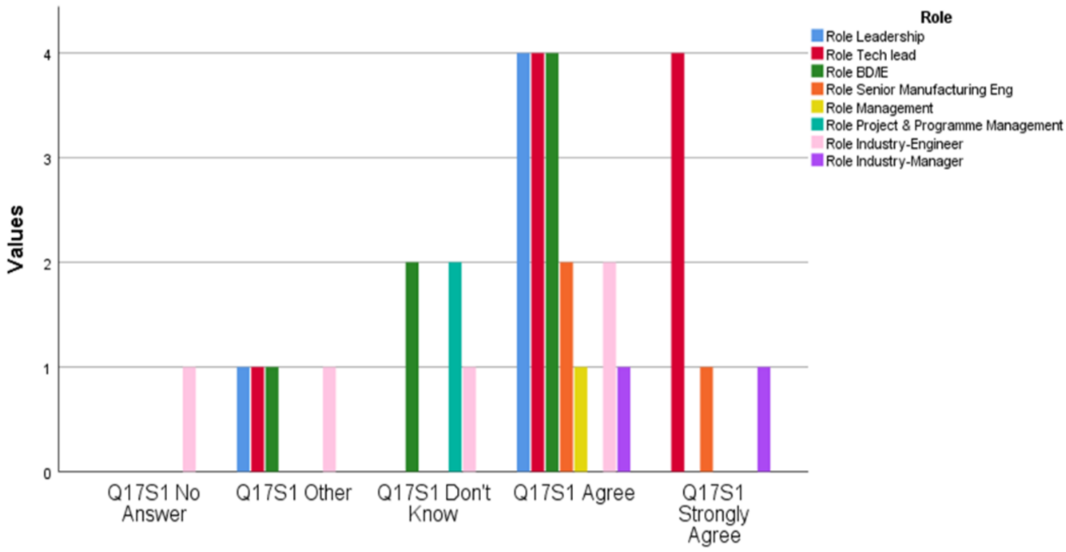


Figure 7.29: Distribution of answers to Q17, S1 based on participants' role

Secondly, 56% of participants either strongly agreed or agreed with Q18, i.e. CMF will help with improving transparency between HVM Catapults. On the other hand, 6% disagreed with that, and 24% selected 'Don't Know.' Also only 3% did not provide any answer, and 12% selected 'Other.'

Figure 7.30 below shows distribution of responsive based on participants responsibilities. It should be highlighted that only 2 participants disagreed with Q18, and those participants have strategic responsibilities and operational responsibilities. Also one person who is involved in operational activities selected 'Don't Know'. Also one person with combined TOS responsibilities did not provide any answer, and another 3 from the same group selected other together with one participant from operational and strategic group. Participants who selected 'Other' left the following comments:

- *It could with the appropriate level of moderation P111*
- *It 'could', but that's not to say it 'will' P108*
- *Possibly P122*
- *Not sure as some of the assessments of maturity seem to be subjective P123*

Fig. 7.30 certainly highlighted that participants with technical responsibilities agreed with Q18 more than others.

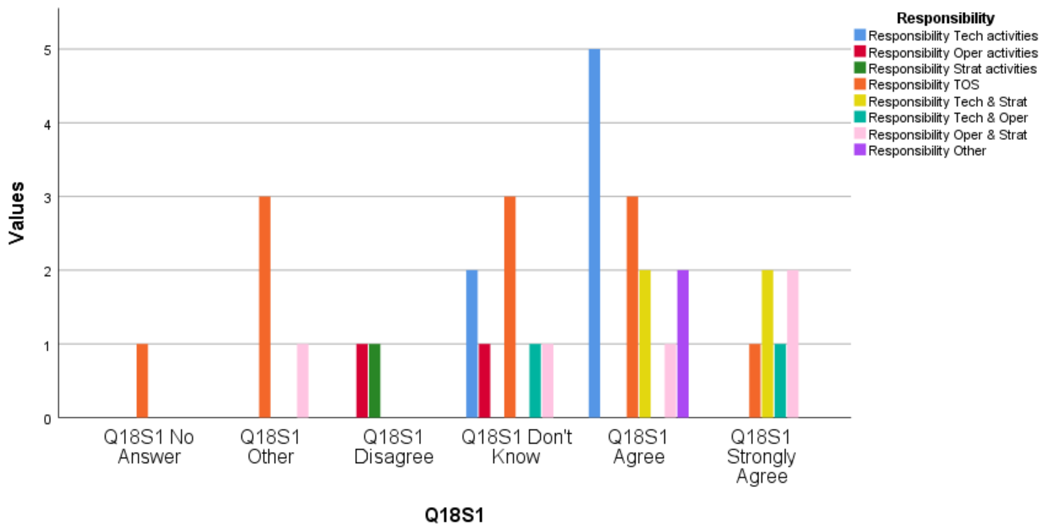


Figure 7.30: Distribution of answers to Q18, S1 based on participants' responsibilities

Lastly, **71% of participants either strongly agreed or agreed with Q19, i.e. CMF could help with transferring knowledge and building common strategy between HVM Catapults**. What is more**, no one disagreed** with Q19 S1, 12% selected 'Don't Know,' another 12% did not provide any answer, and 6% selected 'Other.'

Figure 7.31 below shows that 3 participants who are involved in technical activities, and one who is involved in TOS activities selected no answer. Unfortunately, there are no comments related to those answers. Most likely, participants 'skipped' that question. Also, 2 participants selected 'Other' as their answer, where one (P122) added comment *'Possibly'* and the other did not leave any comment. Hence, Fig 7.31 shows that **majority of participants from various background, but with most participants involved in TOS activities, provided positive responses.**

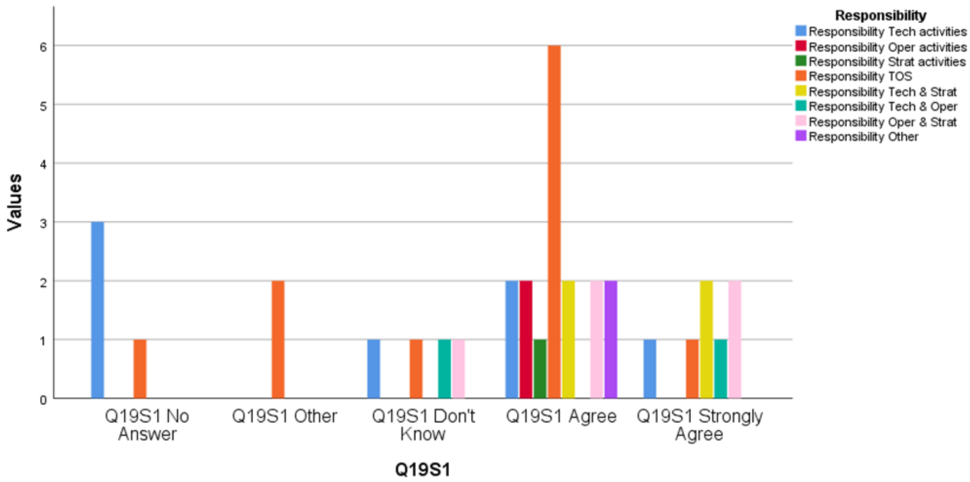


Figure 7.31: Distribution of answers to Q19, S1 based on participants' responsibilities

7.14 Summary

This chapter focused on the validation results involving 34 experts (participants). 79% of participants work at a research centre, and 21% works at industrial companies who collaborate with those research centres. The study showed that even though participants are aware of readiness/maturity tools available to industry, only a small percentage know how to use them or had a chance to use particular tools in the past. For example 30% use (or used) TRLs, and 12% used MRLs (and those were two answers that received the most votes). Those tools are not applicable to research centre environment as they do not consider research centres' capabilities and their structure. Therefore, this research aimed to underline a need for a framework developed specifically to benefit research centres. This chapter's structure, and the questions asked during validation process were created in order to highlight that gap in the knowledge. The key findings from sections 7.2 - 7.13 are summarised in Figures 7.32 – 7.43 below.

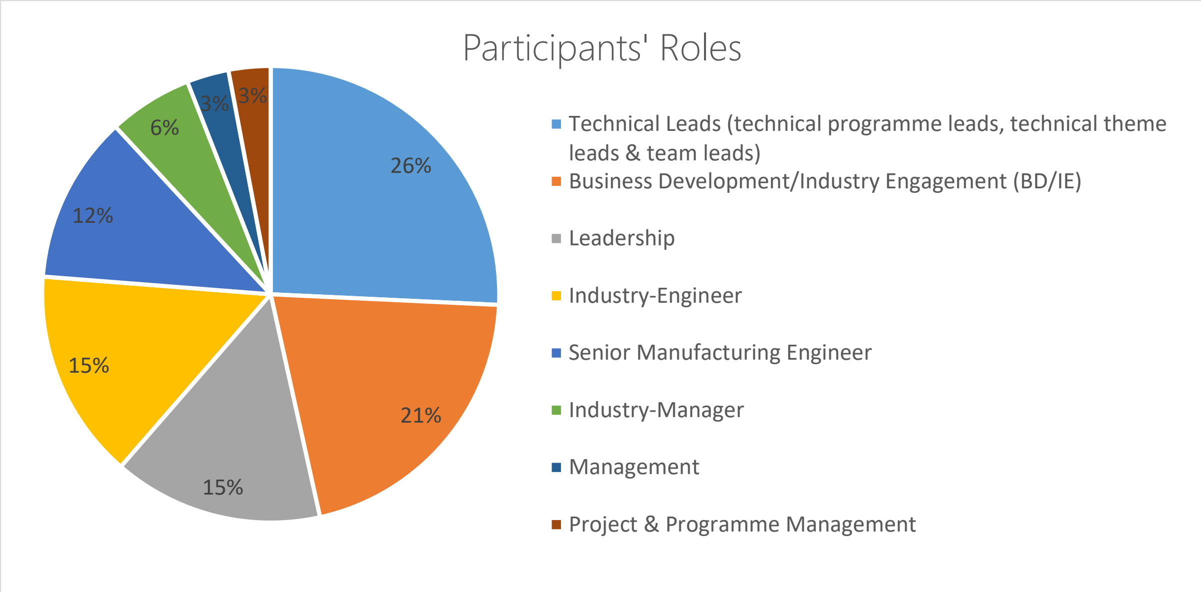
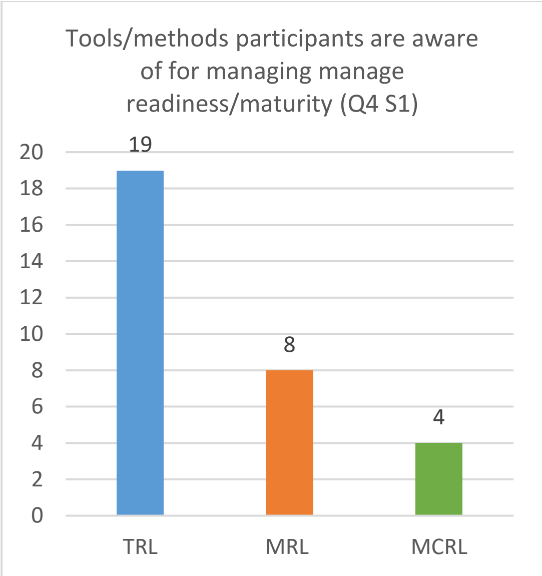


Figure 7.32 Visual summary of key findings from section 7.2 Participants background: Participants Roles (top); Participants Responsibilities (bottom)



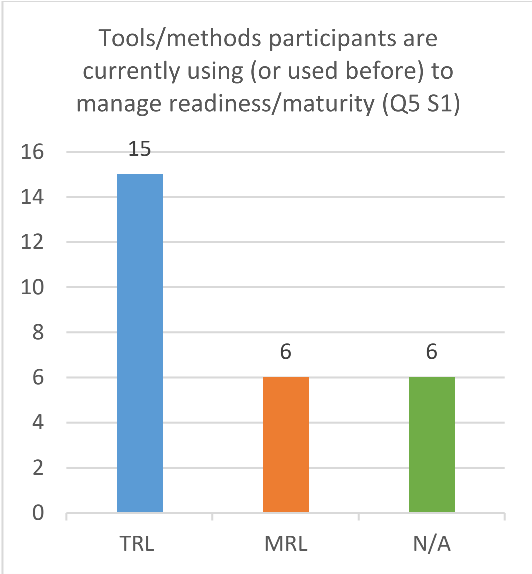


Figure 7.33 Visual summary of key findings from section 7.3 Tools to measure readiness/maturity

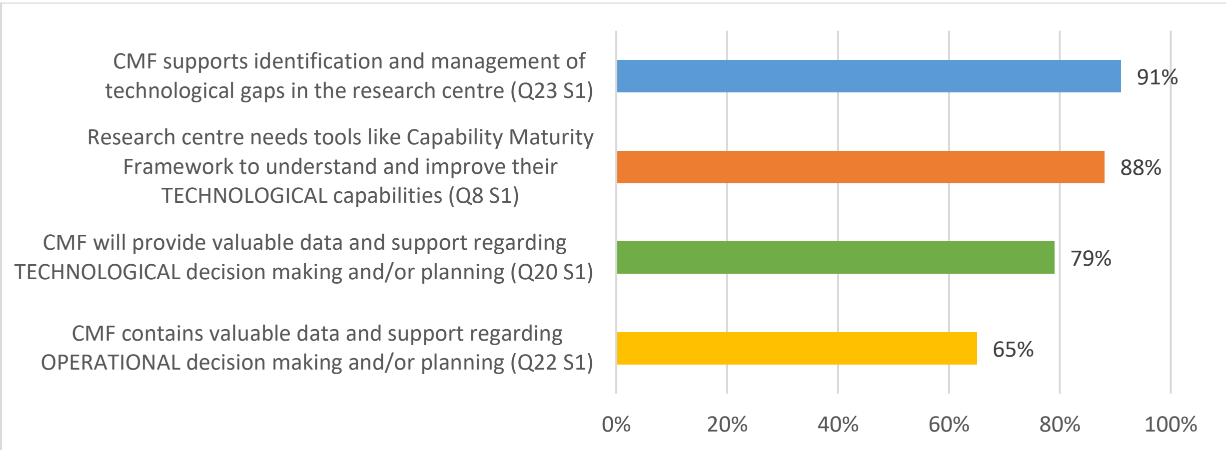


Figure 7.34 Visual summary of key findings from section 7.4 Users' goals (Technical vs Operational)

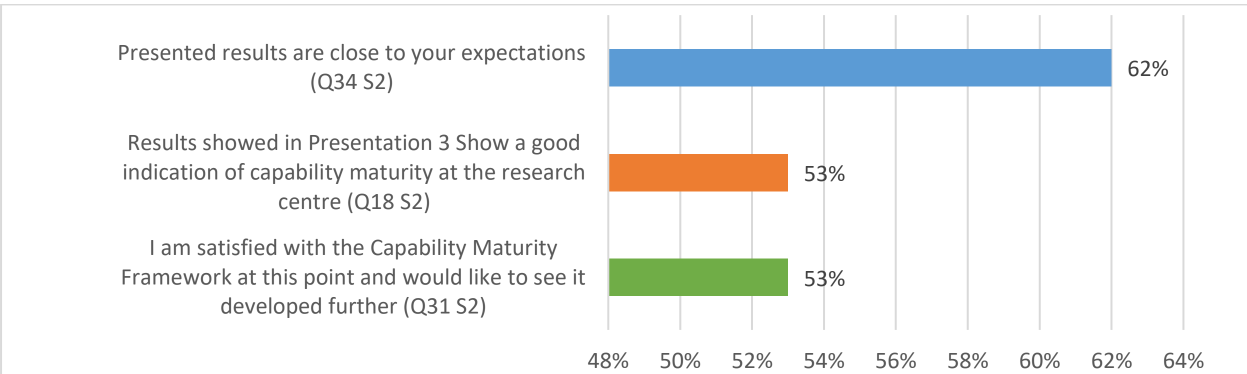


Figure 7.35: Visual summary of key findings from section 7.5 Users' expectations

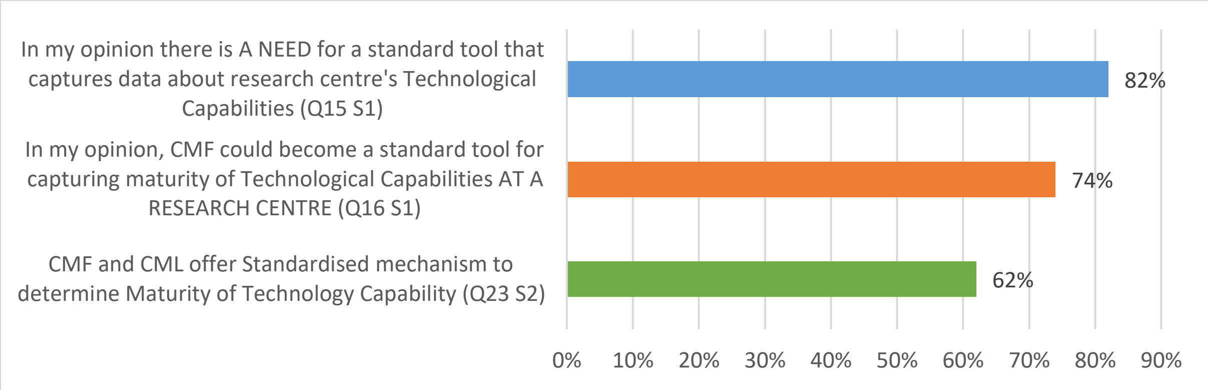


Figure 7.36: Visual summary of key findings from section 7.6 Need for standardisation

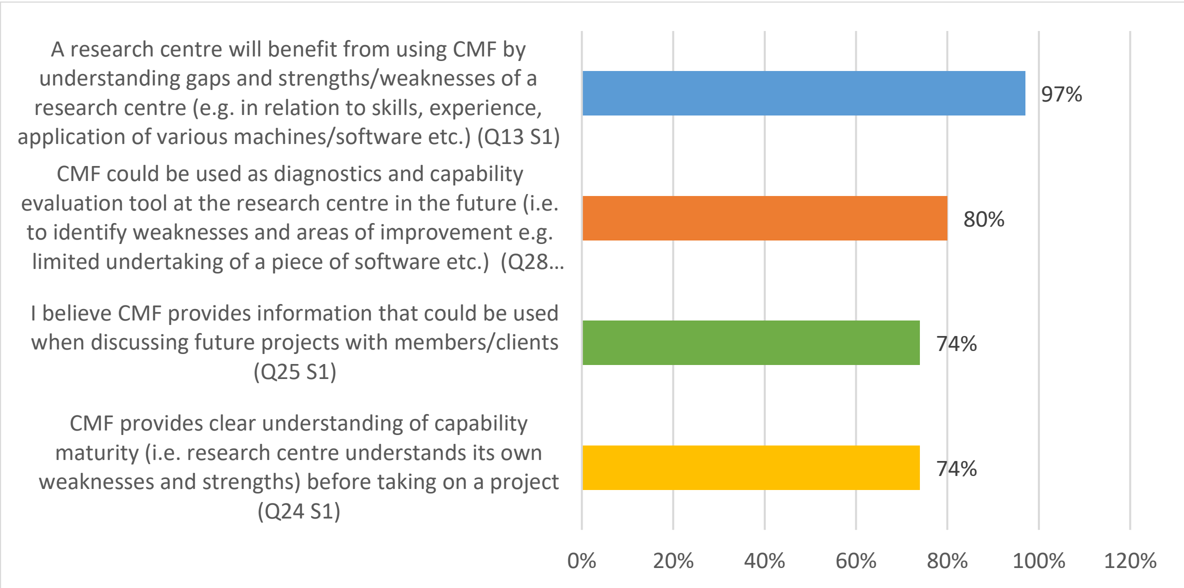


Figure 7.37: Visual summary of key findings from section 7.7 Purpose and benefits of CMF

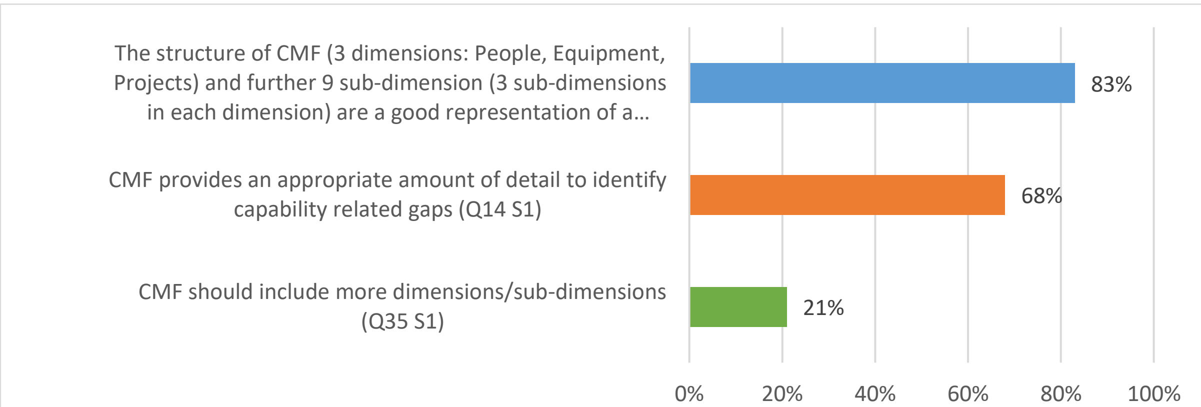


Figure 7.38: Visual summary of key findings from section 7.8 Mechanism/ Structure of CMF

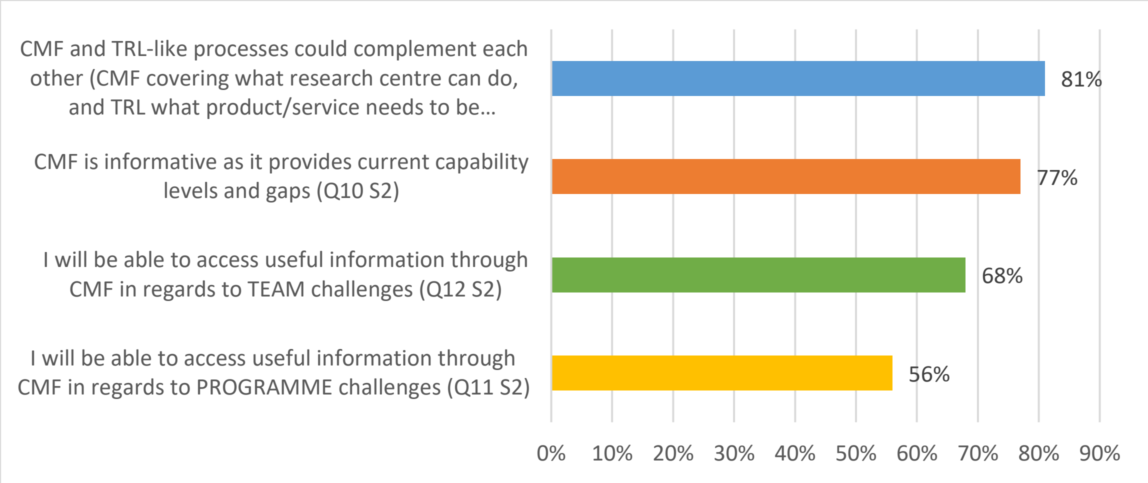


Figure 7.39: Visual summary of key findings from section 7.9 Practicality of CMF

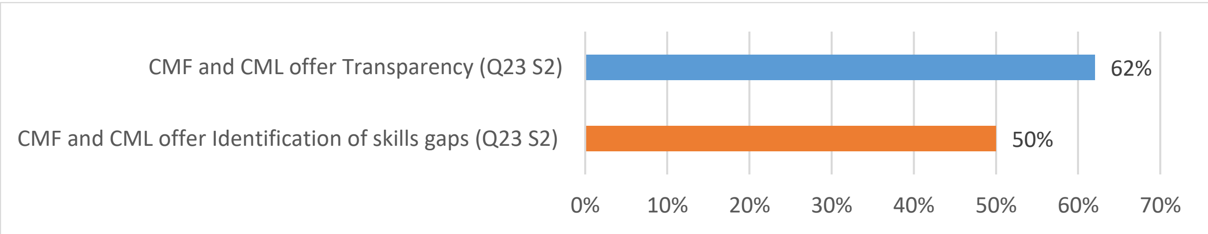


Figure 7.40: Visual summary of key findings from section 7.10 Transparency of CMF

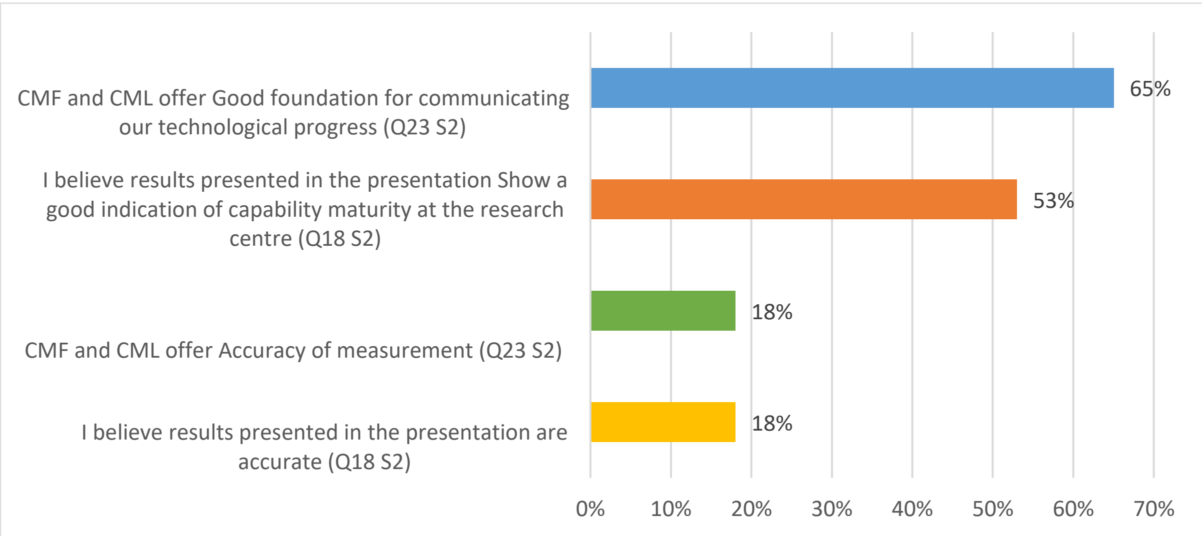


Figure 7.41: Visual summary of key findings from section 7.11 Reliability of CMF results

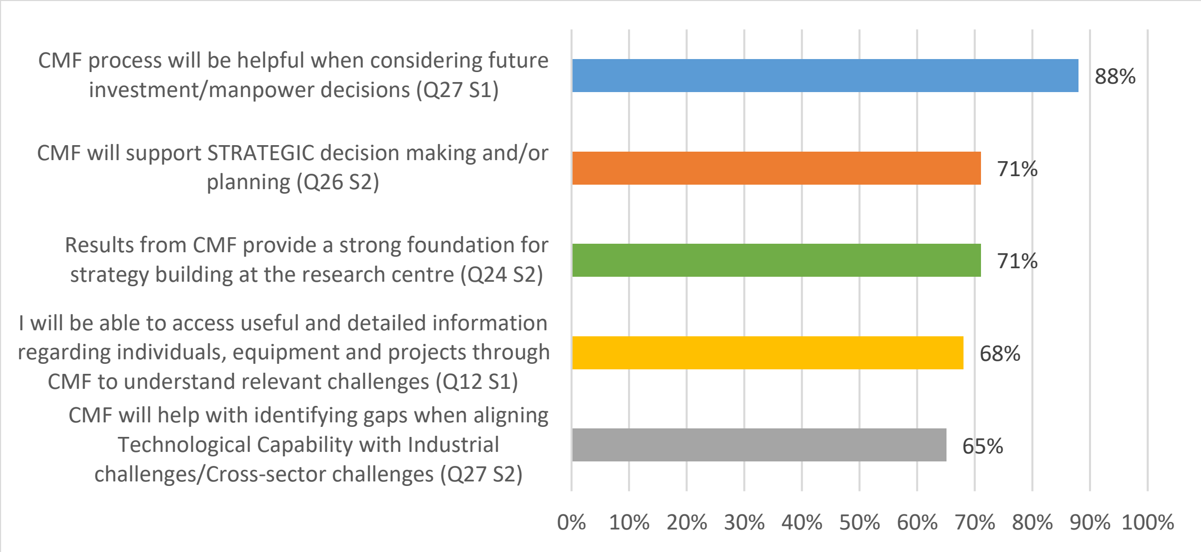


Figure 7.42: Visual summary of key findings from section 7.11 Strategic Importance

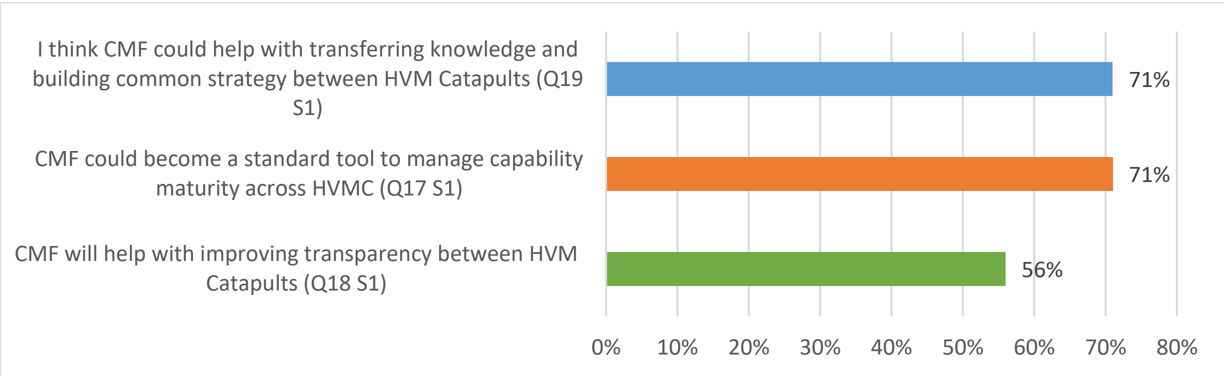


Figure 7.43: Visual summary of key findings from section 7.12 Applicability to HVMC

The evidence discussed in this chapter (and presented in Figures 7.32- 7.42) showed that **there is a need for a standard tool that captures data about research centre's Technological Capabilities**. **82% of participants agreed that there is A NEED for a standard tool that captures data about research centre's Technological Capabilities** (Q15 S1). Additional **74% expressed their opinion that CMF could become a standard tool for capturing maturity of Technological Capabilities AT A RESEARCH CENTRE** (Q16 S1).

Moreover, **88%** of participants thought that **CMF process** will be **helpful when considering future investment/manpower decisions** (Q27 S1). It links to another finding which was supported by **97%** of participants: A **research centre will benefit from using CMF by understanding gaps and strengths/weaknesses of a research centre** (e.g. in relation to skills, experience, application of various machines/software etc.) (Q13 S1). Therefore, participants understood the purpose and benefits of CMF.

Also, **83%** of participants thought that proposed structure of CMF is **a good representation of a research centre's capabilities** (Q11 S1), which confirmed that the structure of CMF was well developed.

Lastly, **81%** of participants agreed **CMF and TRL-like processes could complement each other** (Q14 S2), which is important as CMF could cover capability maturity aspects of RC and TRL based approaches can be still used for next steps of product development, i.e. understanding readiness of a product.

Considering above evidence, it is clear that **the need for a capability maturity solution for research centres was captured.** Participants had a chance to go through three presentations that explained the mechanism and reasons why CMF was created. Gathered feedback showed that participants understood aim and functionality of CMF, and also expressed positive comments when asked about their expectations. Therefore, all those evidence showed that gap in the knowledge (identified previously in Chapter 4) has not been addressed and **CMF is the first solution created for research centres that addresses that gap**, as it was created for RCs but also with the support and participation of RCs' practitioners. Next, Chapter 8 discusses academic and industrial contributions of this research.

Chapter 8: Discussions

8.1 Introduction

Using results from Chapter 7, this chapter concentrates on highlighting academic and industrial contributions of this research (sections 8.2 – 8.4). Moreover, section 8.3 will discuss answers to the three research questions previously introduced in Chapter 1.

Sections 8.5 – 8.7 will discuss concerns pointed out by participants during validation process. Those concerns were related to:

- Reliability of data presented by CMF
- Future control/review mechanism
- Implementation of CMF

Lastly, section 8.8 will introduce new areas of research inspired by development of CMF.

Table 8.1 shows the structure of this chapter and topics discussed in each section.

Table 8.1: Structure of Chapter 8

Section	Discussion Topics
8.2	Academic Contributions • Research Contribution no 1 • Research Contribution no 2 • Research Contribution no 3 • Research Contribution no 4 • Research Contribution no 5
8.3	Answers to Research Questions • 8.3.1 RQ 1 Is there a need for capability maturity framework applicable to manufacturing research centres? • 8.3.2 RQ 2 Could a novel framework fill in the need for capability maturity framework at manufacturing research centres? • 8.3.3 RQ 3 Could a novel framework fill in the need for capability maturity framework ACROSS various manufacturing research centres?
8.4	Industrial Contributions
8.5	Future control/review mechanism
8.6	Implementation of CMF
8.7	New areas of research investigation

8.2 Academic Contributions

Past studies suggest how existing models and frameworks support product development as they concentrate on product and internal tangible resources (RBV) needed to deliver new product (Liu, et al., 2019), (McKelvie & Davidsson, 2009). However they overlook aspects related to 'intangible resources' (also mentioned by RBV) and how they are managed (e.g. (Qi, et al., 2020), (Chavez, et al., 2017), (Hitt, et al., 2016)). Hence, the questions 'can we deliver the product?' seems not to be answered properly without offering any justification. Understanding gaps in a research centre environment is as important (if not more) as in a manufacturing company. Therefore, this research presents five research contributions.

Research Contribution no 1: The first contribution is recognition of lack of uniformity related to definition and objectives of research centres (Cadorin, et al., 2019). Literature presents various names for research centres, e.g. technology transfer offices (Cunningham, et al., 2020), (Leischning & Geigenmüller, 2020), (Good, et al., 2019), technology and innovation centres (Kerry & Danson, 2016), intermediate research organizations (Spring, et al., 2017), innovation intermediaries (Kerry & Danson, 2016), incubators, or accelerators (Fini, et al., 2018) (Chapter 2, section 2.5.3). However, none of papers used a specific definition of research centres as a basis for their research. For example, Teece's dynamic capability definition is referred to by other papers, as it is considered a starting point of any discussion about DCT (Chapter 2, section 2.5.1). In case of research centre, such definition has not been introduced yet. Every author introduced their own definition, or authors use different terminology to describe research centres (as mentioned above). That is misleading especially when conducting literature review and searching for specific keywords. Therefore, there is a lack of uniform definition and objectives of research centres, which makes research related to research centres challenging.

Research Contribution no 2: Even though results from Chapter 7 (section 7.3) showed that TRL is still the solution that participants are most aware of, it shows that nothing new has been introduced to research centres. It means that research centres lack the standardised processes to evolve and grow. Therefore, as literature concentrates on industrial companies (Chapter 2, section 2.5.3), the need is only addressed from industrial perspective (e.g. CMMI).

Research centres struggle with recognition of mature and immature capabilities, as they do not use any consistent process that will review what research centres know and do not know. That is why it was important to investigate what maturity means to research centres (Chapter 4, section 4.2.5.1), and how they define (Chapter 4, section 4.3.5.1) and capture their capabilities (Chapter 4, section 4.4.5.5.). One of the participants described maturity as "moving from one level to the next, it needs to be in terms of meeting certain criteria, so that is possibly the hardest part of the process." Because existing processes were created with criteria that do not match the ones at research centres, they cannot be applied there. Therefore, it showed the need for a Capability Maturity Framework developed specifically for research centres.

Research Contribution no 3: Having identified that there is no common/standardised approach for research centres (Research Contribution No 2), another contribution relates to the emerging discussion on research centres and their capability maturity challenges, as well as their operational challenges (which are experienced on a regular basis). Those challenges were explored by identifying how research centres work and overcome those challenges (Chapter 4, section 4.3.5).

This study also captured information about how research centre justify their capability to clients, which confirmed lack of any formal process (Research Contribution no 2).

Apart from gathering information through interviews (Chapter 4, section 4.2 – 4.4), that aspect was also observed by the author during her work at one of the research centres. An issue of understanding and defining what capability mean to a research centre was identified through those observations. Therefore, 'capability' means different things to different TC leads. That causes further confusion in how capability challenges are understood and how should they be overcome (considering that literature does not offer applicable solution to research centres). Hence, the following definition of capability is proposed:

Capabilities are "repeatable patterns of actions in the use of assets to create, produce, and/or offer products to a market" [(Wade & Hulland, 2004) in] (Lee, et al., 2020).

It is important (for each research centre) to introduce a clear definition of capability across all TCs. It eliminates confusion and vagueness and it ensures that every TC lead (as well as every team member) has the same understanding of capability. To mature capabilities, tangible and intangible resources need to be included as part of the process (i.e. three dimensions of capability: people, equipment, projects and their sub-dimensions).

Validation process gave a chance to test the CMF and highlight its weaknesses. The results (Chapter 7, section 7.6) showed that CMF has a potential to become a standard tool for capturing maturity of Technological Capabilities at a research centre (Q16 S1), as indicated by 74% of participants. 83% also agreed that CMF structure is a good representation of a research centre's capabilities (Q11 S1) (Chapter 7, section 7.10). It shows good level of support and understanding from future users, which was very important. It was also encouraging to see supportive comments from some participants, e.g.:

- *I can see what you are trying to do, I can see the logic P101*
- *I like the structure and the logic – it's repeatable and that's very important P109*
- *I understood the* process, *the logic, the maths and structure P117*

Research Contribution no 4: Research centres have not received the same level of attention, even though they are important contributors to technological innovations. Only in the last few years, academic interest in research centres have been identified (Chapter 2, section 2.5.3). It shows that there is a need for more academic investigations related to research centres.

It is clear that Capability Maturity Framework (developed through this EngD project) will provide a helpful foundation for technology managers, leaders, researchers and policy makers, providing information needed to improve technological capabilities in manufacturing research centres and bridging the valley of death.

Even at the beginning of this process (Chapter 4, section 4.2), participants expressed their positive view on creating CMF. Throughout the process (Chapter 4, section 4.3 and 4.4), participants were supportive and enthusiastic when discussing CMF. Although they highlighted potential limitations related to developing or implementing CMF, 82% of participants agreed that there is a need for a standard tool that captures data about research centre's Technological Capabilities (Q15 S1) (Chapter 7, section 7.6).

Research Contribution no 5: The Capability Maturity Framework was designed (Chapter 4), developed (Chapter 5) and validated (Chapter 7) to support capability maturity process of research centres in manufacturing sector. This contribution is perhaps the most important one as it delivers mechanism that can be applied in research centres, because it was created and tailored for research centres (instead of being created for industrial company, and tried to fit in a research centres). The process involved understanding how research centres operate and identifying most important aspects of their operations. The findings from three phases of interviews (Chapter 4, section 4.2 – 4.4) contributed enormously to development of dimensions and sub-dimensions of Capability Maturity Framework.

Also, understanding what challenges participants face when using existing software/tools was helpful as it improved understanding of what should be avoided when creating new interface (Chapter 4, section 4.4).

In addition, (Schoemaker, et al., 2018) mentioned that if companies want to strengthen their capabilities, "managers can conduct a capability audit in which they list the specific competencies they need, identify the gaps between current and desired levels, and take steps to reinforce those that are most critical to supporting a given strategy." By developing CMF, managers at research centres now have the option to evaluate their capabilities.

Furthermore, CMF has created a positive impact already as it is currently being used as part of a project on capability study at one of the HVM Catapults. The aim of the publicly funded project is to diagnose what is the current state of capability for a specific TC and what aspects (i.e. sub-dimensions) should be improved.

8.3 Research Questions - Discussion

Research questions were previously introduced in Chapter 1. Table 8.2 recalls the three research questions which formed the basis for this study.

Table 8.2: Research Questions

Section	#	Research question
8.3.1	RQ 1	Is there a need for capability maturity framework applicable to manufacturing research centres?
8.3.2	RQ 2	Could a novel framework fill in the need for capability maturity framework at manufacturing research centres?
8.3.3	RQ 3	Could a novel framework fill in the need for capability maturity framework across various manufacturing research centres?

8.3.1 Research Question 1: Is there A NEED for capability maturity framework applicable to manufacturing research centres?

The lack of research dedicated to research centres and their capability management left a gap that was addressed in this research project, i.e. a need for a standardised capability maturity process applicable to research centres.

The aim of RQ 1 was to investigate the need for capability maturity framework applicable to manufacturing research centres. Results presented in Chapter 7 showed positive yet strong evidence to support the need.

82% of participants either strongly agreed or agreed that there is A NEED for a standard tool that captures data about research centre's Technological Capabilities (Q15 S1). Participants with various roles and responsibilities (senior engineers, project & programme managers, industrial managers, etc.), saw the need for a tool like CMF that captures data about research centre's Technological Capabilities, i.e. not only participants from technical background, but also participants responsible for operational and business activities. Everyone from BD/IE group agreed with Q15; that is very positive as BD/IE are responsible for building connections with industry and articulating what a research centre can/cannot do. Hence, even though not all BD/IE have technical background, they all saw the need for capturing technological capability gaps. It shows that for those that are not directly connected to every day technical challenges- they still see the need and benefits of having a solution that captures technological gaps.

In addition, no one disagreed with Q15, which confirms that there is a clear need for a standard solution that captures technological capability information.

What is more, 8 out of 9 of the technical leads group provided positive responses when asked about the need for a new solution. It is encouraging to see that majority of this particular group identified the need for a capturing data about technological capabilities; especially that was CMF's aim.

As discussed previously (Chapter 2) industrial companies have their own internal or well-adjusted solutions in order to meet industrial needs (e.g. TRL, MCRL, MRL, CMM etc.) (e.g. (Bititci, et al., 2001), (Harter, et al., 2000), (Islam, 2010), (Tetlay & John, 2009), (Patón-Romero, et al., 2019)). There is also a lot of information based on dynamics capabilities theory, which focus on "the firm's ability to integrate, build, and reconfigure internal and external competences to address rapidly changing environments" (Teece, 2018). Papers reviewed during literature review process identified that DCT and RBV are only discussed in an industrial context. It links back to Research Contribution no 4: Research centres have not received the same level of attention, despite of their important contribution to technological innovations. That also confirms findings from Phase 1 interviews (Chapter 4): a need for a new framework for research centres.

Therefore, the evidence conducted and presented through this research show that there is a distinction between research centres' needs and industrial needs. For that reason, CMF answered the needs of research centres, as previous approaches concentrate on specific use case or context. In addition, research centres need to respond to multiple companies i.e. multiple use cases, and so they cannot concentrate only on one use case. Their capabilities need to address several use cases. That is why they also need an assessment that will measure how mature their capabilities are. Hence, this research showed that there is a need for a CMF developed specifically for research centres.

8.3.2 Research Question 2: Could a novel framework fill in the need for capability maturity framework at manufacturing research centres?

The answer is yes- CMF could fill in the need for capability maturity framework at manufacturing research centres. Overall feedback about CMF was positive, and even though participants expressed some concerns- those comments create a basis for future work that will only improve CMF. The evidence also showed that participants understood the purpose and benefits of having CMF as a standard tool at a research centres (which was also discussed in Phase 1 interviews, Chapter 4).

The aim of RQ 2 was to explore the mechanism and structure of novel framework in order to fit research centre environment.

74% of participants either strongly agreed/agreed that CMF could become a standard tool for capturing maturity of Technological Capabilities at a research centre. Additionally, all participants from leadership group provided positive responses, i.e. leaders who participated in this study thought that CMF is the applicable tool to implement at research centres. Therefore, they recognised that CMF creates access and availability of capability-related information. Having that option is a big advantage to leadership as they can verify their TC expectations.

Having a chance to review TCs is important for any technology-driven organisation, and it especially should be for research centres who are often asked to scale up a technology/product or innovate a totally new piece of technology. Also, as research centres are expanding, no one can keep track of what skills/equipment/projects research centre has. Thus, there needs to be an internal process that helps with decision making related to TCs.

Furthermore, 91% of participants either strongly agreed/agreed that CMF supports identification and management of technological gaps in the research centre. Those results show that CMF is not only useful for identifying capability gaps but also it supports management of those gaps. That result is very important as it shows that almost all participants expressed positive views about main purpose of the CMF.

Also, none of the participants mentioned that the need is already addressed by any other solution which also confirms that that the gap in the knowledge has not been addressed yet. Even though this is only a starting point- it seems that there is no other solution (applicable to research centres) that could fill in that need.

Moreover, 80% of participants thought that CMF could be used as diagnostics and capability evaluation tool at a research centre in the future. The aim of research centres is to 'deliver innovation and access breakthrough technologies' (High Value Manufacturing Catapult , 2020). For that reason, research centres need to have their own framework that supports maturity process of TCs. It means that CMF can be used as an internal tool to support a research centre's capability development.

Additionally, 62% agreed that CMF and Capability Maturity Levels (CML) offer identification of skills gap, which is very important as it feeds into technological gaps. Thus, being able to identify missing skills or skills gap offers the transparency of (available and missing) capabilities. For example, if you do not have transparency to highlight TCs, then how can decision makers build their short and long term strategy? Identifying crucial skills means that jobs will be created for people with skills that are currently missing at a research centre, which might not have happened otherwise. That point is also supported by the following comments:

- *"We are hiring people who should not be hired- we are duplicating our skills- skills that we already have"' P100*
- *"Also people with core skills (that are needed) are rejected and people who supposed to have those skills – they don't have them in real life and so other people struggle because they do not have any support" P110*
- *"Business cases could be written based on CMF to support hiring people" P111*
- *"The problem is that we are always hiring the same type of engineers" P106*

Above comments show that there is duplication of skills, and the areas that are in a real need of support, are often neglected. It leads to overloaded personnel who does not get support they need, while other teams might not have enough projects to work on, as the same skills are duplicated and underutilised. It means that productivity is lower (for both teams) and the workload is not distributed evenly across a research centre. It could also lead to experts being overworked and not having time to contribute to new projects. It could also link to taking on projects that do not advance research centres' maturity. It means that certain TCs could stay at the same maturity level for a long time.

Furthermore, 74% of participants either strongly agreed or agreed that CMF provides clear understanding of capability maturity (i.e. research centre understands its own weaknesses and strengths) before taking on a project. CMF could be used to show that there are no capability gaps (for stronger and more mature capabilities) which could be used to reassure members or potential clients. When discussing future projects or strategy with members, results from CMF could be used to show which aspects (sub-dimensions) are weaker, and where the investment from members will go. Hence, members are kept on track and project leads will have a straightforward way to show how prepared they are for a new project. It would also be an easy way to explain how the investment is distributed, why investment needs to cover certain aspects (dimensions/sub-dimensions) and what benefits it will bring once the capability gaps are addressed.

Currently, there is no formal process that research centres can apply in order to justify that they have mature capabilities, i.e. they can meet industrial requirements. Hence, research centres refer to conversations between business development personnel and technical team members in order to find out if a research centre has specific capabilities. It is known (from observations) that such approach can lead to miscommunication and other issues later on. For example, those comments were captured while working at a research centre:

- *"Team members with programming skills were not the same people who had knowledge about specific material needed for the project i.e. it was difficult to organise time for them to work together. And so the situation caused issues like team members with programming skills did not know how to make the geometry correctly and they experience software problems"*
- *"The structure design did not work in the software at the centre and there was no other software to use. New software was too expensive to buy and 'old' software did not work in the way we wanted it to work"*

- *"Team member who was supposed to have experience in aerofoils, did not have the experience that was required for this project. He had expertise in analysing and repairing defects in that specific material, but did not have expertise in creating a new product 'from the scratch' using that particular material; i.e. different kind of expertise but in the same technical area" (JO and MOH*).

Miscommunications can happen, especially in a dynamic environment like research centre. However, some projects might leave customers disappointed and cost research centres more time and effort, as projects need to be completed. In addition, it costs the research centre its reputation and a relationship with company suffers. In order to avoid situations like that, an easy check through CMF will identify people with specific skills or software/machine that research centre never used. It is one of many reasons why a standardised process is needed for research centres. Research centres need 'a health check' before they commit to big projects or programmes to avoid issues reported above.

And so, 77% either agreed/strongly agreed that CMF is informative as it provides current capability levels and gaps and that CMF provides clear understanding of capability maturity at a research centre (supported by 74%). That links to 68% of participants who strongly agreed/agreed that CMF provides access to useful and detailed information regarding individuals, equipment and projects and it helps to understand relevant challenges. Results confirmed that access to relevant information is something that's lacking at the moment across research centre, as participants did not mention any other solution that they use. Also, having access to information about team members, equipment and projects will have positive impact as decision makers will be able to see any organisational or strategic challenges ahead. For example if a person with 25-30 years' experience is leaving, decision makers will be able to see which skills will disappear from the team. Therefore, decision makers will have time to identify key issues that need to be addressed. What is more, decision makers might not realise if there is enough people in the team to cover the workload left, and if the rest of the team is capable to complete the work left behind? Is there enough time to train someone to take cover some responsibilities? CMF will not provide answers to all those questions but it will definitely start an important discussion and it will highlight what aspects need to be addressed.

As P109 commented: "The biggest challenge to any organisation is not knowing what your capabilities are." Not knowing what technological gaps you have in your organisation means that you can never improve them. That is why 88% of participants either strongly agreed or agreed that research centre needs tools like Capability Maturity Framework to understand and improve their technological capabilities. Having a solution that highlights immature technological capabilities gives decision makes a chance to review those 'weakest' capabilities. CMF makes decisions makers aware of gaps, but also of strengths of various capabilities.

By not being aware, or not realising that certain capabilities struggle, the research centre will take longer time to grow. And while a research centre does not improve their technological capabilities, some other centre might be evolving quite quickly and – at the same time- offering better technological innovations to industry. Hence, ignoring neglecting technological gaps has significant consequences on development a research centre that needs to attract investments and funding.

Lastly, **79% of participants also recognised CMF support for technological planning and decision making** while **65% agreed that CMF could support operational planning and decision making**. As discussed previously, CMF was created to highlight technological gaps and help decision makers to understand those, plan and act. Even though, CMF does not offer much operational support, the majority of participants still thought that it is useful for operational decision making.

8.3.3 Research Question 3: Could a novel framework fill in the need for capability maturity framework ACROSS various manufacturing research centres?

The initial answer is yes- **CMF could fill in the need for capability maturity framework ACROSS various manufacturing research centres**, as overall feedback was positive. However, in order to fully evaluate if CMF fills in the need ACROSS HVMC network, a wider data pool would have to be collected and validated across all seven research centres. Also, some participants mentioned that "CMF could be a useful tool for internal development but not useful across HVMC" (P115). Therefore, further investigation is required to answer that research question. Nevertheless, it shows that there is a need for a standardised framework applicable to a network of research centres (as discussed initially in Chapter 4, Phase 1).

As one participant (P103) highlighted: "**a standard measure to distinguish between each [centre] will help companies identify catapults that have capabilities that best suit their needs**." Therefore, being able to demonstrate how mature technological capabilities are, will provide a new approach to communicate with industrial companies. By having standardised measure across HVM Catapults, it could help various companies decide if a Catapult suit their needs.

And so, **71% either strongly agreed/agreed CMF could become a standard tool to manage capability maturity across HVMC** (Q17). The majority of participants see the value of having one standardised solution across HVMC. However, some participants did not think that CMF could become that solution in the current version. Another positive finding was that no one disagreed with Q17. Also, no one mentioned that there's already a process/mechanism that is applied across all HVM Catapults, which means that CMF could become a standardised process across various research centres in the manufacturing sector.

Furthermore, **71% of participants either strongly agreed/agreed that CMF could help with transferring knowledge and building common strategy between HVM Catapults**. That also links to 56% of participants who strongly agreed/agreed that CMF will help with improving transparency between HVM Catapults. The majority of participants think that a standardised solution across HVMC could help with transferring knowledge and building common strategy. And so, it would help senior management of HVMC map mature and immature capabilities of each Catapult, as well as the whole network.

Even though each centre concentrates on its own strategy and vison, it does not have to mean that there is no collaboration between centres. Catapults with the same TCs, could be collaborating together to achieve common goal. That way they would (potentially) not only support relationships between Catapults, but also develop their own TCs. Consequently, it could lead to support at regional and sector level, which would impact Catapults that work together. Such collaboration could also result in creating more robust strategy for the HVMC network.

To sum up, above discussion provided evidence to Research Question 3: Could a novel framework fill in the need for capability maturity framework ACROSS various manufacturing research centres?

8.3.4 Summary of answers to Research Questions

Summary of answers related to Research Questions are presented in Table 8.3. Those summaries are based on discussions from section 8.3.1, 8.3.2 and 8.3.3.

Table 8.3: Summary of answers to Research Questions

Section	#	Research question
8.3.1	RQ 1	Is there a need for capability maturity framework applicable to manufacturing research centres?
		Yes, there is a need for a capability maturity framework applicable to manufacturing research centres. The lack of research dedicated to research centres and their capability management left a gap that has not been addressed before.
8.3.2	RQ 2	Could a novel framework fill in the need for capability maturity framework at manufacturing research centres?
		Yes, CMF could fill in the need for capability maturity framework at manufacturing research centres. Overall feedback about CMF was positive, and even though participants expressed some concerns- those comments create a basis for future work that will only improve CMF.
8.3.3	RQ 3	Could a novel framework fill in the need for capability maturity framework across various manufacturing research centres?
		Yes, CMF could fill in the need for capability maturity framework ACROSS various manufacturing research centres, as overall feedback about CMF was positive. However, in order to fully evaluate if CMF fills in the need ACROSS HVMC network, a wider data pool would have to be collected and validated across all seven research centres. Therefore, further investigation is required to answer that research question.

8.4 Industrial/Managerial Contribution

First of all, 91% of participants either strongly agreed or agreed CMF supports identification and management of technological gaps in the research centre. As P100 mentioned: "We need to deliver programmes, not overpromise."

It often happens that before project starts, research centres overpromise, before checking and making sure that certain things will be delivered in a specific timeframe. Because some decision makers might think that research centre is excellent in every technological capability, they overpromise. That is when the challenges start for technical teams who need to deliver projects.

Sometimes it also happens because engineers are overconfident and commit to something that they should not. Hence, those situations should not take place and requirements of each project should be checked. That will provide an alignment between 'what is required' and 'what research centre can do'. That will eliminate overpromising, and even non-technical managers will be able to know if research centre can confidently deliver future projects. And so, CMF can help with mapping current capabilities of a research centre.

Secondly, 83% of participants strongly agreed/agreed that the CMF structure is a good representation of a research centre's capabilities. Some participants expressed an opinion that CMF should only concentrate on people. However, without knowing what machine a research centre has or what is the level of understanding of each machine- the true representation would not be complete. Also, having information about projects' outcomes, project management aspects etc. helps with understanding if support from project/programme management is needed. Therefore, the current structure of CMF indicates 3 most important dimensions of research centres and its environment, which could be referred to as tangible resources e.g. (McKelvie & Davidsson, 2009), (Liu, et al., 2019)) (discussed in Chapter 2). However, CMF also concentrates on intangible resources ((Qi, et al., 2020), (Chavez, et al., 2017), (Hitt, et al., 2016)) in order to capture maturity of TC at a research centre (i.e. the 9 sub-dimensions). Thus, CMF structure captures both tangible (dimensions) and intangible (sub-dimensions) resources.

The above argument links to another result from Chapter 7: CMF provides an appropriate amount of detail to identify capability related gaps (supported by 68%). As previously mentioned: if the structure had less sub-dimensions- it would have shown information related only to one dimension (i.e. not all aspects would have been included). If it had more sub-dimensions, it would have been more complex and more time consuming to complete. Also, having 3 dimensions and 9 sub-dimensions seems logical to participants, i.e. participants expressed supportive comments regarding how CMF is structured and how CMLs are calculated:

- *I can see what you are trying to do, I can see the logic* P101
- *I like the structure and the logic – it's repeatable and that's very important* P109
- *I understood the process, the logic, the maths and structure* P117

It is also worth highlighting that participants did not leave any negative comments regarding this question. Additionally, the biggest advantage of CMF process is that it is repeatable as it is based on vector equation. The calculations take away the subjectivity and deliver vector in 3D space (considering the 3 dimensions in CMF are used as 3 dimensions in xyz plane).

Furthermore, 97% of participants either strongly agreed/agreed that a research centre will benefit from using CMF by understanding gaps and strengths/weaknesses of a research centre (e.g. in relation to skills, experience, application of various machines/software etc.). That links also to 88% of participants who strongly agreed/agreed that CMF process will be helpful when considering future investment/manpower decisions.

Thus, the above results show that participants recognised CMF functionality and its benefits. Those results show a strong support from participants (from various background) and that this functionality is needed (as is the need for a solution like CMF). That is also connected to results presented in section 7.3, where most solutions (that participants are using currently) are documents like individual performance reviews, excel data sheets, historical data and so. This confirms lack of dedicated database but also lack of formal process that results in highlighted technological gaps and maturity levels of TCs.

In addition, 71% either strongly agreed/agreed that results from CMF provided a strong foundation for strategy building at the research centre. One participant (P100) mentioned that CMF "has anything to do with strategy building - that comes from listening to industry and responding to that." That is partially true: in order to response to industrial needs, decision makers need to know how they can respond and if they have technological capabilities to do so. In other words, they need to know how mature their capabilities are before committing to industrial projects.
Therefore, CMF could help to identify where technological gaps are and start a conversation about why certain capabilities have lower maturity. Decision makers will need to understand which capabilities need investment and how it will be spent. Certain capabilities could benefit from investment by hiring more people with specific skills or equipment that will bring more work. What is more, P117 mentioned that "CMF is a great tool to show where the investment should go." Another participant (P111) also mentioned: "the centre will have areas of expertise that they want to maintain or evolve or degrade- they need to decide but they need to know."

More importantly, 81% either agreed/strongly agreed that CMF and TRL-like processes could complement each other (CMF covering what research centre can do, and TRL what product/service needs to be delivered). Therefore, by having two frameworks it is now possible to address the needs of research centres as well as industrial needs.

Industrial solutions concentre on product or service that needs to be delivered in a specific context and environment, i.e. it needs to reach a readiness level. However, those approaches do not evaluate capabilities and their maturity to deliver such product/service. They concentrate of a development of a product/service in a specific timeframe but they do not ask the question 'do we have mature capabilities that can deliver the product?' Hence, when reviewing if a product is ready for next stage of development, the information relates to what tasks still need to be completed, redone etc. but there is no indication if there are capabilities that can complete that process.

What is also important is that maturity is more applicable to research centres, as discussed in Chapter 4. That aspect was also published in the literature (Uflewska, et al., 2017), (Ward, et al., 2017), which added evidence to conversation around research centres' needs and work, and, most importantly, lack of suitable framework. CMF addresses maturity of TC but at the same time, the results show weak and strong capabilities across a centre, i.e. mature and immature capabilities needed to develop new product/service.

Therefore, maturity answers the question 'can we do that?' and readiness refers to industrial product/service and how ready it is for a specific application. Hence, maturity of TCs is more relevant to research centres, and readiness - to industrial application ((Uflewska, et al., 2017), (Machado, et al., 2017), (Ifran, et al., 2019), (Silva, et al., 2019), (Tetlay & John, 2009), (NDA, 2014), (Seablom & Lemmerman, 2012)). Thus, two approaches are needed to support successful delivery of innovation: one that concentrates on maturity concept in research centres, and the other one- on readiness and industrial applications.

To sum up, understanding internal TCs is a big part of building strategy but also managing TC at a research centre. Last year especially showed that as we all have been affected by drastic changes caused by Covid-19 pandemic. The pandemic demonstrated how quickly things can change in any sector or organisation. Hence, in order to react to such changes, decision makers need to know maturity level of their TCs. That way they will know how they can support different sectors or companies. It also helps with knowing which TCs are immature and can only support lower levels of development. Either way, by understanding current level of TCs, senior management will be able to create resilient and adaptable research centre. On the other hand, there is always a risk that current capabilities might not be needed in the future. Hence, research centres cannot operate in their own bubbles, i.e. being separated from new global drivers. That is why it is important to understand current capabilities and plan how to apply them in the future manufacturing environment.

8.5 Future control/review mechanism

This section concentrates on participants' comments regarding future control/review mechanism. Two questions were asked (in Survey 1) about future review of CMF results. Those questions, and answers, are presented in Table 8.4.

Table 8.4: Answers to Q31 and Q32 from Survey 1

	*Q31 S1		**Q32 S1	
Answer	Frequency	%	Frequency	%
Strongly Agree	4	12%	7	21%
Agree	8	24%	15	44%
Disagree	4	12%	1	3%
Strongly Disagree	2	6%	1	3%
Don't Know	3	9%	1	3%
Other	9	26%	5	15%
No answer	4	12%	4	12%

*Q31 S1: Data in the Capability Maturity Framework can only be input by team leads or senior management personnel to protect results from any 'data manipulation'

**Q32 S1: In the future, results should be reviewed by senior management or technical director to ensure participants provided objective information

36% of participants strongly agreed/agreed with Q31. However, 18% either disagreed or strongly disagreed. Also 9% selected 'Don't Know', while 12% did not provide any answer. Additionally, 26% chose 'Other.'

Regarding Q32 S1, 65% of participants either strongly agreed or agreed with Q32, and only 6% either disagreed or strongly disagreed. Also, 3% selected 'Don't Know', and 15% - 'Other,' while 12% did not provide any answer. Those who selected 'Other' to both questions, provided comments which are presented by Table 8.5.

Table 8.5: Comments related to Q31 and Q32 from Survey 1

*Q31 S1		**Q32 S1	
Participant	Comment	Participant	Comment
P106	Unfortunately their opinion is very often biased and not objective	P106	Will they have enough time and capabilities to check the level of objectivity?
P111	This implies a degree of distrust for those not in management roles. I would suggest that the solution is not based on seniority, but rather on peer-review based validation of input data	P111	This implies a degree of distrust for those not in management roles. I would suggest that the solution is not based on seniority, but rather on peer-review based validation of input data
P13	Needs to someone that is responsible for integrity, understanding requirement and refreshing data	P13	Needs to be reviewed with group that meets your objective, this is time dependant as next year/month it might be that Directors are right audience
P122	This is the most critical aspect of the whole process-the quality of data input. And so that needs to be defined. How this level should be defined I could not say, but see huge importance of that	P122	Again, I see this as the most critical issue. The 'crux' being the management
P126	I think that for the people, data could be discussed during the ADR process. If someone move from one team to another the "new" team lead might not know all capacity of the new team member	P121	Without understanding properly the criteria on which a participants enters data it is difficult to decide how objective their answers are likely to be
P119	The data must be collected from multiple sources. However, smart mechanisms for data capture must be developed	P109	There should be a bigger forum that combines team leads and senior management and together –during that forum – they could go through the results and review them together
P108	Data should be in dynamics, let's not create duplication of effort. it should be controlled by line managers		
P118	Agreed but there must then be a consistent way of making assessments i.e. criteria to assess qualifications and experience that leave no room for ambiguity		
P123	if this is the case then it may be more objective		

*Q31 S1: Data in the Capability Maturity Framework can only be input by team leads or senior management personnel to protect results from any 'data manipulation'

**Q32 S1: In the future, results should be reviewed by senior management or technical director to ensure participants provided objective information

As seen in Table 8.5 many participants provided concerns or suggestions regarding how to make sure that gathered by CMF process are reliable. Another challenges captured during validation process was the fact that 'there *are also conflicts between supervisor and team members, so team lead have a conflict with someone and might score them lower – for that reason we need independent review' P110*. One participants also suggested that everyone in the team should input their data, e.g. using '*the approach University of Strathclyde is taking with Engineering 360 degrees- we could do something like that so CMF it would require everyone filling out the form; so everyone would need to fill in your datasheet and then you would take a sort of average from all data'* P117.

Therefore, it is clear that inputs of accurate data is important (which was already discussed in section 8.4). However, in order to avoid any irregularities, a control mechanism needs to be reliable.

Majority of participants mentioned that CMF needs a control mechanism in order to verify results in the future. However, participants provided different ideas about how that process should look like. Table 8.6 below presents comments from participants about control mechanism.

Table 8.6: Comments related to control/review mechanism

Participant	Quotes
P100	*senior management needs to review it*
P107	*It would be good to have independent auditor who could go through data – then it would be objective; Someone from outside completely. Independent auditor would ask for evidence to support data e.g. if we scored ourselves as 7 or 8- they would ask for evidence of that*
P107	*Review by senior management would be good as well*
P107	*So there could be 2 levels of review: internal and external; But independent assessment would be really useful*
P109	*Peer review assessment will be needed for the organisational element so for example reviewers sit together so that would be a sort of collective review- That would be an opportunity for discussion and it would provide better input. The collective review would bring this additional context so that a group will reach a consensus*
P109	*People who could be involve in such review would be: people responsible for teams so team leads and senior management e.g. research director (as it is their responsibility to describe our capability) + other senior personnel like key internal stakeholders like COO e.g. Sarah, Helen, Iain etc. Or maybe technical people too?*
P109	*Owners of capabilities and senior management should be involved*
P110	*Independent review with external experts- that would be good or like in linked in – you get reviewed by community/across community- here you could also get reviewed by a community of external experts*
P110	*Also- no one checks the technical outputs – so how do we know that this is good*
P116	*As per above – do you have an idea of error bands? Given the subjectivity of scoring – is a project which scores 28.28 vs one that scores 32.92 really over 20% worse (5 vs. 7)? Will be hard to adapt for this but how to maybe "sign off" this data to ensure correct conclusions are being drawn?*
P117	*Not sure if senior management could review it properly*
P117	*There should be a review process added by someone who worked with people who are evaluated on a project or in some past activities*
P111	*Senior management/management needs to control the input*
P111	*Management team needs to be careful about undermining trust in the team - because then management might just use the tool without sharing it, so there is no transparency or they will share it but they might not trust the results (if they don't trust the team)- need to be careful about the terminology*
Q13S2 P109	*Due to the initial subjective nature of the assessment, the accuracy of the data could vary significantly. There needs to be appropriate checks and balances to ensure rigorous evaluation of data before it is entered into the CMF.*
Q37S1 P103	*Further work would need conducted - it is an ideal tool to benchmark your own capabilities but each research centre is slightly different so using it as a standardised tool across multiple centres would require more work… how do you standardise a capability? Does a technology mean something slightly different at a different centre? Who fills the CMF out to prevent bias?*

Using information from Table 8.6, four main suggestions were identified:

- Review by senior management
- Review independent auditor

- Peer review assessment
- Two-level-review: internal and external

As not everybody was persuaded that senior management would review the results properly, it seems that the best approach here is **to have 2-level review: internal and external**. That approach could be transformed into **a so-called gated review process** that is sometimes used in industry. In some companies, reviewers are not directly connected to the project they are reviewing (in order to avoid bias).

However, in a research centre environment it might be hard to find person not directly involved with project (as research centres are often much smaller then industrial companies). In that case, **independent reviewer should be introduced into the process**. It could be someone from HVMC network (e.g. nominated by HVMC senior management team). In that case, evidence and justification explain why each TCs achieved specific CML would need to be provided. Figure 8.1 below presents possible review process, which also includes outcomes of gated review process performed by an independent auditor (Review Stage 2). Once independent reviewer(s) go through the data and justifications presented, they can recommend

- no or minor actions,
- actions recommended (that do not have to be immediately completed but could cause issues in the future, if not completed)
- Immediate actions that need attention from senior management.

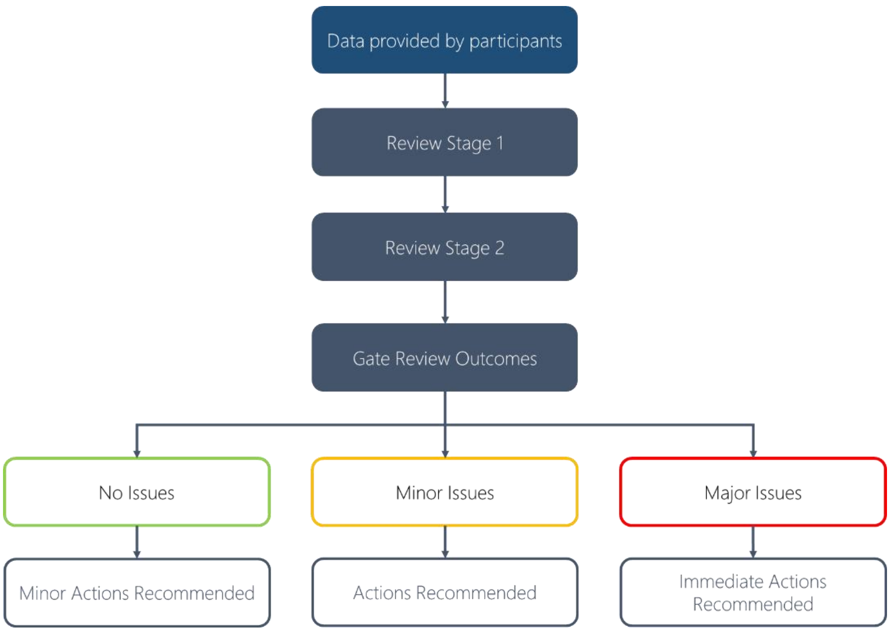


Figure 8.1: Proposed Review process/Control mechanism

8.6 Implementation of CMF

Table 8.7 presents comments provided by participants when asked what steps should be applied in order to adopt CMF. All comments were allocated into one (out of 4) categories: Implementation steps, Concern, Connect CMF with research centre's goals, Support from the centre. One participants did not suggest anything as they considered themselves "not qualified to answer" (P120). Also one participants expressed concern regarding structure of CMF. However this topic was previously discussed in Chapter 7.

Table 8.7: Answers to Q41 S2: In your opinion, what steps research centre could implement in order to adopt the CMF?

Participant	Comment/Quote	Category
P100	*Needs to be validated against a number of completed projects.*	Implementation steps
P102	*CMF is very good. In two minds whether combining people, equipment and projects is right approach*	Concern
P103	*Trial assessment. Review/validation/verification. Feasibility roll-out. Review. Implementation.*	Implementation steps
P107	*The centre needs a business model with clear goals and values to allow CMF to feed into*	Connect CMF with research centre's goals
P108	*An annual or biannual assessment of capability. alignment with strategic roadmaps*	Connect CMF with research centre's goals
P109	*Training & buy in from managers*	Support from the centre
P110	*Embed data collection and update into an annual / bi-annual process. Data external verification*	Implementation steps
P13	*Needs to be part of road mapping process.*	Connect CMF with research centre's goals
P114	*There should be webinar, case study with each team and data updated every year to maintain standard*	Implementation steps
P115	*someone to maintain it; I remain to be convinced I'm afraid, would need to know it was going to be maintained and supported not just thrown at the team / theme leads to populate in isolation*	Implementation steps
P116	*Every year have a 360 approach review of capability in the centre, a continuous improvement exercise*	Connect CMF with research centre's goals
P103	*CMF needs buy in from all levels of the business*	Support from the centre
P104	*Looks like a good start, I think it needs to be regularly reviewed*	Implementation steps
P120	*Not qualified to answer.*	-
P116	*Could report to steering board as a way to ensure it is updated/questioned.*	Support from the centre
P114	*It needs more demonstration first*	Implementation steps
P131	*Senior Management approval & Using the CMF in a regular basis for example every year*	Support from the centre
P125	*It would need widespread adoption to be effective*	Implementation steps
P121	*You would need broader set of use case examples that incorporates other HVMC centres*	Implementation steps
P120	*People may not take part willingly / correctly.*	Support from the centre

Therefore, comments from Table 8.7 will be discussed in the following order: Support from the centre, Connect CMF with research centre's goals, Implementation steps. However, before implementation steps are discussed, obstacles regarding implementation should be first highlighted.

8.6.1 Obstacles towards CMF implementation

At various points of this research, participants mentioned different obstacles that need to be considered before CMF is implemented in a research centre environment. For example

- gamification (Chapter 4, Chapter 7), e.g. as any system might be sensitive to manipulation of data;
- Concerns about data input: (P110) mentioned that data could be also manipulated by team leads, e.g. if they had a fight with some other team members or fi they don't like them- they would input false data, and that senior management does not know if the results will be true or not;
- Time and effort needed to provided data into CMF

The first two concerts were already addressed in section 8.5: Future control mechanism. It explains an idea of two-stage formal review process that eliminates gamification as well as any subjectiveness in review process.

The last comments suggests that simplification of CMF might be needed (all relevant comments are included in Table A11 in Appendix 24). However, it should be highlighted that data collection for each TC took between 1-2 hours per person who provided data. That was the only aspect when participants (TC leads) had to dedicate time and effort to CMF.

Some participants assumed that CMF process looked highly intensive as it a lot of information was included in three presentations that participants went through during validation process. Hence, it might not have been clear that the only effort required is from TC leads to provide initial data. In order to make it clear to new users, an explanation will be added at the beginning of the CMF process, so that users are not overwhelmed with the amount of information (and to avoid any confusion of what is required from new users).

The rest of CMF process will be managed by an objective person dedicated by centre lead (i.e. CMF champion). CMF champion will then calculate CML using data provided. That is also not time consuming as a template for calculations (including saved equations in MS Excel) already exists and can be replicated.

Moreover, moving CMF into a digital environment (e.g. making a CMF a cloud based tool) would add simplification to the whole process. Next section described future work regarding digital improvements of CMF.

8.6.2 Support from the centre

In order to successfully implement CMF to any research centre, senior management team needs to support CMF. It will influence how managers and team leads react to new framework, but it will also have an impact on how quickly teams start to use CMF. Hence, a "buy in from all levels" (P101, P103) is very important. Otherwise there is a threat that "people may not take part willingly / correctly" (P120). That is why senior management team needs to be 100% involved in CMF introduction and communicate that clearly to all teams.

(Ferradaz, et al., 2020) highlighted importance of senior management commitment by mentioning that "the cultural shift, thus, must come from top management and **should diffuse throughout all organizational levels**. It is imperative to point out that evolution happens optimally with commitment. It is top management assignment **the dissolution of behavioural and cultural barriers**, and **transmits the goals' significance** so employees can understand the relevance of changes either perceive their role in the endeavour." If there is a clear support from centre's leadership group, e.g. leadership group asked for results to be delivered through CMF – there is a higher possibility that teams will start using CMF (and not refer to their 'old, familiar ways' of presenting information- as some people prefer to use outdated solutions even if they are ineffective).

As suggested by one participant (P108), there is a threat that CMF "will get a lot of resistance though if it is not done with sufficient support as the current structure means people are very busy and won't have time or motivation to learn it". That is why "Senior Management approval & Using the CMF in a regular basis for example every year" (P131) is an extremely important aspect of CMF implementation in any research centre. Without that support, the implementation process will be much longer and results will not be delivered for every TC (i.e. there will be missing data, which does not increase reliability of CMF).

On the other hand, senior management might decide that the best way to introduce CMF is to incorporate it into annual performance review. That way data from each TC would be collected as part of a formal (and broader) process. That idea is discussed further in Chapter 9 (part of section 9.5 New areas of research investigation).

8.6.3 Connect CMF with research centre's goals

The second important aspect **is to connect CMF with research centre's goals**. As suggested by (P119) *"the centre needs a business model with clear goals and values to allow CMF to feed into."* Hence, by having clear goals, and by communicating them to all teams across research centre, it will be much easier to understand what needs to be achieved in a specific time frame. Having a clear goal would then support decisions that need to be taken now (in order to work towards this goal).

One solution would be to visualise those steps thorough a roadmapping process (P13). **In a roadmap, current capability gaps can be illustrated and linked to next steps**. Hence, decision makers will have an overview of how capability gaps could affect next steps in their strategy. Those roadmaps could be reviewed annually or bi-annually (P115), or even more often if that what's decision makers need. However, it should be highlighted that **results delivered by CMF can be fed into a roadmapping process and connect to research centre's goals.**

Therefore, relationships between dimensions and sub-dimensions of capabilities (depending on level of detail decision makers would like to access) will be visualise with current and planned projects. What is more, immature capabilities could be highlighted in different colours to differentiate them from other items on a roadmap. Visualisation like that could be helpful not only to senior management but also to programme managers who need support from several TCs to complete a programme.

Some advanced roadmapping tools (e.g. SharpCloud) offer to 'dive into' each item presented in a roadmap. Thus, users can click on each item and find out more about it, e.g. what maturity particular TC has now, what maturity it would need to achieve to support specific projects. For instance, Figure 8.2 (a) shows industrial requirement titled 'Augment reality' that needs to be scaled up from TRL 3 to 5. As an example Digital Visualisation TC is selected here to show how results from CMF can be implemented into a roadmapping process.

Let's assume that Augmented Reality is now at TRL 3, and Digital Visualisation at CML 4. Let's also assume that we want to achieve TRL 5 for Augmented Reality, which required Digital Visualisation to reach CML 6. By clicking on Digital Visualisation tab, it would take a user into another (more detailed) roadmap dedicated only to this TC. And so, Figure 8.2 (b) shows where TC is now (i.e. what is the sub-dimensional maturity level of all sub-dimensions that support this TC) - represented by a blue colour. It also shows how this TC could achieve CML 6 needed to support Augmented Reality requirement, represented by a green colour in Figure 8.2 (b).

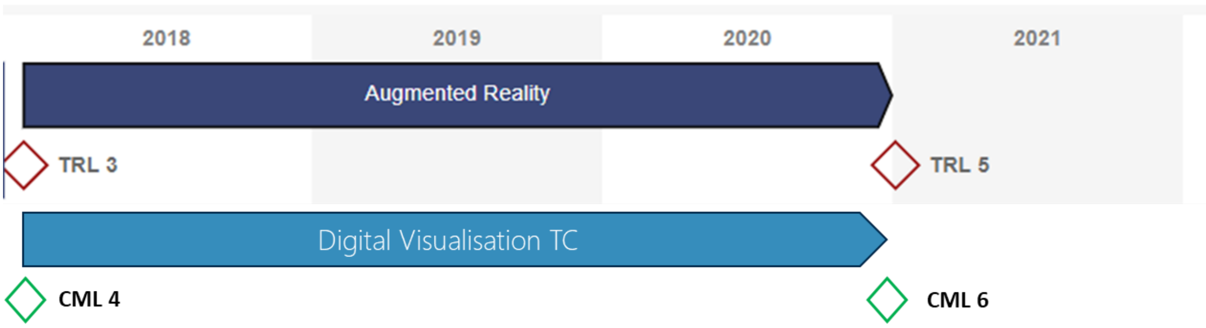


Figure 8.2 (a): How CMF can support roadmapping process

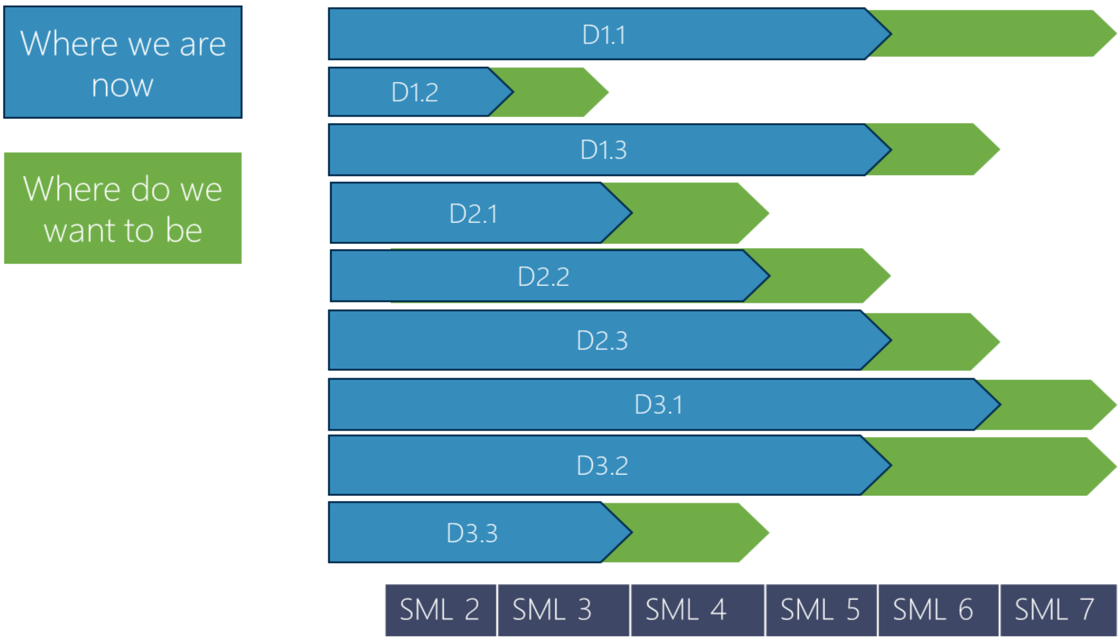


Figure 8.2 (b): How sub-dimensions of a TC can be represented in a roadmap

Figures 8.2 (a) and (b) show that it is possible to add target level of a specific sub-dimension into a roadmap. It will help visualise where TC is at the moment, and where senior management team would like to be in the future. That could help visualise gaps in recruitment or where the investment is needed. Having visual representation of capability gaps would be helpful when planning long-term strategy and making sure appropriate steps are taken to achieve research centre's vison.

It also should be noted, that maturity is more relevant to research centres than readiness (as discussed in Chapter 4). And so the visualisation of CMF sub-dimensions, as presented in Figure 8.2, refer to maturity of specific capability at a research centre. However, CMF will provide answers to decision makers who will be able to identify if TC can scale up Augmented Reality to TRL 5.

8.6.4 Implementation steps

According to (Kosiedzka, 2017) "uncoordinated implementation of different concepts also often leads to failure." That is why it is very important that the implementation of CMF is well-planned and thought through before the real-life implementation happens. This sections offers a 9 step implantation plan of CMF.

Assuming that communication with senior management team will guarantee support for CMF, it means that clear message needs to be communicated to all teams. Firstly, communication to team and TC leads must happen. The purpose and benefits need to be clearly presented to those stakeholders.

Once that step is successfully, message can be communicated further to all team members. It could be through one 'all staff' session, or it could be more helpful to organise several sessions for each team or TC. People will be more likely to ask questions in smaller groups and they usually feel more comfortable to speak out when they are with their colleagues (instead of during all centre meeting). All concerns can be captured during those smaller sessions, and (if there's enough time) answered, or continued in an offline session.

Once CMF has been introduced to everyone, and it is accessible to users, a webinar will be organised to familiarise users with CMF. P114 suggested that "*There should be webinar, case study with each team and data updated every year to maintain standard*". Hence, there could be an example created for each team, so that they can replay it any time help is needed.

Also, once users had time to access CMF and familiarize themselves with the basics, an online workshop will be organised to make sure users know how to access all necessary areas of CMF. If one workshop is not enough, again, multiple workshops will be organised in order to support all users.

Lastly, drop in sessions will be organised on a regular basis for everyone who is interested. It is possible that more than one person will struggle with the same problem, so regular drop in sessions would benefit users who know basics but struggle with something specific when using CMF.

However, the idea is that users will only need to provide data and view the results, as all calculations will be performed automatically. The idea is that CMF becomes as user friendly as possible.

It is very important to communicate clear message to all users and provide necessary support because CMF implementation will not be successful if it is *"just thrown at the team / theme leads to populate in isolation"* (P115).That is why **a CMF champion needs to be nominated to monitor and maintain CMF after implementation is completed**. Therefore, there needs to be a CMF champion who will **provide guidance and support** to anyone who needs to use CMF at any time. It will also mean that any problems, that users might have, will be documented on a regular basis. That will help in the event of CMF champion being unavailable.

Moreover, if CMF is moved to a digital environment, the maintenance of data will not require great effort. Just like with ADR- every information is put into online system, the same approach can work for CMF (as it already works for different online tools). Therefore, maintaining and making sure that everything is properly stored will be much easier. However, that aspect (i.e. digital transformation) is discussed in Chapter 9. All the steps described above are presented in Figure 8.3.

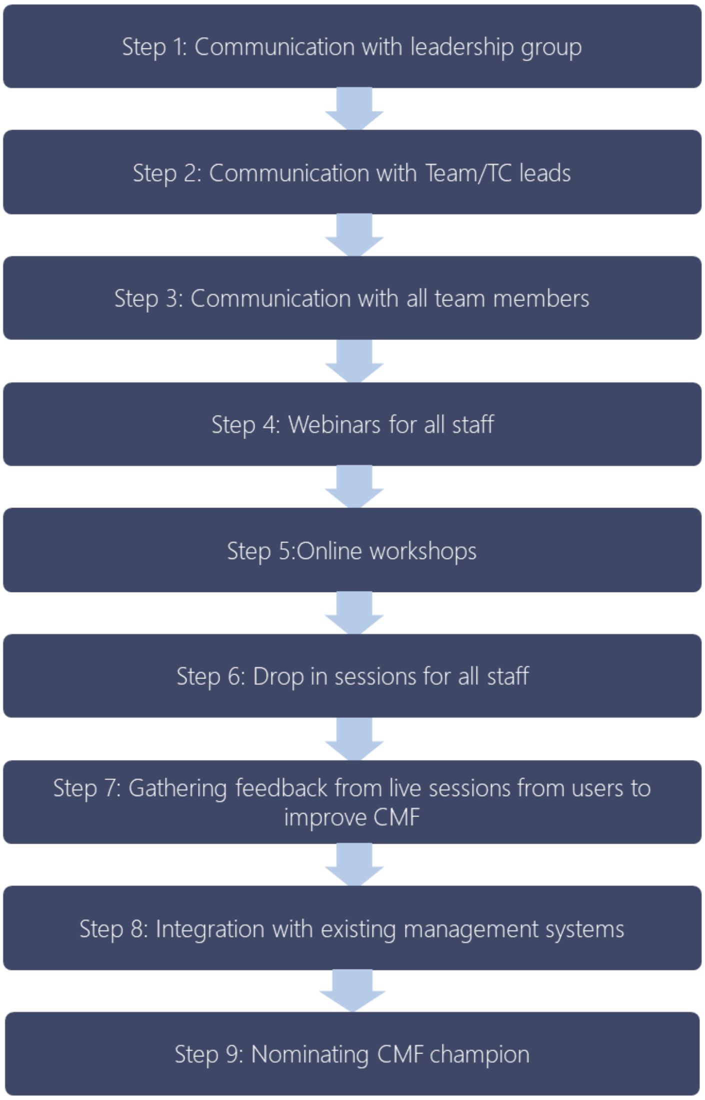


Figure 8.3: CMF implementation steps at an individual research centre

Above steps could be divided into 3 groups: **Communication** (Step 1-3), **Technical support** (Step 4-6) and **Integration with existing system** (Step 7-9). Those 3 aspects are presented in Figure 8.4. Apart from that, support from research centre (section 8.7.1) and alignment to research centres goals (section 8.7.2) are also needed to be considered.

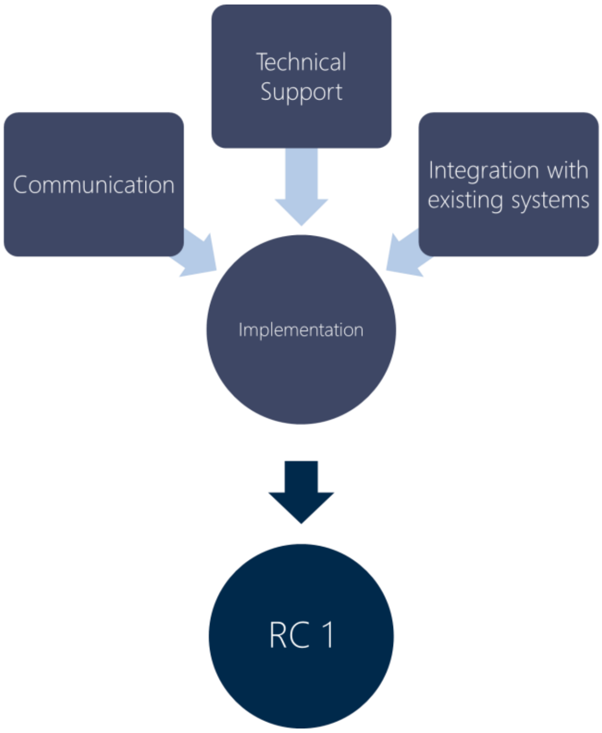


Figure 8.4: Three aspects of implementation at a research centres

Lastly, in order to understand how CMF works in a wider environment, implementation across HVMC would take place. The same steps (as described above) would be undertaken in each Catapult in order to allow testing of CMF in a broader environment. That will address the following comments: *"It would need widespread adoption to be effective"* (P125), *"you would need broader set of use case examples that incorporates other HVMC centres"* (P121).

It also means that **if one Catapult implements CMF successfully, it can share its lessons learnt with other Catapult.** That would speed up implementation process of CMF across HVMC. As P108 highlighted "Practicalities of implementing something like this are very challenging / demanding." However, as mentioned previously, with **well-defined implementation plan and support from senior management team**, it is possible to implement CMF (or in fact any new solution). Hence, the same steps introduced by Figure 8.3 and 8.4 would need to be applied across HVMC.

8.7 Summary

This chapter presented academic contributions of this research along with evidence supporting the three research questions. Using results from validation process, the need for a capability maturity framework was identified and developed to address the gap regarding capability measurements in research centres. As discussed before (in Chapter 2), it is difficult to create an optimised solution if there is not enough information in the literature about research centres and how they operate, or even how they are defined.

Section 8.4 discussed managerial contributions, i.e. how CMF can be helpful in a research centre environment (i.e. benefits of CMF).

On the other hand, issues identified during validation process were also discussed

- Control/review mechanism (section 8.5)
- Challenges of implementation of CMF (section 8.6)

It is worth highlighting, that even though sections 8.5-8.6 mentioned issues identified during validation process, solutions to address those issues were also proposed in those sections.

Moreover, implementation is a challenging step and it will depend highly on senior management (as it is the case with any new framework/software). However, by highlighting implementation steps (section 8.6) and identifying potential obstacles related to CMF roll-out, section 8.6 discussed how some of the concerns can be addressed (e.g. by getting support from research centre, connecting CMF and research centre's goals). Also section 8.6, presented step-by-step plan of how CMF could be implemented.

CMF summarises a number of underlying questions that research centres' managers and technical leads can use to support and reflect on their technological challenges to deliver innovation and create value proposition. By understanding research centre's unmet needs and challenges, research centre can use CMF to plan and manage a technological capability development using internal solution to access all required information.

Even though, it seems that CMF is more applicable to individual research centres (than a whole network), CMF provides a good foundation for capturing capability maturity across multiple research centres. It is believed that successful implementation at one research centre will demonstrate the CMF potential and benefits, which will motivate the implementation of CMF across HVMC.

Chapter 9: Future Work

9.1 Introduction

Comments gathered through Survey 1 and 2, as well as follow-up discussions with participants led to suggestions for future work. This chapter is divided into the following sections:

- 9.2 Definitions
- 9.3 Risk and recommendations
- 9.4 Validation process
- 9.5 New areas of research
- 9.6 Additional Comments

Above sections describe future activities that will help with improving overall user experience of CMF. Participants' comments also captured how validation process could also be improved for the future.

9.2 Definitions

Even though some participants highlighted that "methodology is sound and logical" (Q43 S2 P117), the concerns about subjectivity of data needs to be addressed.

According to (Kosiedzka, 2017), "a certain degree of subjectivity can be observed in the responses depending on the management level, years of service, experience and the level of familiarity with all the concepts at hand. For example, respondents in senior management positions had a more strategic perspective." **Therefore, the first step is to eliminate that degree of subjectivity**, so that data collection process is clear to those that input information and those who need to review the results.

All comments regarding changes to definitions are presented in Table A12 in Appendix 25, and they include feedback from participants who selected 'Other' in Q15 S2 and Q19 S2. However, comments from Table A3 can be categories into three future activates:

- Make definitions more direct and clearer; it will eliminate any vagueness that leaves them open to interpretation.
- Potentially change number of Capability Maturity Levels (e.g. instead of 9 change them to 7 or 5).
- Provide clear instructions to reviewers (during future validation process) on how definitions (and their equivalent numerical indicator) were assigned, i.e. add explanation saying that all bullet points from each definition (for each CML) need to be 'ticked/checked' in order to achieve that specific CML.

It is proposed that changes are applied to definitions of CML that caused concern during validation process. One suggestion was that definitions should be as precise as possible (i.e. definitions should be 'dehumanised'), for example definitions would include numerical limits so that it is easier to justify why a participants had select certain definitions. Hence

- Definitions would include experience 0-1 year, 1-3, years etc.
- Definitions would specify if the expertise was academic or industrial
- Definitions specify if the knowledge regarding certain process was used in the last 1-2 year, 2-5 years, 5-10 years etc.
- Definitions would specify if someone worked as project lead/team lead (i.e. is that person experienced in training others)

The same changes will apply to equipment and projects. **Including more quantitative definitions would eliminate vagueness and in result CML definitions will not be open to interpretation**. Every participants will be clear while reading definitions, and/or when going through results. In addition, making definitions more quantitative will eliminate bias and provide objective results.

9.3 Risk and recommendations

Considering results presented in Chapter 7, it was concluded that further investigation regarding risk and recommendations is needed. Even tough, questions related to risk and recommendations received positive answers, some of the participants suggested that those two aspects could be improved. Participants' feedback is included in Table 9.1.

Table 9.1: Comments from participants related to risk and recommendations

Question/Participant	Comments
Q16 S2 P109	*As an initial study, they appear to provide useful indications*
Q17 S2 P111	*While the process appears objective and auditable/repeatable, the input data remains subjective*
Q17 S2 P109	*I think that there are some areas that do not appear to reflect reality - e.g. Additive judged to be level 6, yet is still an emerging technology globally; Material Testing level 5, yet this is a very well established set of technologies, and one that the AFRC is considered to be a leader in the HVMC. This confirms my earlier statements on voracity of initial assessment data*
Q17 S2 P105	*Will need to look into the input results further*
Q17 S2 P108	*indicative rather than accurate I would suggest*
Q22 S2 P109	*Complex*
Q22 S2 P100	*To be honest I got confused here - needs to be explained better, not sure what is trying to be achieved*
Q22 S2 P106	*I don't agree with it*
Q22 S2 P121	*Feels like risk needs another element of narrative based criteria that alludes to the consequence factor of say a very high risk?*
Q30 S2 P111	*Care must be taken to ensure the detail of outputs does not artificially exceed the level of granularity of input and analysis. I would be concerned if in the early stages, this moved from decision support to decision making tool.*
Q30 S2 P103	*Sorry don't understand the qu… i think the cmf gives a good level of detail. I think more outside this will make it overwhelming*

Some of the comments in Table 9.1 did not focus on the questions asked, but on other aspects that were discussed before in Chapter 8 (e.g. inputs and subjectivity of inputs). As those issues were discussed already, they will be discussed here again. In addition, it should be highlighted that participants only had a chance to see recommendations for one TC, and not for all TCs analysed during this project. Therefore, to gain better understanding on recommendations as well as risk, further investigation is suggested.

9.4 Validation process

When asked about the validation process, participants highlighted three things: transparency, number of data points and normalisation of the process. Table 9.2 below shows relevant comments left by participants.

Table 9.2: Aspects needing improvements (in regards to validation process)

	Participants' comments	
Transparency	(1) *I think that the subject of transparency of data collection is challenging, and that the process described is a good start for sure, but it will first require practical implementation, then focussed continuous improvement activities to refine* P109 (Q33 S1)	(2) *I agree, however the human factor is still in place when you enter data. May be better to have the team lead and someone external to the team, but who has a knowledge of the centre/people, to fill the information* P126 (Q33 S1)
Small number of data points	(3) *How the data was collected as transparent. However, the collection method is flawed as it relies on too few data collection points* P119 (Q34 S1)	(4) *more data, hopefully you will get the chance to get more data to fine-tune your CMF and CML charts* P112 (Q34 S1)
Other	(5) *You've said how it was done, but have you done any analysis of how to normalise responses? The psychology of how people respond differently to the same question will* P107(Q34 S1)	

Comment no 1 relates more to the implementation of CMF, and Comment no 2 refers to subjectivity of data (and introducing control mechanism to overcome that challenge)– both of those aspects were already discussed on Chapter 8, hence they will not be discussed here again.

Comment no 3 links back to the fact that data was collected only from those participants who wanted to contribute to this study. During data collection process (which lasted from August 2019 till January 2020), every Catapult centre was contacted and asked for participation, however, only few responses were collected. Due to the time constrain of this research, it was decided that research has to continue without other data collection points, which is considered a limitation of study.

On the other hand, wider data pool has its benefits as it would have helped with optimising CMF and CMLs (comment no 4). In order to avoid that in the future, a support from centre leads will be curtail to collect wider data.

Comment no 5 highlighted aspect that was out of scope of this project but could be something that is considered for future work i.e. the psychology of responders during validation process. That could be interesting study and could even expand involve Psychology Department to find out more about responsiveness of participants.

9.5 New areas of research investigation

Using participants' comments from various questions as well as follow-up sessions, Table 9.3 was created. All comments in Table 9.3 were grouped into the following six categories and each category is discussed below in the following sections:

- Section 9.5.1: Further optimisation
- Section 9.5.2: Alignment to market needs
- Section 9.5.3: Introduction of wider capability maturity process
- Section 9.5.4: Integration of CMF with existing management systems
- Section 9.5.5: Forecasting and financial analysis
- Section 9.5.6.: Digital transformation

Table 9.3: New areas of investigation based on this research

Participant	Comment/Quote	New Areas of Research
Q36S1 P112	*Hope this tool will be used efficiently by everyone. More feedback means more optimized tool.*	Further optimisation
Q36S1 P109	*People need to understand this tool is developmental, and will require use to feedback improvements.*	Further optimisation
Q36S1 P119	*I think though this needs much more complex and deeper data collection points. This is definitely the right route to progress forward with. The visualisation of the data and user experience should be created using principles of simplification*	Further optimisation
Q36S1 P118	*How to address the finer capability gaps to meet finer detail of market need fluctuations?*	Alignment to market needs
Q36S1 P101	*Further scope for HR use*	Integration of CMF with existing management systems
Q36S1 P132	*The tool needs to be user-friendly*	Digital transformation
Q37S1 P115	*Capability can be demonstrated for our slice of a tech area but the pie is often much larger*	Introduction of wider capability maturity process
Q37S1 P103	*Further work would need conducted - it is an ideal tool to benchmark your own capabilities but each research centre is slightly different so using it as a standardised tool across multiple centres would require more work… how do you standardise a capability? Does a technology mean something slightly different at a different centre? Who fills the CMF out to prevent bias?*	Further optimisation
Q40S2 P13	*Further standardising across framework needed but this will come with use.*	Further optimisation
Q40S2 P114	*Include actual performance of research centre in the framework*	Introduction of wider capability maturity process
Q42S2 P100	*Projects do not address the voice of the customer. CSQ (customer satisfaction questionnaire) does*	Integration of CMF with existing management systems
Q43S2 P115	*An assessment of technology penetration in to supply chain. How hard to get industry to adopt?*	Alignment to market needs
P111	*Forecasting- would that be possible to add into CMF?*	Forecasting and financial analysis

P100	*It would be useful as an interactive tool to assist in modelling investment decisions*	Forecasting and financial analysis
P133	*CMF is complex. Try to simplify to departmental level*	Introduction of wider capability maturity process

9.5.1 Further optimisation

As some of the participants mentioned, further development of CMF will involve gathering more data inputs. New feedback would help with standardising CMF, as well as considering other aspects that have not been mentioned by group of participants who contributed to this research.

In order to do that, HVM Catapults will be contacted again to take part in continuation of this research. Previous data collection took place between August 2019 and January 2020; a new data collection process could start as soon as possible. It will provide information about previously analysed TCs, and a new comparison between TCs' CML from 2019 and 2021 will be possible to calculate. That will give an overview of any new changes related to those TCs.

New data collection points could be used as reference points and could help with comparing results between different centres, for example if there will be a significant changes – a deeper analysis based on skills, equipment etc.

Wider data pool will also help with generalisation of the CMF methodology and it would be beneficial to identify if CMF works for all TCs across all HVM Catapults.

9.5.2 Alignment to market needs

Connection to market needs was considered out of the scope of this project. However, having information on how mature capabilities are (and where the gaps are) it could be helpful to link them with market drivers.

Once those market drivers are identified, mapping between industrial needs and capabilities will be possible. By aligning capabilities with market drivers, it will be possible to identify which industrial needs a research centre can address. This approach will help with answering the following question: Does a research centre have mature capabilities to address that challenge or does it need investment in one of the dimensions of CMF to mature their capabilities?

Going further, results from CMF could link to a roadmapping process. Hence, if a research centre already uses IfM (institute for Manufacturing, University of Cambridge) methodology for roadmapping, results from CMF can help answering question 'How do we get there?' i.e. how is a research centre going to achieve its short/middle/long term plans.

Adding CMF results to a roadmapping process would also add a degree of transparency. It would give TC leads, senior management and sector experts (e.g. business development personnel) clarity of what new market trends are, which would be a starting point to planning of how those market needs could be addressed by current capabilities, and if the capabilities are mature enough to address those market needs.

9.5.3 Introduction of wider capability maturity process

Having developed CMF for TC, next step will be to introduce a solution that concentrates on technology processes available at a research centre. TC can be a higher level of technology processes i.e. several technology processes contribute into a TC (Figure 9.1). That investigation would require to repeat methodology introduced in this research and apply it to technology processes. Once that investigation is completed, a calculations for technology processes would also need to be investigated. It is also possible that calculations used to achieve maturity level of technology processes, could be also applied to TCs. Then an investigation regarding how to combine CMF and new solution for technology processes could start.

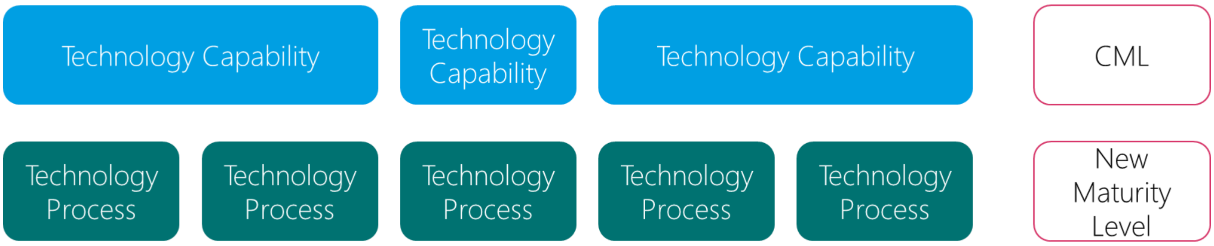


Figure 9.1: Future maturity levels based on the structure of research centres

9.5.4 Integration of CMF with existing management systems

CMF could be helpful not only to capture technological gaps but also to provide information about team members during annual progress reviews. Integrating CMF with already existing management systems would need to be discussed with relevant departments, for example, HR department.

Before that happens, a research into modern HR tools and management techniques would need to be completed to understand how HR manages their work. Once that stage is completed, CMF results could be uploaded into HR systems. That would require support from software engineering expert, but it could still provide new insight into HR management systems.

On the other hand, different Catapults can use different HR systems, which links into area of research that concentrates on HR within HVM Catapults to try to understand if all those systems can be supported by CMF.

Furthermore, CMF could also support other departments/teams, for example Quality Team. During Phase 3 of interviews described in Chapter 4, a discussion with quality team representative took place. Unfortunately, when asked about feedback from industrial customers (in regards to completed projects by a research centre), there wasn't significant amount of feedback from industrial customers. At that point it was decided that this aspect cannot be linked to CMF as data was insufficient. However, if that aspect was important, feedback from customers could be linked to data collected though CMF. Therefore, if customer provided poor feedback, it would be possible to go back and see which team took part in that project. It is possible that this alignment could also help with identification of immature capabilities. Hence, if a capability is immature, it would not only show by TC lead (who provided data) but also by customers' feedback. That would send a stronger message to decision makers who would need to decide next steps regarding such capability.

9.5.5 Forecasting and financial analysis

As discussed before, in order to implement forecasting function more data points needs to be introduced , and also data collection needs to be repeated on a regular basis. That would help with understanding how CMLs are changing for different TCs and perhaps in different Catapults. It is also possible that some CMLs of some TCs will not change. However, having more data will help with identifying which forecasting method is the most suitable. Forecasting implementation would require research into computer science and/or statistics to support most reliable method.

Furthermore, forecasting method could also support such aspects as risk related to different TCs and their maturity level. It aligns to risk management which could support decision making process as well. Therefore, forecasting and risk management could become two additional functions of CMF.

Moreover, one participant mentioned that *"It would be useful as an interactive tool to assist in modelling investment decisions"* (P100). It could align well if forecasting and risk calculations are already added to CMF. Investment modelling could be added based on current CML of TCs, as well as level of probability that those CMLs stay the same or grow. It will require research in mathematics and/or finances (or financial mathematics) but so far literature does not offer any solution that connects capabilities and investment options. If this new are of research concentrates on financial side of capabilities, decision makers will be presented with information like how much development of TC costed so far, how much income current projects are bringing, and (using forecasting and risk functions) how risky it is to invest in a capability, or how much investment is needed to mature specific TC to gain satisfactory (for decision makers) level. Again, that area of research would require someone with strong financial or mathematical background. However, adding financial aspect to CMF would create a very powerful solution for research centres.

9.5.6 Digital transformation

Future work certainly requires transformation of CMF into digital (cloud based or website based) tool. It will improve user experience and it will also allow multiple users to access it at the same time. Also, considering how everyone had to adapt to different ways of working, and how important digital solutions has been- it is necessary that such a transformation of CMF happen as soon as possible. Therefore, transforming CMF into an online tool will require software engineering support.

That change is also welcomed by participants as some of them suggested more advanced improvements, for example: *Further development would involve a more sophisticated tool for displaying results more simply* (P128, Q43 S2) and/or *Needs better graphics*, *charts visual dashboard results* (P100, Q43 S2).

Once CMF digital version is applied in all HVM Catapults, the whole CMF process could be automated further by so-called 'web scarping' function, i.e. automated process of gathering information from websites. Transformation of CMF into a powerful tool like that will make CMF more user friendly and, what's more important, automated, which means less manual work, i.e. simplification. Therefore, CMF will become first digital and automated data driven tool for capturing capability maturity for research centres.

9.6 Additional comments

This section includes information from Q37 S1, and Q40 - Q43 S2 (full list of questions from both survey is included in Appendix 26). The comments included here are those that did not fit in any other category discussed in this chapter or in Chapters 7 or 8.

When asked for additional comments/suggestions, some participants asked about aspects that were out of the scope of this project. Table 9.4 shows those comments

Table 9.4: Additional comments (aspects out of scope)

Question/Participant	Comment
Q36 S1 P128	*The framework doesn't address capacity (i.e. availability or not) or scarce resources*
Q37 S1 P13	*Capacity is missing from operational view. Need capacity to complete projects.*
Q42 S2 P13	*Capacity is missing. Capacity is a key item for delivering projects and linking with operations.*
Q42 S2 P116	*Funding and economical aspects could be highlighted in the framework*
Q43 S2 P13	*Adding in capacity to project sublevel.*

Comments showed in Table 9.4 relate to capacity and funding aspects, which were left out of scope for purpose. The reason was that there are already advance tools/software that manage capacity and funding/financial data. Hence, instead of duplicating work of those already existing tools, it was decided that development of CMF will be more beneficial as capability maturity results can support financial and/or capacity decisions. The rest of comments that could not fit into any category are also included in the Appendix 26.

9.7 Summary

This chapter presented concerns expressed by participants through surveys or through follow-up discussions. Those concerns were addressed by future activities which aim to improve CMF and make sure that future version of CMF is more advanced than the one presented in this thesis.

Nevertheless, apart from concerns and suggestions discussed above, participants also provided positive comments, which provide evidence that 1) CMF is needed, and 2) as a starting point to capture capability maturity at research centres, CMF made good impression on participants. Comments presented in Table 9.5 summarise positive observations captured during validation process.

Table 9.5: Positive feedback captured through survey 1 and 2

Question/Participant	Comment
Q36 S1 P107	*I am hugely impressed with what you have created. Some concerns expressed above - evidence*
Q36 S1 P13	*TRL is standardised approach, where most should arrive at same rating. CMF getting close to this.*
Q36 S1 P117	*I think this will be a very useful tool in determining future areas of investment and development.*
Q36 S1 P133	*CMF looks like a good tool, if utilized can highlights the capability of the centre*
Q36 S1 P124	*Good presentation material which clearly sets the scene and offers explanations in a succinct way*
Q37 S1 P122	*CMF appears to be self-consistent, the value to research management remains to be proven.*
Q37 S1 P124	*I think you have demonstrated enough value to explore this through a pilot programme*
Q37 S1 P121	*Some well described scenarios around which the tool can be used is needed.*
Q40 S2 P131	*Useful work to quantify the research centre maturity*

Chapter 10: Conclusions

10.1 Overall Summary

Manufacturing sector in the UK relies heavily on the research centres helping to develop new technologies in order to overcome the valley of death (VoD). "The valley of death concept has been essential to the success in the United Kingdom of raising awareness of HVM (High Value Manufacturing) issues, especially in the United Kingdom where it has driven the establishment of the HVM Catapult network" (Ward, et al., 2017). It should be highlighted that HVMC's mission is to address the valley of death. That is also linked to the assumption that work is undertaken at middle TRL, which happen to be problematic for many industrial companies.

That challenge was the starting point for this research. By creating CMF for research centres, it is now possible for research centres to understand how mature their capabilities are and if they can address middle TRL issues, that industrial companies struggle with. By setting up clear aim and objectives, the development of CMF has been achieved.

This research thesis was divided into 10 chapters that described every step undertaken during this project. Main contributions of this research are highlighted in blue in Figure 10.1. Those are the development of CMF as well as justified need for CMF and validated purpose and relevance of CMF. However, the results gathered through this research (highlighted in green in Figure 10.1) should be used as a basis for future work and further research investigation, as discussed in Chapters 8 and 9.

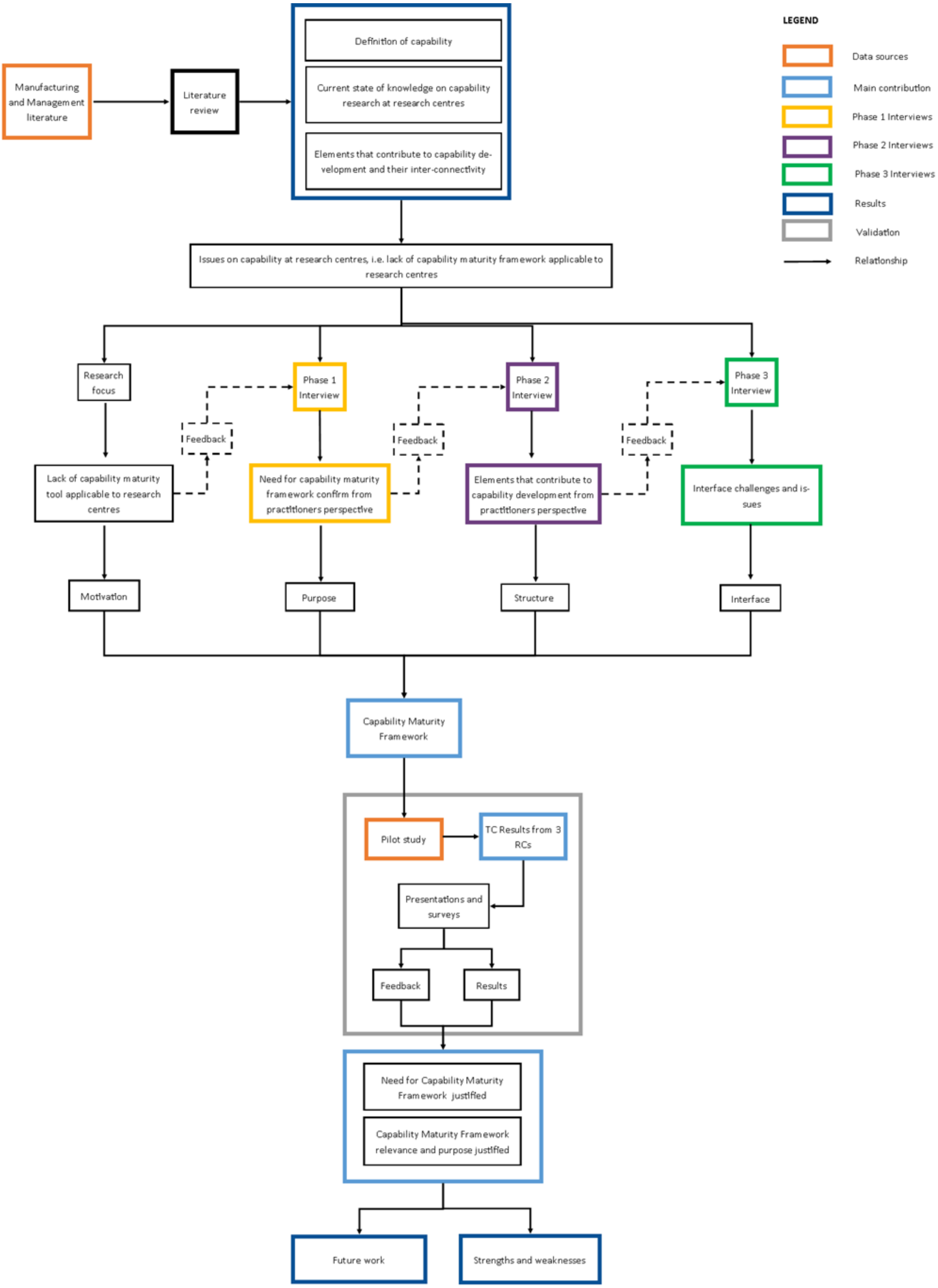


Figure 10.1: Summary of work

Before highlighting key findings of this research, let's recall motivation for this research (section 10.2- previously introduced in Chapter 1), as well as aim and objectives (section 10.3- also introduced earlier in Chapter 1).

10.2 Project deliverables and achievements

As highlighted in Figure 10.1, the biggest contribution is the development of CMF for research centres. Next biggest contribution is justified need for CMF and provided evidence of usefulness and relevance of CMF (Chapter 8, sections 8.2 - 8.3). The practicality and usefulness of CMF was supported by participants who agreed that (Chapter 8, section 8.4):

- CMF structure is a good representation of a research centre's capabilities (83%),
- CMF supports identification and management of technological gaps in the research centre (91%),
- A research centre will benefit from using CMF by understanding gaps and strengths/weaknesses of a research centre (e.g. in relation to skills, experience, application of various machines/software etc.) (97%).

Furthermore, the academic contributions (Chapter 8, section 8.2) involved:

- Recognising the lack of uniformity regarding definition and objectives of research centres
- Identifying that research centres lack the standardised processes to evolve and grow
- Highlighting the issue of understanding and defining capability in the context of research centres
- Emphasising that research centres have not received the same level of attention, despite of their important contribution to technological innovations, as industrial companies

10.3 Strengths of this research project

This research provided in-depth view of current knowledge gap (which was previously conformed by literature review, Chapter 2). Therefore, it provided basis for development of CMF, which means that the need for CMF was confirmed through literature review and through interviews (Chapter 4), i.e. contribution to knowledge addresses gap from academic and industrial viewpoint.

Due to the fact that the author was working at one of the research centres, provided a significant advantage to this project. Working at a research centre provided access and created trust with participants from that research centre. The opportunity helped with understanding existing processes and procedures, but also issues related to technology management. Hence, observations provided a learning experience gained from within and beyond one single research centre.

Moreover, Interviews provided opportunity to find out about how different teams interact, participants' viewpoints about different aspects of work at research centres (operational/strategic/technical) that were not considered at the beginning of this project. That is also linked to the fact that participants from different backgrounds were involved in this research. It gave an opportunity to gather information on how participants from different groups, work places and with different responsibilities view the need for capability maturity framework and their perspective on proposed solution. This greatly enhanced the generalisation of the CMF in terms of its functionality and deliverables.

Furthermore, CMF was validated and results of that process were reported in Chapter 7, 8 and 9. It should be highlighted that not every researcher has a chance to validate their study, thus this is considered as a significant advantage. Also, the validation results provided information about what aspects need further improvements. As validation feedback was already discussed, modifications to CMF can start straightaway.

10.4 Weaknesses of this research process

This research depended greatly on discussions (interviews) that aim to "incorporate stakeholder perspectives" (Easterby-Smith, et al., 2015). Thus, the following limitations had direct impact on the progress of the project:

- Limited availability of participants
- Meeting cancellations
- Limited participation from other research centres (i.e. difficult access to data)
- Covid-19 pandemic

Because of those external factors, meetings/interviews/informal chats/discussions had to be re-scheduled, which took a lot of time considering that participants already had busy schedule. It could be concluded that this aspect of research had the biggest impact on the study. That also affected number of participants in every stage of this research, which links to a second weakness of this study: small data pool.

Due to time contains, it was not possible to gather the 'wider' feedback at the time of the study. Having said that, future work might have more flexible timeframe, which will allow to contact larger number of potential participants. Feedback from wider data pool could add diversity and highlight concerns that were not identified before.

10.5 Reflections

This research demonstrates transparent and data-driven process resulting in development of existing technological capabilities at research centres. In a joint effort with research centres' directors, senior managers, programme leads, team leads, technology capability leads, senior technology officers, business development and knowledge research fellows, as well as engineers and managers from industrial companies, I worked through the grey areas of creating Capability Maturity Framework (CMF) for manufacturing research centres.

It was interesting and challenging to work on this project as it started from understanding how participants defined maturity and capability. For different people those terms meant different things, for other- they meant the same things but they used different terminologies to define the same concepts. It showed that research centres need transparency and clarity relate to concepts they use before discussing anything further.

However, by conducting many interviews, I was able to gather those perspective and identify similarities and differences between participants' definitions of capability. Hence, collecting data and analysing large volume of data definitely improved my analysis skills.

Moreover, necessary data could have only be collected through interviews. That was perhaps the most stressful aspect of this research. Therefore, by approaching practitioners and technical experts, I had to learn how to network, but also how to describe my research in a very short time in order to persuade them to take part in my study. The process definitely helped me gain more confidence, as all participants that I had an interview with were always helpful and positive about CMF.

Lastly, some follow-up discussions provided an opportunity for few participants to share their experience when they were PhD/EngD students. That certainly helped me to complete this projects, as it opened a discussion that (I think) every PhD/EngD student need: a reassurance that other fellow researchers struggled with similar challenges during their PhD/EngD journey. It definitely built a sense of belonging to the same community and knowing that I am not the only one who face those challenges. I think that it is important for any researcher to have that reassurance as it encourages us to continue with our research work.

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Appendices

Appendix 1:

Table 2.2: Categorisation of identified journals by research themes recognised through systematic literature review, Full version, Chapter 2

Journals/Research Themes	ST 1a	ST 1b	ST 2a	ST 2b	ST 2c	ST 3a	ST 3b	ST 3c	ST 3d	ST 3e	ST 3f	ST 3g	ST 4a	ST 4b	ST 4c	ST 4d	ST 5a	ST 5b	ST 5c	ST 6a	ST 6b	ST 7a	ST 7b	ST 7c
Journal of Operations Management	15	20	7		6	11	28	21	10	9	18	17	4	3	7	14	8	12	5	5	3	2	6	9
The Journal of Technology Transfer	5	11	6		6	2	5	4	3	3		3	2			1	1	1	3	1		8	3	9
Journal of Management Studies	1	5			1	3	4	6	8	1	1	4	6	4	1	6	2	13	3				2	
International Journal of Production Economics	4	9	3	1	6	4	14	3	1	3	2		3		4	2	3		5			1		2
California Management Review	2	18			1	2	11	2	5	2	4	2	4	1	1	2		5	2			1	1	2
CIRP Annals - Manufacturing Technology	3	22					9	1	2		2		2			2	3		7	2			2	1
Journal of Product Innovation Management	1	9				1	11	2	7	1		6	2			1	2	4				1	3	2
Management Science	2	5	2		3	1	4	1	8		1	2	1			1	2	13	1	1			1	2
International Journal of Management Reviews	4					2	9	2	6		1	7		1		1	1							
British Journal of Management	1	2			1	2	11	2	2	1	3	2				1	1	3				1	2	
Journal of Management	1	5		1			5	1	1		1	1	2	1		2	3	6	1				2	2
Academy of Management Journal		3			1	1	2	3	3		3	3					1	1	1			1		
Academy of Management Perspectives		5	1				1				2	3						3				1	2	3
Technological Forecasting and Social Change	1	1				1	3	1		1		1			1				1		1			
Technovation						1	4		1	1	1				2	1	1	1				1		
Journal of Manufacturing Technology Management		1		1	1	1	1	1	1						1									
IEEE Access		1				1	1						1			1	1							
Procedia CIRP				1	2											1								
Academy of Management Annals	1								1		1							2						
CIRP Annals		1							1				1						1			1		
Procedia Computer Science		1					2	2																
Procedia Manufacturing						1	1	1			1					1								

Journals/Research Themes	ST 1a	ST 1b	ST 2a	ST 2b	ST 2c	ST 3a	ST 3b	ST 3c	ST 3d	ST 3e	ST 3f	ST 3g	ST 4a	ST 4b	ST 4c	ST 4d	ST 5a	ST 5b	ST 5c	ST 6a	ST 6b	ST 7a	ST 7b	ST 7c
Radiography						1	1					1			1	1								
International Business Information Management Association				1	1		1	1								1								
European Management Journal		1			1	1		1																
Information & Management							2		1															
The International Journal of Advanced Manufacturing Technology	1	1				1	1																	
Systems Engineering				1	1					1													1	
R&D Management						1			1				1			1								
Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering (QR2MSE)						1	1	1																
International Journal of Information Management																	1		1					
IEEE Engineering Management Review							1	1								1								
IET Software		1										1												1
World Patent Information			1	1	1																			
Systems Research and Behavioral Science				1	1															1				
Journal of Intelligent Manufacturing		2																						

Journals/Research Themes	ST 1a	ST 1b	ST 2a	ST 2b	ST 2c	ST 3a	ST 3b	ST 3c	ST 3d	ST 3e	ST 3f	ST 3g	ST 4a	ST 4b	ST 4c	ST 4d	ST 5a	ST 5b	ST 5c	ST 6a	ST 6b	ST 7a	ST 7b	ST 7c
Industry & Higher Education																								1
4th International Conference on Signal-Image Technology & Internet-Based Systems (SITIS)		1						1																
International Conference on Automation, Computational and Technology Management (ICACTM)										1														1
Journal of Innovation and Enterpreneurship					1	1																		
Procedia Engineering					1																			
Management Information System Quarterly							1	1																
Journal of Cleaner Production				1	1																			
Academy of Strategic Management Journal										1														
IEEE							1																	
IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)								1																

Appendix 2:

Table 2.4: Definitions of dynamic capability – Examples from literature, full version, Chapter 2

Definitions	Authors
Dynamic capability has been defined as 'the **capacity of an organization to purposefully create, extend, or modify its resource base** *(Helfat, 2007, p. 1)'. The dynamic capabilities literature also points out that these capabilities are* **identifiable organizational processes**, **which are firm specific**, *but also share commonalities among firms facing similar environmental conditions*	(Malik & Kotabe, 2009)
Dynamic capabilities, which we define as the **abilities to reconfigure a firm's resources and routines** *in the manner envisioned and deemed appropriate by its principal decision-maker(s). Indeed,* **the creation and subsequent use of dynamic capabilities correspond to the entrepreneur, the entrepreneurial team, or the firm's senior management's perception of opportunities to productively change existing routines or resource configurations**, *their willingness to undertake such change, and their ability to implement these changes. This ability is largely determined by the motivation, skills and experiences of the firm's key managers*	(Zahra, et al., 2006)
Dynamic capabilities are **organizational routines that can accumulate knowledge via learning processes**. *Dynamic capabilities emerged as a complement to the RBV (resource-based view) in an attempt to explain competitive advantage in rapidly changing environments. There is a great deal of concern with dynamism, which seeks to address how competences are renewed over time so as to provide innovative responses to market changes.*	(Hsu & Wang, 2012)
Our overall results support the view that dynamic capabilities are **far from being a well- defined construct based on a coherent theoretical tradition and validated with strong empirical evidence**	(Vogel & Güttel, 2013)
The essence of **dynamic capabilities is a firm's behavioural orientation in the adaptation, renewal, reconfiguration and re-creation of resources,** *capabilities and core capabilities responding to external changes.*	(Wang & Ahmed, 2007)
"Broadly defined, dynamic capabilities are seen as the firm's **ability to integrate and change resource bases** *to address changing environments. Thus, dynamic capabilities can be seen as those processes where resources are acquired, integrated, transformed or reconfigured to generate new value-creating firm-based activities*	(McKelvie & Davidsson, 2009)
Dynamic capabilities enable managers to adapt, integrate, and deploy internal and external organizational skills, resources, and functional competencies to achieve alignment with the changing business environment. Moreover, **dynamic capabilities are a source of sustainable competitive advantage** *when they are based on a configuration of useful skills, resources, and competencies.*	(Slater, et al., 2014)
Dynamic capabilities are based on collections of organizational routines *and* **need to be understood as multidimensional constructs** *(Winter, 2003), reflected by a set of specific routines that represent their dimensions. The term routines refers to rule-based behavioral patterns for interdependent corporate actions*	(Schilke & Goerzen, 2010)
Dynamic capabilities **builds on the notion of core competencies** *but* **focuses on the role of management in building and adapting these competencies to address rapidly changing environments** *(…). With dynamic capabilities, sustained competitive advantage comes from* **the firm's ability to leverage and reconfigure its existing competencies and assets** *in ways that are valuable to the customer but difficult for competitors to imitate. Dynamic capabilities help a firm* **sense opportunities and then seize them by successfully reallocating resources**, *often by adjusting existing competencies or developing new ones.*	(Harreld, O'Reilly, & Tushman, 2007)
Dynamic capabilities are not abstract academic concepts but **a concrete set of mechanisms that help managers address the fundamental question of strategy**, *which is to develop a truly sustainable competitive advantage. Interestingly, we are beginning to realize that sustainability is fleeting unless it is aligned with capabilities to continually sense how the marketplace is changing and seize these changes through dynamic organizational realignment.*	
Dynamic capabilities are **a learned pattern of collective activity and strategic routines through which an organization can generate and modify operating practices to achieve a new resource configuration and achieve and sustain a competitive advantage** *(Teece et al., 1997, Teece, 2007).*	(Brusset & Teller, 2017)
The aim of the DC approach is to explain the **competitive advantage of firms over time** *(Teece and Pisano, 1994).*	(Ferreira, et al., 2020)
This research [i.e. Teece's research in 1994] stated that "our view of the firm is somewhat richer than the standard resource-based view … it is not only the bundle of resources that matter, but the	

mechanisms by which **firms learn and accumulate new skills and capabilities**, and the forces that limit the rate and direction of this process".	
In general, research on DCs is interested in **how firms build and adapt their resource base to maximize organizational fit with the environment.** One of the distinctive features of the DC perspective is the notion that **such adaptation can be based on organizational routines - learned, repetitious behavioural patterns for interdependent corporate actions.**	
Results suggest **that dynamic capabilities are associated with competitive advantage** in dynamic, munificent settings, and may enable the effective combination of differentiation and low-cost orientations in such environments. Additionally, dynamic capabilities are associated with competitive advantage in stable, non-munificent environments for firms with a low-cost orientation.	(Fainshmidt, et al., 2019)
Organizational agility and performance can be explained by the dynamic capabilities framework, i.e., **sensing, seizing, and managing threats** (Roberts and Grover 2012; Teece et al. 2016). **Sensing**, according to Teece (2007), is the process of ascertaining environmental changes—for example, in science and technology, customer, and supplier landscapes—and directing R&D efforts accordingly. **Sensing** is related **to exploration, which involves the outward examination of new information, applications of existing know-how, and dynamism of markets and science and technology** (March 1991; Teece 2017). **Seizing**, conversely, includes **business model definition and operationalization, securing complementary assets, implementing routines for decision making, and instituting leadership, communication, and cultural supports** (Teece 2007). Seizing is related to exploitation, which refers to the operational aspects of following through on innovations and realizing efficiencies (Lavie et al. 2010; March 1991).	(Sanjay, et al., 2020)
While all firms may become more steadfast in response to competitive threats (Killaly 1998; Toh and Kim 2013), **young small firms may be more likely to benefit from a proactive approach to growth than from competitive aggressiveness**, compared to larger, well-established firms (Lumpkin and Dess 2001), suggesting that they may be more likely to change when encountering environmental uncertainty. In the absence of higher order routines that can alter an SME's lower-level capabilities, entrepreneurial managers may instead redirect resources and pursue strategic shifts directly (Teece 2012).	
Dynamic capabilities enable firms to **identify profitable configurations of competencies and assets, assemble and orchestrate them, and then exploit them with an innovative and agile organization.** Ordinary capabilities **enable identification of important process innovations**, and dynamic capabilities help **identify new products and services**, potentially **opening new markets** where rivals have not yet appeared. Each type is important in different ways. Dynamic capabilities are about doing the right things at the right time, based on new product (and process) development, unique managerial orchestration processes, a strong and change-oriented organizational culture, and a prescient assessment of the business environment and technological opportunities.	(Schoemaker, et al., 2018)
Developing and maintaining dynamic capabilities takes time and resources. A single visionary leader in a small startup is a possible shortcut, **but it takes conscious effort, time, and team work for most firms.** To strengthen dynamic capabilities, managers can conduct **a capability audit** in which they list the specific competencies they need, **identify the gaps between current and desired levels, and take steps to reinforce those that are most critical to supporting a given strategy**	
Dynamic capabilities under the capability-building **mechanism can generate more sustained impacts on organizational performance by enabling firms to constantly renew, reconfigure, and recreate** the requisite resources and capabilities for responding to environmental changes	(Lee, et al., 2020)

Appendix 3:

Table 2.5: Definitions of capabilities according to RBV – Examples from literature, Full version, Chapter 2

Definitions	Authors
The resource-based view (RBV) provides a useful perspective to investigate the strategic resources with the potential to deliver comparative advantages and superior performance to a firm (Barney, 1991).	(Qi, et al., 2020)
Furthermore, based on the RBV, Peng et al. (2008) argue that those routines are the resources for a firm to create static or dynamic capabilities.	
The RBV explains that the basis for the competitive advantages of a firm lies primarily in the application of the resources at the firm's disposal (Barney, 1991). Resources refer to tangible and intangible assets, such as money, people, technology, routines, knowledge and relationships, that are inherent to a firm (Peteraf, 1993). Firms are heterogeneous and have different capabilities because they have unique bundles of resources (Peteraf, 1993), which are valuable, difficult to imitate or substitute and rare.	
RBV posits that organizational resources encompass both asset-type resources (e.g., physical assets) and capability-type resources (e.g., human capital)	(Lee, et al., 2020)
According to Wade and Hulland, resources can be defined as "anything tangible or intangible the firm can use in its processes for creating, producing, and/or offering its products (goods or services) to a market," while capabilities denote "repeatable patterns of actions in the use of assets to create, produce, and/or offer products to a market" (p. 109).	
The RBV suggests that competitive advantage can be obtained and sustained over time from the internal organization of resources (Eisenhardt and Martin, 2000). Resources in this context refer to anything that might be thought as strength (or weakness) to the firm such as assets, patents, brand names, capabilities, processes, attributes, distribution locations, information and knowledge (Miller and Shamsie, 1996, Wernerfelt and Karnani, 1987).	(Chavez, et al., 2017)
The RBV adopts an internal view wherein the firm is the primary unit of analysis and competitive advantage accrues from the exploitation of tangible and intangible resources (Lavie, 2006).	
Teece et al. (1997) proposed dynamic capabilities as an extension to the work on RBV. Both, the resource-based view as well as the dynamic capabilities approach usually draw a distinction between resources and capabilities.	(Ojha, et al., 2020)
Resources are "stocks of available factors that are owned or controlled by the firm" whereas capabilities define a firm's "ability to deploy its resources, usually in combination, using organizational processes to achieve some desired end result" (Amit and Schoemaker, 1993, p. 35).	
The RBV argues that firms process resources, a subset of which enables them to achieve competitive advantage, and a further subset of which leads to superior long-term performance.	(Wade & Hulland, 2004)
Capabilities transform inputs into outputs of greater worth Capabilities can include skills, such as technical or managerial ability, or processes, such as systems development or integration.	
One of the key challenges RBV theories have faced is to define what is meant by a resource. Researchers and practitioners interested in the RBV have used a variety of different terms to talk about a firm's resources, including competencies (Prahalad and Hamel 1990), skills (Grant 1991), strategic assets (Amit and Schoemaker 1993), assets (Ross et al. 1996), and stocks (Capron and Hulland 1999).	
The mechanisms underlying how exactly key resources benefit the firm are also poorly specified in the RBV.	
The RBV argues that a firm's competitive advantage is primarily dependent on the resources owned by the firm [17], [18]. However, merely possessing resources cannot maintain a sustainable competitive advantage [19]. Resources, in fact, tend to be tradable in markets, and few of them can be productive on their own.	(Liu, et al., 2019)
Firms should also accumulate capabilities to leverage resources, which are strictly idiosyncratic [20]. Therefore, there is an inner connection between a firm's resources and capabilities.	
Among a firm's various resources, technological capability, which offers know-how, is the first important resource for NPD [new product development]]. Meanwhile, technology management capability can be considered as the exploitation and development of technological capability.	
These resources are tangible or intangible assets such as geographic location, factory equipment, a superior sales force and intellectual property.	(Liu, et al., 2018)

Strategic research has indicated that possessing rare, valuable, durable and inimitable resources and capabilities offers a firm a comparative advantage.	
Resources include equipment, tools, materials, final products, and in this context also human resources. The physical assets and humans contain and possess data, information, and knowledge tangible that are important to be shared and processed.	(Li, et al., 2019)
Sirmon and his colleagues (2007) explained that resources (tangible and intangible) were bundled to create capabilities. For example, scientific equipment, technology and human capital are bundled to create a research and development capability. Some OM research differentiated resources from capabilities, especially those integrating the RBT and dynamic capabilities perspectives (e.g., Vaidyanathan and Devaraj, 2008); however, this was not the norm.	(Hitt, et al., 2016)
Tangible resources can be seen as the physical resources such as plant, equipment, computers and machinery that will allow a new product or service to be produced and/or distributed	(McKelvie & Davidsson, 2009)

Appendix 4:

Table A1: Capabilities – definitions and examples from literature, Full version, Chapter 2

Category	Definition	Authors
Technology	*We prefer to view* ***technology as physical systems or tools- restraining the softer perspective on technology to be part of the skills and knowledge of human beings. Hard technology may be machinery, tools, equipment, software, programs, database and so on***	(Drejer & Riis, 1999)
	The broad definition of technology often imposes some difficulties with respect to assessing the role of technology in industrial enterprises. By perceiving technology as an integral part of a competence, the notion of technology may be confined to the more technical elements. This allows to us to be more specific as to identifying various technologies in an industrial enterprise. Furthermore, ***technology is placed in an application-oriented context by seeing technology as an integral part of competencies***	(Drejer & Riis, 1999)
	"Traditional definitions of technology have focused on the ***physical characteristics of technology, as a system consisting of components and linkages among the components****. More recently, scholars have been following the lead of Layton (1974) in expanding the* ***definition of technology*** *from that of* ***a physical, concrete device*** *or artifact to include the* ***proprietary design knowledge embodied in the physical artifact****. This knowledge is socially constructed (Pinch and Bijker 1987), recognized, and protected as a property right through the institutions of patents or royalties (Nelson 1982), and imprinted with the standards and values of a society at the time of its creation (Thirtle and Ruttan 1987). Combining these two approaches,* ***we view technology as artifact and knowledge that together serve a specific functional need****.*	(Das & Van de Ven, 2000)
	Technology is not only recognized as an asset but also as an essential constituent that influences all management disciplines.	(Shenoy, et al., 2019)
	In the TRL literature and at NASA, the term "technology" is most commonly ***conceptualized at the level of a component technology featuring new materials, scale, or working principles.*** *The component technology of interest could be a new invention or an adaptation to an existing technology*	(Olechowski, et al., 2020)
Technological capability	*Technological capability is a key resource. It consists of* ***technological knowledge, know-how engendered by R&D and other technology-specific intellectual property*** *[31]. A firm's* ***technological capability is a kind of tacit resource, which is hard for its competitors to acquire.***	(Liu, et al., 2019)
	Technological capability has a significant effect on productivity growth and firm performance.	(Arana-Solares, et al., 2019)
	Technological capabilities are those competencies that are required from the firm to convert inputs into outputs (i.e. capabilities needed for producing products or services).	(Mikalef, et al., 2020)
Human Beings/Human Capital (HC) /Employees	*Human beings are to us the most obvious part of competence;* ***if no humans use the technologies, then nothing will happen.*** *Therefore,* ***human beings are the focal point of competence development.***	(Drejer & Riis, 1999)
	HC is at the heart of IC (intellectual capital) and it ***is defined as the combined knowledge, skill, innovation and ability of employees*** *(...) HC, one of the underlying strategic resources, is both supportive and necessary for success since* ***employees' knowledge and skill are essential*** *in today's fast-paced, changing competitive climate*	(Hsu & Wang, 2012)
	Companies with greater HC (i.e. higher education or skill) are likely to have better entrepreneurial judgement. ***As long as HC continues to be developed, staff can improve their job performance and ultimately improve the firm's performance***	
	If workers can adjust quickly and easily to new tasks, delays in shifting between products and the time it takes to get up to speed can be reduced sharply. Workers that have ***multiple skill sets*** *should be able to produce a variety of products.*	(Zhang, et al., 2003)
	organizations can enhance the ***skills*** *of their workforces both by hiring high-quality individuals and by improving the level of skills in their current workforces*	(Jiang, et al., 2012)
Intellectual Capital	*IC plays a fundamental role within modern organizations and is part of the foundation of business in the 21st century. Studies have begun to examine the IC process by which*	(Hsu & Wang, 2012)

	those effects are ultimately realized (Martinez-Torres, 2006; Rudez and Mihalic, 2007). IC has thus been identified as one of the key drivers of firm-level performance	
Learning/Absorptive Capability	*Learning refers to **use of repetition and experimentation to improve organizational processes**. Reconfiguration delineates firm capabilities in identifying external opportunities through scanning, and then changing the asset structure of firms to take advantage of opportunities. Coordination capabilities relate to how managers within firms coordinate and integrate internal activities.*	(Malik & Kotabe, 2009)
	An organization might be able to learn in ways that are distinct from the accumulated learning of individuals. They built their views on a model of decision-making within firms which emphasizes the role of rules and procedures in response to external shocks. This suggests that learning plays a significant role in the creation and development of dynamic capabilities	(Hsu & Wang, 2012)
	Learning plays a determinant role in new product development projects because it allows new products to be adapted to changing environmental factors, such as customer demand uncertainty, technological developments or competitive turbulence."	(Alegre & Chiva, 2008)
	Learning capability (...) - a bundle of tangible and intangible resources or skills the firm uses to achieve new forms of competitive advantage.	
	The knowledge that the firm is able to "identify, assimilate, and exploit" (Cohen and Levinthal, 1989, p. 569) from the environment is dependent on the knowledge accumulated previously through R & D activities (Cohen and Levinthal, 1990). Thus, firms' absorptive capacity will influence their ability to innovate as it determines the extent to which they can take advantage of external knowledge.	(Saemundsson & Candi, 2017)
	*Regardless of which strategy they intend to pursue, firms will need to incorporate **learning into their strategic planning and tactics**, as this has a significant direct impact on market orientation as well as resource orientation. Management should encourage and enable their employees to learn continuously and to **critically evaluate their processes, external needs, and technologies of their customers and competitors.***	(Paladino, 2007)
	"As learning occurs, a firm is able to employ capabilities or resources garnered in one situation to serve a different one"	(Miller, et al., 2002)
	Exploratory market learning leads to the development of unique products/services, while exploitative market learning enhances cost-effectiveness	(Slater, et al., 2014)
Knowledge	*"**knowledge resources that are important for the firm's development** are sometimes provided by members of the firm's network or social capital, i.e. individuals who are neither founders nor employees (Aldrich and Zimmer, 1986; Davidsson and Honig, 2003). It is therefore important to supplement the above with direct assessment of the effects of specific expertise available to the firm, regardless of who provides it and regardless of what specific mechanisms led to the development of such expertise."*	(Thompson & Walsham, 2004)
	*" '**knowledge' could be considered as 'a set of organized statements of facts or ideas, presenting a reasoned judgement or an experimental result, which is transmitted to others through some communication medium in some systematic form"***	
	*"Organizations specializing in advanced technologies need individuals who are **knowledgeable, with excellent problem-solving skill and the ability to make effective decisions**."*	(McKelvie & Davidsson, 2009)
	Capabilities are complex bundles of skills and accumulated knowledge embedded in organizational processes and routines and serve as critical sources of sustainable competitive advantage by enabling firms to coordinate activities and make use of assets (Day, 1994).	(Liu, et al., 2018)
Adaptive Capability	*"Adaptive capability is defined as a **firm's ability to identify and capitalize on emerging market opportunities.** (...).The development of adaptive capability is often accompanied by the evolution of organizational forms."*	(Wang & Ahmed, 2007)
Organizational capability	*An organization's capability resides in and is exercised through its processes and routines (Song et al., 2005). As a way of integrating various capabilities, an organization's capability configuration essentially represents the coordination of the organization's different processes and routines (Teece et al., 1997, Eisenhardt and Martin, 2000, Teece, 2007)*	(Liu, et al., 2018)
	Organizational capabilities are formed on the basis of firm-specific combinations of organizational assets and business routines [50], known as capability hierarchy [54].	(Lee, et al., 2020)

	Such high-level organizational capabilities are difficult to imitate [27,48], thus making a firm's competitive advantage resist erosion by its competitors—long-term competitive advantage	
Resources	*From an operational point of view, manufacturing practices are the resources of a firm because they* **enable the firm to accumulate knowledge and develop capabilities** *(Peng et al., 2008).*	(Qi, et al., 2020)
	Amit and Schoemaker (1993) ***defined capability as a firm's capacity to purposefully deploy a combination of resources and processes to achieve a desired goal****. Grant (1966:377) understood organizational capability "****as a firm's ability to perform repeatedly a productive task which relates either directly or indirectly to a firm's capacity for creating value through effecting the transformation of inputs into outputs****".* ***Resources or inputs appear to be critical elements of capability;*** *however, it is clear that capability is more than just a question of resources. Resources can be defined as the tangible or intangible assets or inputs to production that an organization owns, controls, or to which it has access on a semi-permanent basis (Helfat and Peteraf, 2003).*	(Liu & Huang, 2018)
Resources and capabilities	*Resources are stocks of available factors (human capital, physical assets, knowledge, and other tangible and intangible factors) that are owned or controlled by the firm and can be converted into final products [5].* ***Meanwhile, capabilities are firms' capacities to deploy and coordinate resources to perform tasks*** *[6]*	(Liu, et al., 2019)
Manufacturing capability	*The notion of manufacturing capabilities was first introduced by Hayes and Wheelwright (1984) as the dimensions along which companies choose to compete (Krause et al., 2001, Narasimhan and Das, 2001). These* ***capabilities are associated with a set of supportive decisions and practices regarding the structure and/or infrastructure of operations*** *(Wheelright, 1984). The result is that manufacturing capability has been typically conceptualized as an operational strength manifested as competitive performance (Peng et al., 2008).*	(Chavez, et al., 2017)
	Manufacturing capability refers to the ***manufacturer's actual competitive strength relative to primary competitors*** *(Swink et al., 2007), which should be aligned with the strategic goals of the organization (Ho et al., 2002).*	

Appendix 5:
Table 2.6: Examples of maturity models/solutions identified in literature, Full version, Chapter 2

Tool/Method	Description	Disadvantages	Lit example
Technology Readiness Levels (TRL)	• *TRLs are "a type of measurement system used to access the maturity level of a particular technology"* (NASA, 2012) • *"Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the projects progress. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest"* (Mai, 2012) • *The TRL scale is regarded as an effective tool to help drive a successful deployment of technological, as well as manufacturing, systems* (Islam, 2010)	• It adds a degree of unnecessary ambiguity to a project, i.e. not accurate enough for some projects • It does not apply to system integration • *"TRLs are context specific. A technology that is mature in one operating plant cannot be assumed to be as mature in a different one. Even those that appear the same might have significantly different operating conditions"* (NDA, 2014) • *It does not imply that the technology "will result in successful development of the system"* (NDA, 2014) • *"Operators use TRL (…) for tracking readiness of all equipment for installation. Every nut and bolt of every equipment is included in an Excel sheet. You can imagine such a spread sheet will become very large* (Olechowski, et al., 2015) • *"Despite this increase in uptake of practice, little research has been formally conducted to understand and describe TRL application"* (Olechowski, et al., 2020)	(Lee, et al., 2007), (Islam, 2010), (NASA, 2012), (NDA, 2014), (Olechowski, et al., 2015), (Uflewska, et al., 2017), (Olechowski, et al., 2020)
Manufacturing Readiness Levels (MRL)	Ten point scale is describe in the following manner (Fernandez, 2010) • *MRL 1-3: Pre-Concept Development (Innovation Stage)* • *MRL 4: Concept Development* • *MRL 5-6: Technology Development* • *MRL 7-8: Engineering and Manufacturing Development* • *MRL 9-10: Production and Deployment*	• *"It describes today's position, without providing close support (…) in how to plan or execute a specific project or lower level task"* (Ward, et al., 2012)	(Fernandez, 2010), (Ward, et al., 2012), (Uflewska, et al., 2017)
Manufacturing Capability Readiness Levels (MCRL)	Nine point scale is presented as follows (House of Commons, 2013) • *MCRL 1-4: Conception and assessment of Manufacturing Technology* • *MCRL 5-6: Critical 'pre-production' phase, where expensive full-scale equipment and processes must be used but ahead of product launch, or factory* • *MCRL 7-9: implementation of the process on the shop floor, and also confirms volume production with assured quality*	• In relation to MCRL 4-6: *"investment is high, but there is no certainty that (…) the proposed process will be successful"* (House of Commons, 2013) • Size of the framework is overwhelming and it is time-consuming	(House of Commons, 2013), (Uflewska, et al., 2017)
Innovative Manufacturing Readiness Levels (IMRL)	(Islam, 2010) described the five point scale as • *IMRL 1: Understanding materials' properties at micro and nano-scale, technical and manufacturing strategy planning and detailed design* • *IMRL 2: Materials processing capabilities, validation, and component technologies dependencies* • *IMRL3: Adequacy and integration (scale-down challenges), system engineering, prototypes, and overall production preparation* • *IMRL 4: Combined systems tests, verification, inspection and trial production*	• Applicable only to micro and nano-manufacturing technologies i.e. not applicable to large/medium technologies/products (due to specific parameters) • Practicability and applicability of this framework is still in question as it is a conceptual approach	(Islam, 2010), (Uflewska, et al., 2017)

	• *IMRL 5: Overall systems are in operation, quality measurement and initial market audit*		
Capability Maturity Models (CMM)	• *"Based on the specific software practices adopted, the CMM classifies the software process into five maturity levels. (...) "Maturity levels were associated with a software product based on the maturity level of the IT firm at the beginning of a product's design. The maturity level of a product that benefited from process improvements later in the product's life-cycle stages (e.g., coding stage) was assigned a commensurate increase in maturity level."*	• such tool has to be adjusted to the needs of specific industry and addresses common problems that affect multiple actors • subjectivity of data	(Harter, Krishnan, & Slaughter, 2000)
Capability Maturity Model Integration (CMMI)	• *In the late 1980s, the software engineering community proposed the idea of improving product quality by controlling and improving software processes with reference to the way the manufacturing industry improved product quality by controlling and improving technological processes. Among such models, the most representative and widely used is CMMI* (Huang, et al., 2019) • *"CMMI divides an organization's research and development capabilities into five levels: the initial level, managed level, defined level, quantitative management level and optimization level."* (Huang, et al., 2019) • *The main objective of this model is to assess and improve the processes of organisations within the scope of the development, operation, and maintenance of information systems and software products.* (Patón-Romero, et al., 2019)	• *"Processes that depend on the interaction of individuals can be difficult to quantify. This leads to the evaluation results that vary according to the context in which they are applied"* (Silva, et al., 2019) • *Although management and processes are emphasized in CMMI, it lacks corresponding norms and constraints for people who undertake management and processes."* (Huang, et al., 2019) • *"When it comes to links that require executive staff to judge subjectively or actively contribute their experience and wisdom, the subjective initiative of the individual can influence the effects of process execution; for example, in the QA audit process, review process, testing process, etc., Therefore, it is necessary to consider people-orientation in these processes."* (Huang, et al., 2019)	(Patón-Romero, et al., 2019), (Huang, et al., 2019), (Silva, et al., 2019)
Portfolio techniques/ Portfolio Matrix	*"Portfolio techniques are powerful tools in that they allow products and R&D projects to be analysed in a systematic manner, providing an opportunity for the optimization of a company's long-term growth and profitability."*	• *"The question arises as to how many variables need to be taken into consideration in order to make correct assessment of the projects. How can these variables be combined in order to ensure orthogonality? How does subjectivity influence consensus across different organizational functions for managing a portfolio of R&D projects? What are the implications for innovation management?"* • *"difficulties in identifying and assessing external and internal factors, difficulties in dealing with multi-attributes leading to high ambiguity in measuring business strength and industry attractiveness"* • *"Most of them (i.e. portfolio management tools) have very limited definitions in characterizing project success."* • *"Portfolio techniques usually serve to solve a particular set of complex issues faced by R&D management, unique to each firm."*	(Mikkola, 2001)
Performance Measurement Model	• *"the ultimate goal of performance measurement should be learning rather than control"* • *"Today, performance measurement is based around business structures, units, processes and workflows measuring efficiency and effectiveness of actions using variables such as cost, quality and time"*	• *"The use of performance measures can, and indeed does, lead to dysfunctional behaviours and poor overall performance. (...) performance measures and targets create a command and control culture which often generates hidden costs and demoralizes people by sub-optimizing various parts of the system"* • *"Today's frameworks and models for performance measurement may not be able to deal with (...) complexity and dynamism."*	(Bititci, Suwignjo, & Carrie, 2001)

ISO/IEC 15504 and 330000	• *ISO/IEC 15504: known as software process improvement capability determination (SPICE) was developed by the International Organisation for Standardisation (ISO) and International Electrotechnical Commission (IEC). This family of standards proposes a set of models for the evaluation and improvement of processes related to information systems.* • *ISO/IEC 33000 [15]: developed by ISO and IEC, it is the new family of standards that replaces the ISO/IEC 15504 family for the assessment and improvement of the capacity and maturity of the processes of organisations. It involves a reorganisation and extension of the ISO/IEC 15504 family of standards*		(Patón-Romero, et al., 2019)
Roadmaps	*"a visual aid that crystallises the links between research programs, development programs, capability targets and requirements"*	*"roadmapping activity for particular items is conducted independently of other items"*	(Lee, et al., 2007)
TQM	*TQM mainly includes the following core concepts: 1) traction on requirement; 2) customer satisfaction evaluation; 3) product system engineering operation; 4) prevention first; 5) continuous improvement; 6) based on data; 7) people-oriented.*		(Huang, et al., 2019)
Mental Models	*"Schema and mental models provide frames of reference for storing information and knowledge acquired through education and experience. An individual's mental model might reflect firm beliefs about customer expectations, the expected actions of competitors, the role of manufacturing in strategy making, opportunities created by technology, and societal obligations toward other cultures and the natural environment."*	• *"Manufacturing managers who have formed mental models in more stable times will likely face difficulty in the more fast-paced decision environment of the next decade"* • *"It is common (...), for mental models to become rigid and out of synchronization with environmental realities, leading to biased, over simplified decisions. The complexity and uniqueness of strategic decision-making makes it an especially attractive candidate for bias."*	(St John, et al., 2001)

Appendix 6:

Table 2.7: Research centres - definitions, focus, importance (examples from literature), Full version, Chapter 2

Definitions	Authors
Definitions of the various roles that TTOs should pursue diverge between those who favour a narrow role for TTOs—primarily as a switchboard—and those who favour a broader role—of helping two-way communications between HEIs [higher education institutions] and the outside world such as identifying curriculum development needs.	(Cunningham, et al., 2020)
Overall the main function of a TTO is to provide a formal, above the board, and a relatively effective mechanism for those researchers who wish to commercialise their ideas.	
TTOs themselves should hire individuals with both research and industry backgrounds and/or experiences in technology transfer with the industry in order to sufficiently support outward technology transfers.	(Leischning & Geigenmüller, 2020)
The Catapult helps to alter the institutional architecture to make it possible for UK manufacturing firms to be more competitive.	(Spring, et al., 2017)
Catapults are an example of what Mina et al. (2009) call 'intermediate research organizations' in that they sit between commercial firms conducting private research and universities carrying out publicly-funded research. After other firms such as suppliers and customers, businesses see intermediate research organizations as the most important external sources of knowledge related to innovation (Hughes, 2008). A 2008 study estimated that such organizations accounted for around one third of UK expenditure on R&D conducted outside the firm: 80% of the firms surveyed reported that they 'could not have achieved the same results by just working in-house or with a university' (Oxford Economics, 2008)	
The first of these functions is the reduction of uncertainty through the provision of information. Catapults have brought together existing and new resources within coherent and readily-identifiable organizational structures. As a result, firms can more easily find the resources they need, without having to research, say, individual university departments one by one	
The second function is the management of conflicts and cooperation. Catapults allow universities and firms to co-operate or collaborate effectively, and such collaboration is a critical part of the Catapult model. They bring together entities who are positively disposed toward collaboration in principle (…). The buildings housing Catapults are neutral territory and have institutions or 'rules of the game', such as cultures, conventions and membership structures with defined rights, that allow sometime-competitors to work together on projects of common interest.	
Catapults are underpinned by government funding. In this sense, they provide firms with financial incentives to access resources that they could otherwise not afford on their own. In the HVM Catapult, the core funding allows the creation and maintenance of capabilities and facilities of a standard, scale and intensity that would be otherwise unfeasible for any single firm. Through successive projects, both the Catapult's individual Centres and the firms participating in them develop their capabilities, making subsequent projects likely to be even more productive.	
The recent emphasis of the UK government's policy initiatives has been on assisting activities that generate innovation through the formation of publicly funded technology and innovation centres.	(Kerry & Danson, 2016)
[Catapults are] creating an infrastructure that bridges the spectrum of activities between research and commercialization of technology. They have been created for UK industries that have global markets, world leading research capabilities and the ability to exploit technology and finance investment	
Innovation intermediaries (organizations such as CATAPULT Centres) operate at the overlapping areas of the three helixes and are known to help facilitate innovation (Nakwa and Zawdie, 2012). (…) These centres are intended to increase the level and success of innovation generating activities and of those involved with them.	
Innovation intermediaries such as CATAPULT Centres are ideally placed to play a role in helping drive the adoption of open innovation at a regional level. The Centres aim to 'de-risk' innovation by providing a range of services throughout the research and development cycle, acting as both an anchor and a catalyst for new markets, innovative sectors, clusters and networks.	

Given the great challenges that are involved with transferring science to the market, many universities have established technology transfer offices, science parks, incubators, and university venture funds – an organizational assemblage labelled the technology transfer (TT) ecosystem. By reviewing the extant literature on the TT ecosystem and its components, this paper aims at providing an understanding of the organizational design of the TT ecosystem.	(Good, et al., 2019)
TTOs are organizations that have been given the responsibility to facilitate the transfer of technology from a directly affiliated research institution (or multiple research institutions) to market by acting as a bridge between the two environments.	
Activities of TTOs: Encourage the participation of researchers in technology commercialization, Build trust and relationships with researchers, Identify high potential technologies, and Assess commercialization potential of technologies.	
In an attempt to favour knowledge transfer activities, research centre administrations have created intermediary organizations to broker between science and commercial applications. For instance, TTOs, research centres, incubators, accelerators, and broker services have flourished across the globe over the last decade. There has been a tremendous shift from a situation in which only a few pioneers had infrastructures to support science commercialization, to a condition in which virtually all research organizations have such intermediaries. Hence, science commercialization is increasingly seen as a legitimate activity in which several organizations engage.	(Fini, et al., 2019)

Appendix 7:
Table 2.8: Challenges related to decision makers' role, Full version, Chapter 2

Challenge	Example from literature	Authors
Identification of opportunity	*"The first difficulty facing academic entrepreneurs is to identify and select a viable productive opportunity.* **Opportunities are objectively identifiable but their recognition is subjective** *and often depends on access to special knowledge"*	(Druilhe & Garnsey, 2004)
	"Developing the "right" new products is critical to firm success and is often cited as a key competitive dimension (Roussel et al. 1991, Cooper et al. 1998). Companies that make **poor choices** *with respect to their new product development (NPD) portfolio run the risk of losing their competitive advantage."*	(Chao & Kavadias, 2008)
Utilization of knowledge/Complexity of operational systems/tools	*"Managers face difficulties not in accessing knowledge, but in* **utilizing knowledge in decision making and in embodying knowledge in products/services and processes**. *(…) The trouble that managers face in developing and integrating knowledge management practices is that an effective knowledge management system is in itself a complex combination of a series of organizational subsystems which are themselves complex"*	(Soo, et al., 2002)
	"Managers need models that help them understand the organizational and environmental antecedents and outcomes of detailed but uncomplicated classifications of learning and knowledge. These models should be helpful in revealing the influence of CEOs and top management teams; governance structure and mechanisms; culture and strategy at different levels; strategic alliances and networks, as well as the roles of industry, globalization and technology"	(Herrmann, 2005)
Uncertainty & uncompleted information	*"***Making decisions under uncertainty and with incomplete** *information requires decision makers to draw inferences about future events"*	(Nerkar & Paruchuri, 2005)
	"Information inadequacy can arise from both **project ambiguity and project complexity**. *Ambiguity refers to a lack of awareness of the project team about certain states of the world or causal relationships (Schrader et al. 1993). Project complexity means that many different actions and states of the world parameters interact, so the effect of actions is difficult to assess"*	(Pich, et al., 2002)
Learning from mistakes	*"One estimate is that 46 percent of R&D goes toward products that ultimately fail"*	(King, et al., 2003)
Capturing relevant information	*"To compete successfully, managers need to be able to scan their environments, identify relevant opportunities and threats, to design responses that will satisfy customers in ways that competitors can't easily imitate, and, finally, to ensure that these plans are implemented, even as the firm competes across a variety of geographies and markets and in mature businesses as well as emerging ones. Yet,* **capturing and distilling relevant information** *isn't a natural capability for most senior management teams"*	(Harreld, O'Reilly, & Tushman, 2007)
Communication	*"The most sophisticated analyses in the world are worthless if findings cannot be communicated to decision makers in ways that will encourage their use. Likewise, if decision makers cannot communicate their needs to analysts, modelers, and outcome managers, or if database administrators cannot communicate with data modelers for that matter, then the entire data-to-knowledge process is at risk. A director of decision support for a consumer goods company says his biggest problem is getting business analysts to present their findings to product managers in ways that they will be understood and accepted as useful."*	(Davenport, et al., 2001)
Evaluation of skills, capabilities and resources	*"Managers of firms seeking to build analytical capabilities* **must evaluate the level and structure of skills needed to support their organization's data analysis capabilities.** *If the skill levels of the business analysts, data modelers, and decision makers in an organization are inadequate, then a firm cannot be getting full value from its transaction data."*	
	"Knowledge management sits well within our understanding of what drives change and motivates innovation. This creates a convenient solution for managers trying to deal with the intangibility of knowledge. Most critically, managers can measure	(Soo, et al., 2002)

	the change in innovative outputs that flow from knowledge management strategies and practices".	
	*"***Resource orientation*** enhances firm performance by improving internal effectiveness and efficiency to achieve new product success, whereas market orientation improves performance by enhancing customer value. These results suggest that managers seeking new product success should* ***focus less on customer value and more on resource value****"*	(Paladino, 2007)
New attribute	*A successful R&D manager is, in many ways, an agent of change. R&D managers must respond effectively to changes in domestic and global competition, product and process technologies, customer requirements, regulatory matters, and senior management's perception of the role R&D plays in a firm. The responses to these changes flow downstream from R&D to other parts of the organization, in the form of new materials, methods, processes, and products. (...) R&D managers may want to rethink who they hire and the kinds of skills needed for the new R&D environment. With R&D needing to collaborate more closely with several groups inside and external to the company, it may want to consider, in hiring, the criteria of technical expertise; the ability to work creatively and productively across the organizational boundaries; and the ability to understand the commercial goals and requirements of the business. These same qualities can be used to evaluate one's current personnel.*	(Gupta & Wilemon, 1996)

Appendix 8:

Table 2.9: Required skills/abilities of decision makers (literature findings), Full version, Chapter 2

Skills	Description	Authors
a 'sense-making' skill	*"the concept of sense-making is so valuable because it highlights the invention that precedes interpretation"*	(Thompson & Walsham, 2004)
Horizon scanning	decision makers have to *"balance threats of loss and opportunities for gain when making strategic decisions"*	(Steensma & Corley, 2001)
	"manufacturing firms will need managers who understand technologies, can tolerate ambiguity and quickly recognise emerging opportunities and can rapidly implement changes"	(St John, et al., 2001)
	That skill is necessary not only in choosing projects but also when considering bottlenecks and approaches to solve issues related to technology or management, or when external conditions changed and organisation has to adapt	(Kaplan, 2011)
	"Managers must ask not only where are the opportunities, but also why should their firm be able to capture and exploit them better than potential competitors. (…) Inevitably, managers will have to shape capabilities according to such related opportunities"	(Miller, et al., 2002)
Visions and integration skills	*Managers' (and entrepreneurs') visions and integration skills that make an important difference in directing the development of these capabilities. Thus, there is a need for managerial vision in thinking about the firm's competitive arena and the trajectory of its future evolution*	(Zahra, et al., 2006)
Leaderships skills	*"An effective leader exhibits specific leadership traits: they (1) exude passion; (2) articulate strategic intent and market vision; (3) imbue technologists with a customer value orientation; (4) provide physical protection (insulate the radical innovation organization to minimize distractions and short-term pressures), psychological support and encouragement (to the radical innovation project team even during the inevitable low points of the project); (5) dedicate sufficient resources and apply appropriately different metrics to assess success than for conventional innovation; and (6) recruit, develop, and retain people who have the robust set of skills, knowledge, and mindset to drive radical innovation"*	(Slater, et al., 2014)
	"Moreover, the leader communicates important organizational values both symbolically and substantively (in storytelling, behaviors, and decisions), and the firm's culture affects both how leaders lead and how new leaders are selected"	(Slater, et al., 2014)
Knowledge management/evaluation	*"Understanding existing knowledge in the strategic context of the firm also facilitates an understanding of the interfaces among products, product families, and technologies and creates a collective sense of strategic direction"*	(Marsh & Stock, 2006)
	"Managers must critically evaluate their resources and talents in looking for hidden gems—trying to determine which are the best employees, which people and units work together best, which technologies show promise, what types of projects and products succeed, and what sorts of customers are attracted to the firm. The best outcomes of reflection are imaginative "re-framings" of the value of different resources, experiences, and relationships"	(Miller, et al., 2002)
	"Leaders must determine which emerging capabilities are most promising and then "select" or embed them as priorities for development. If the targeted set of capabilities is overly large or varied, resources will be too thinly spread to achieve critical mass and competitive superiority. Core or fundamental capabilities must take the lion's share of funds, talent, and visibility—even where this hurts other activities. However, to commandeer resources from "secondary" activities, priorities must be reflected in accountabilities, performance criteria, rewards and promotions, and also in dedicated units and teams and in planning and information systems"	
Revisiting/reviewing failures	*"Organizations that routinely examine their failures as well as successes may, over time, destigmatize failure. (…) if failure is destigmatized, it may lead to more experimentation in the organization, which results in improved new product development performance"*	(Marsh & Stock, 2006)

Appendix 9:

Table A2: Phase 1 interviews 2016– questions for research centres representatives, Chapter 4

#	Questions
1.	Could you introduce yourself also stating your position at the company/research centre?
2.	Could you explain in your own words what a technology readiness measurement process is?
3.	Do you think it is an important process? • 1-not very important • 5-very important
4.	How often do you use readiness measurement process? • 1-not very important • 5-very important
5.	How long have you been working with/using readiness measurement framework?
6.	What does it help you to achieve?
7.	What is the most difficult stage when filling up the framework?
8.	What would you change about it (that particular stage)?
9.	What benefits the framework brings?
10.	What drawbacks the framework has?
11.	Are you familiar with any other frameworks/methods that could be used instead of the one you're currently using?
12.	Do you think it is important to have good verification process? • 1-not very important • 5-very important
13.	What challenges modern research centre struggle with the most?
14.	Do you think readiness measurement framework could help with some of the challenges?
15.	Is there a reason why a readiness measurement framework was not implemented in research centres before?
16.	Do you think it will be difficult to implement such framework? • 1-very easy • 5-very difficult
17.	If a research centre started using their own framework (for early stages of technology development) - would you consider it a good or a bad thing? • 1-very bad • 5-very good
18.	Do you think such framework would/wouldn't be useful? • 1-not very important • 5-very important
19.	If research centre would start using their own readiness framework – do you think that would change anything in the relations between company and research centre? And why?
20.	Do you think it would help if a framework was applied to all Catapult centres (instead of just one research centre using it)? • 1-not helpful at all • 5-very helpful
21.	What kind of benefits/issues a framework would bring if it was actually applied to 7 Manufacturing Catapult Centres?
22.	Why do you think, research centres have not developed such a framework already?
23.	How would you describe maturity?
24.	How important is the concept of maturity? • 1-not very important • 5-very important
25.	How would you describe readiness?

26.	How important is the concept of readiness? • 1-not very important • 5-very important
27.	Do you think the framework should only focus on levels 1-4 or should it cover 1-6? Why?
28.	Do you think the framework should be flexible enough so it can be applied/work well with industrial partners' readiness framework? And why?

Appendix 10:
Table A3: Phase 1 interviews 2016 – questions for participants from industrial companies

#	Questions
1.	Could you introduce yourself also stating your position at the company/research centre?
2.	How involved are you with readiness measurement process (when using readiness measurement as reference and/or as a tool)?
3.	Could you explain in your own words what a technology readiness measurement process is?
4.	Do you think measuring readiness of a technology is an important process? • 1-not very important • 5-very important
5.	How long have you been working with/using readiness measurement framework?
6.	What does it help you to achieve?
7.	What is the most difficult stage when filling up the framework?
8.	What would you change about it (that particular stage)?
9.	What benefits does the framework bring to a company?
10.	What are advantages of the framework brings?
11	What drawbacks the framework has?
12.	Are you familiar with any other frameworks/methods that could be used instead of the one you're currently using?
13.	How does verification process look like at the company?
14.	Do you think the current verification process is good and reliable?
15.	Would you change anything about it?
16.	From the company perspective, if a research centre that you cooperate would start using their own framework, would you consider it a good or a bad thing? And why?
17.	Do you think such framework would/wouldn't be useful for the projects that company is involved? • 1-not very useful • 5-very useful
18.	Do you think it would be helpful if such framework could be implemented into already existing company's readiness process? Or could it actually cause problems? And why?
19.	Do you think it would help if a framework was applied to all Catapult centres (instead of just one research centre using it)? • 1-not helpful at all • 5-very helpful
20.	What kind of benefits/issues a framework would bring if it was actually applied to 7 Manufacturing Catapult Centres?
21.	Why do you think, research centres have not developed such a framework already?
22.	How would you describe maturity?
23.	How important is the concept of maturity? • 1-not very important • 5-very important
24.	How would you describe readiness?
25.	How important is the concept of readiness • 1-not very important • 5-very important
26.	What challenges modern research centre struggle with the most?

Appendix 11:
Table A4: Phase 2 Interviews, 2017- questions, Chapter 4

Section	#	Question
Section 1	1.	Could you tell me a bit about your research centre? What is the focus of this research centre?
	2.	What are the strengths/competencies of this research centre?
	3.	Can you tell me about your responsibilities at this research centre?
	4.	Are your responsibilities directly or indirectly related to technology readiness or product development process?
Section 2	5.	Are you familiar with the concept of Valley of Death?
	6.	How would you describe Valley of Death, to the best of your knowledge?
	7.	Is it a major issue to you and your organisation? • If yes: how this issue has affected the research centre? Is there any current approach to deal with this issue? • If no: why do you think this is not a major issue?
	8.	Do you think this issue, if exists, should be managed by a systematic approach? • 1 – Strongly disagree • 5 – Strongly Agree
	9.	Why do you think some technologies cannot have a successful transition between innovation and full commercialisation stage?
	10.	Could you describe any examples in relation to this research centre?
Section 3	11.	How is 'success' defined at this research centre?
	12.	How do you make a project successful?
	13.	What is the impact of a successful project on this research centre/research community?
	14.	What are the consequences/trade-offs of a successful project?
	15.	What does it mean for research centre when research project fails?
	16.	What is the impact of unsuccessful project on this research centre/research community?
	17.	What are the consequences/trade-offs of an unsuccessful project?
	18.	How would you describe 'success factor', to best of your knowledge?
	19.	Could you name some of the success factors that could be considered crucial when developing a technology?
	20.	Do you agree that each project depends on different 'success factors'?
	21.	Would you say any of them is more important than another?
	22.	In your opinion would it be possible to use those success factors when considering capability of research centre to deliver a project/technology?
	23.	What in your opinion is meant by capability of research centre?
	24.	What do you understand by maturity of technology, and the process of maturing a technology depends on?
	25.	Do you think that maturity of technology could be one of the project success factors? • 1 – Strongly disagree • 5 – Strongly Agree
	26.	If agree or strongly agree, how important maturity of technology would be (i.e. try to compare maturity with success factors respondents named before)?
Section 4	27.	Do you use any process or framework that helps with managing the technology development process? • If yes o Is it a software/methodology/policy that you use? o Why do you use this process? o Was this framework based on any commercial framework? Or was it created especially for this research centre?

		○ What is the outcome of that tool? ○ What is the tool measuring/what are the inputs? ○ What kind of benefits does it have? ○ Are there any shortcomings of this tool? • If no ○ How do you manage product development process? ○ Why any of the industries approaches has not been implemented at the research centre? Any particular reason why? ○ Would it help if a research centre had a framework that could help with managing the product development?
	28.	How do you justify to clients that your research centre can deliver certain projects?
	29.	Do you think it would be more beneficial for research centre to have a framework that focus on technology maturity or rather one that focus on capability maturity of a research centre? • Why do you think that framework would be more suitable/more applicable?
	30.	In order to make the framework practical, what should be the outcome/deliverables of such framework?
	31.	If those deliverables are achieved, what in your opinion they could help with?
	32.	What elements/aspects, in your opinion, should be considered as inputs (to be used by the framework)?
	33.	Why do you think those factors should be measured?
	34.	If there was a framework that could help with managing technology development- do you think it would be better if it was in the form of • software or • management methodology or • policy?
	35.	Why would that format be preferable? Why do you think that format would be better than others?
	36.	If such format was applied- do you think the development process would be better understood by research team or other people at research centre?
	37.	What issues you can think of, if framework with such format was applied to a research centre?
	38.	Do you think it would be possible to implement such framework to all HVM Catapults (to have one technology maturity framework with optional aspects that could be added/removed based on the nature of research centre)? Why?
	39.	Would you say there would be some potential benefits/issues if a framework was applied to all HVM Catapults?
	40.	Would you say that's the reason why such framework has not been developed already?
Section 5	41.	Are you familiar with road-mapping process?
	42.	In your understanding – what is a road-mapping process?
	43.	Do you use road-mapping at the research centre? • If yes: to what extent? Is it used at operational, tactic or strategic level?
	44.	What is the key output of the road-mapping process?
	45.	Could you name some of the benefits that road-mapping brings?
	46.	Would you say that road-mapping process is suitable for technology/innovation development? • 1 – Strongly disagree • 5 – Strongly Agree
	47.	What challenges modern research centre struggle with the most?
	48.	Does road-mapping help with those challenges? • 1 – Strongly disagree

		• 5 – Strongly Agree
	49.	What types of challenges affect technology development the most?
	50.	What aspects or what kind of activities/tasks need immediate improvement?
	51.	Would you say some of the challenges happen due to lack of appropriate strategy for development process or due to lack of clarity of how advanced research centre is at certain processes/activities?
	52.	Would maturity management framework help with some of the challenges or would it be better to have a capability framework for evaluating certain aspects of research centre? • If yes- with which ones?

Appendix 12:

Table A5: Phase 3 Interviews 2018- questions, Chapter 4

Category	#	Questions
Software X	1.	Do you use Software X?
	2.	How useful do you think it is? On a scale from 1 to 5: 1 - not useful 5 – very useful
	3.	Why do you use it/Why you do not use it?
	4.	What do you think is the biggest benefit of Redmine?
	5.	What do you think is the biggest challenge/problem when using Redmine?
	6.	The most recent projects, (e.g. from 2018) are not included in Redmine, which means that people have stopped using it. Why do you think that is? Is there another program that they use instead? Why do they prefer other program over Redmine?
	7.	Do you know what are the outputs delivered by Redmine?
	8.	If possible would you like to see some other results delivered by a programme like Redmine?
	9.	What else would you like to change about it? What functions would like it to have? What do you think is missing at the moment?
	10.	Do you think a simpler programme e.g. Excel would help with the challenges that you previously mentioned?
	11.	Do you think it would be helpful for RC 1 to have one database that captures information from different team/projects?
Customer feedback		In the customer feedback form there are 5 categories: Quality score, Delivery score, Working relationships, Responsiveness of RC 1 and how likely customers are to recommend RC 1 to others.
	1.	The results show that the lowest score RC 1 received was for Delivery of service/support and for responsiveness to clients – why would you think that is?
	2.	Do you think that results could be improved?
	3.	How do you think RC 1 could improve those results?
		The lowest scores (the ones that were just mentioned) were obtained from Directly Funded or CORE projects.
	4.	Do you think those projects are run/managed in a different way than other projects?
	5.	In general, what do you think could change with regards to how projects are managed? What steps or tools are missing at the moment? a. Do you think –the steps you just described- how difficult it would be to implement them? b. Who would need to get involve to implement those changes/steps?
	6.	When a negative feedback is received from customer – the feedback is passed on to management team, what happens next? What actions are taken?
	7.	Do you know how does a team react to a negative feedback? (i.e. how the team usually plan to improve the score/do they think of some steps to improve it)?
	8.	Based on results from customer feedback forms, clients are the most satisfied with working relationship with RC 1. Would you agree or disagree with that?
	9.	Would you say there are other aspects that should be asked in the customer feedback?
	10.	How would you describe the collaboration between teams at RC 1 at the moment? Is there anything lacking in how the teams are managed or how information is passed between teams?
	11.	Do you think that the customer feedback results affect how different teams interact with each other at RC 1?
	12.	Do you think that the collaboration between different teams could be improved? If yes- how?
Funding	1.	What is the biggest challenge when applying for funding?
	2.	Once the funding is assigned - what are the biggest difficulties when managing such funding?
	3.	Could you tell me what details the team or RC 1 need to provide when applying for funding? For example, do details like what kind of machinery we have or what knowledge we have – do all those details have to be highlighted?
	4.	How those details are captured? Is there any system/process/data that support statements like that?

	5.	Is it usually one source where the team gets the funding from or does it differ depending on the project?
	6.	Once the funding is assigned to a project, who is then managing the funding? Is it a team leader or a different team member?
	7.	Do you know how the funding is managed during the lifetime of the project?
	8	Are there any challenges connected to funding, during the lifetime of a project?
	9.	What happens when a team or a research centre applied for funding and did not get it? What are the next steps?
	10.	Does it happen often that the application for funding is rejected?
	11.	Would you know why funding could be rejected? Or not assigned to a project?

Appendix 13:
Table 4.10: Challenges regarding programme management software (full version), Chapter 4

Challenges	Explanation	Quotes - Examples	Frequency
Not intuitive, not automatic, limited functions	Requires additional steps in order to modify data or to see different visual results	*"for example if you are going to log your hours or change some you know minus some date you know and everything, then it takes ages, it's loading, loading, loading, but it may take like a couple of minutes to refresh it, and sometimes it doesn't do it, so you have to keep doing it. (…) it slows down your progress,"* Participant 7	10
		"overall it wasn't very functional. The system what it was trying to do I think is what we all want, but just that system wasn't up to it." Participant 18	
Time consuming	Affects team's efficiency, requires extra time to add/modify information	*"it requires programming and lots of manual manipulation of the data to get from point A to point B. also time consuming."* Participant 1	9
Not user friendly/poor interface	Hard to find information, difficult to upload information, a lot of manual manipulation is needed, it's not automatic, it's slow	*"I think the biggest frustrations are the ease of use of the system"* Participant 3	9
		"The biggest challenge is really extracting all the information you might need." Participant 9	
		"the user interface isn't that good. Visibility of it isn't that good" Participant 14	
		"I think there is something in the system that doesn't allow the people to upload easily information and make sure that information is right" Participant 16	
Not reliable/outputs are not reliable	crashed before and lost a lot of data	*"the whole program has been written is very poor, and I know that might be to do with configuration, but the reality is is that a latency, so you can use a gatnt chart, but there's a latency on it, so you've constantly got to refresh it so you've updated your gantt chart but when you've updated it's not reflected in what you've done"* Participant 8	8
	if information showed is wrong- you cannot see if it is wrong, the visual representation does show every information – it's not accurate	*"I think the reason why they're unhappy when they have to use redmine is because they are not convinced that the information that's being taken out of it, it's worthwhile. They can't rely on it and because they can't rely on it they think it's a waste of time putting the information in"* Participant 10	
		"unfortunately it doesn't have accurate information, I cannot rely on it" Participant 11	
		"it's never correct, it's never, it will never be 100% correct but it should be a snap shot which is as accurate as the day it was at that time, but it's not even close to being good enough to educate how we actually make decisions" Participant 13	
Only used because there's nothing else	Used out of necessity	*"It is the only program available here"* Participant 4	6
		"why do you use it? Necessity. I do use it when its necessary. So out of necessity." Participant 5	
		"I think it's used just because it's just, we've actually chosen as a centre to use, and so it is actually out of necessity." Participant 12	
Not good for project planning/cannot compare projects	limited access to use it/poor usability, difficult to add new tasks	*"Another problem with that is if you run the project, middle of the project you realise okay (…) you need to create a task, then what will happen is, - (…) a new task, then sometimes it confuses and then it like doesn't work very well. Yes so you need to have all the tasks loaded from the beginning"* Participant 7	6
		"I think it's quite difficult to navigate, to actually use as a tool, and I believe also it's quite difficult to then modify" Participant 15	

	It doesn't show bigger picture, nor incoming load	*"there's a lot of bugs within it, so multiple projects wouldn't talk to each other and the information the team leads for instance the output to get the correct information (…) and things like that isn't correct"* Participant 18	
	It doesn't show baseline information for the whole team	*"people are frustrated by the lack of capacity planning from it. It doesn't have, I don't know if it's very good at capacity planning"* Participant 5	
		"It's difficult to say how people are loaded at certain times." Participant 17	
	It's difficult to check progress	*"the output that it gives varies every time that you do it."* Participant 13	
No maintenance, it's not up to date	No ownership of the programme, no one can fix the bugs	*"If there is any problem there is no maintenance, no people fix it. The system is not maintained, so if like one function is not working then not working for all the projects."* Participant 2	5
		"I think the AFRC systems doesn't make it clear who is responsible to look after it. That makes it useless, otherwise the software might be works, I looked at it in the past, I used it to some extent, but because it's not up to date, it's not useful anymore." Participant 11	
Scalability is not possible	The volume of data is too big for the programme	"the number of projects grow, the complexity of projects is growing, that the system is not able to cope with the demands of what we need to use it for," Participant 4	3
		"it's unreliable and when you do try and use it it can't take the volume of what we're throwing at it, so it just falls over." Participant 13	
It doesn't work people are using different things i.e. no standardization	No standard procedure in terms of how teams capture data and compare projects, therefore every project summary is different	*"it kept falling over, and essentially it wasn't able to do anything we wanted to do, and it was just easier to stick to the spreadsheets to be honest."* Participant 10	3
		"redmine doesn't have the functions that team leads actually need" Participant 12	
		"people just started using other systems." Participant 13	
People are not trained to use it properly, to its full ability	No training was provided to teams, hence teams don't know how to take full advantage of the programme	*"I don't use it frequently enough to fully understand its function, I always have to go through a re-reminder, but also I get other people to potentially fill it out for myself as well."* Participant 12	2
Cannot connect with other tools/not compatible	Not able to add it to MS Project or Power BI etc.	*"you can't directly link Power BI to EasyRedmine database, because no one really knows how it works."* Participant 1	2
		"in scalability or connection to the system it isn't there, so you can't write stuff into Microsoft Project or vice versa and it doesn't translate very well when you start putting stuff in." Participant 14	
It's corruptible	People can 'trick' the system	*"but people also play the system of Redmine, so it's corruptible, so it doesn't give a true representation of what happened in the centre"* Participant 12	1

Appendix 14:

Table 4.11: Why would a centralised database/system be helpful at the research centre?, Full version, Chapter 4

Category	Quotes - Example	Frequency
Access to information and transparency across RC 1	"Yes, that's my dream (to have one database at AFRC that captures all the information)" Participant 1	8
	"Yes, I think since we're growing and we've got different you know activities around the centre, I think it would be very helpful to have one, something which is perhaps in house or maybe we get some subscription to some other like a very helpful software which are available on the market, then using them, yes." Participant 7	
	"we need very very quick answers to all the information and really have the projects and clients and so on, for example for me it is very important to have information about biggest contacts for a certain company, and I would like to know where the projects are exactly, with that company, because it might be part of how I conduct my projects and so on, so the information on the project, everything is very important there." Participant 9	
	"Yes we need that, so with the metrology team especially we work across every project almost, if the manufacture is apart and you measure it, it comes through our lab, and that's one of the problems that I face with Redmine, and even now, is that you're only given access to the project if you have an activity on it." Participant 13	
Centralised system/database controlled by RC 1	"Yes I think for any system it is essential that you have a central, like for example, like this, you have a central data and provide different whatever people want, so either generate a report on different aspects or provide different phases of information. Otherwise it's the data consistency that's a problem it always cause" Participant 2	7
	"one database that people input the plans, the milestones, the work packages, that they book their hours against, you know all of these things so it's from one single source, it's managed through a single source, and that means the reporting is only done through a single source as well" Participant 3	
Managing workload within the team and outside a team	"Yes definitely, it allows you to better program, because most of our projects are multi-disciplinary, they're across the different teams and not just sitting in one team, so we definitely need something where we can do that." Participant 6	5
	"I would like to know where the projects are exactly, with that company, because it might be part of how I conduct my projects and so on, so the information on the project, everything is very important there. (if you had access to say like how the projects are going, if there's like a good progress or a bad progress because that would influence how you have the conversation?) Yes, absolutely, the topics and the projects and the types of funding, yes so and we have an idea for a project that might be good for that company, but I need to know if somebody already has projects under that title or under that topic and so on, so at the moment finding things out, searching the background takes quite a lot of time, and you need it all in a snap shot, all appearing on the screen ideally." Participant 9	
	"it will be good to have something in front of me to say oh the scoop press is not available through that period of time, and that system actually does that, it tells you highlights of scoop press might be in use during that period of time for like 50% or 10% of the time, and then you can then plan your work accordingly" Participant 11	
	"you want to have everything centralised and look at things like allocation, look at machines and things and everything in totality, if you do it in isolation you'll get clashes and you'll get miscommunications and stuff like that." Participant 14	
	"Absolutely. With team allocation and resourcing, to see if someone is busy" Participant 15	
Introduction of standard	"there should be a database for the RC 1 that allows you to distract the information from it in many different ways, it could be done by teams, it could be done by sector, by contact, just whatever" Participant 10	2

method to collect and present information	"I think there's software packages where you can record the information once, then you can manipulate that data, present it however you wish, but you've still got the same data set" Participant 12	
Useful for management	"this kind of information it will be good for people who are managing RC 1" Participant 17	2
N/A	Participant 5, Participant 16	2
Not useful to have database	"Well that might be for the director, I'm not sure how much use that would be to me. I think my answer to that would have to be no not really" Participant 8	1

Appendix 15:

Table A6: How the customer feedback forms could be improved? (full version), Chapter 4

How it could be improved?	Quotes - Example	Frequency
Managing customers' expectations	*"managing expectations is a big part of the reason why we get bad scores for customer satisfaction I think"* Participant 6	6
	"it might just be a case of making the client base a bit more aware of what's involved. So if somebody phones up and says can I have a quote for something, you say certainly, just bear in mind, and it's like adding these extra two sentences on, so people understand." Participant 8	
	"there's an expectation the skills are already there, you are already the expert and you're going to deliver work like in a consultancy approach, which is not the case in research. I think the expectations are different, that's why they score differently." Participant 16	
Ask more details/more qualitative comments	*"I think is we can detail them a little bit further, to ask more, so we are now measuring more quantitatively, we just have one comment about, but it would be better to have more words coming out of them, more qualitative comments as well, but obviously we want to put a boundary."* Participant 1	6
	"I mean they're quite high level, I guess we could go into a bit more depth" Participant 14	
	"I've seen the form we use, are a bit is very high level, I think we are asking, targeting the right area, you know it is not wrong, but we could be more clever and capture more clever information you know about communication, about reporting, the quality of the delivery, the quality of the reports, so I think we are too vague" Participant 16	
	"It can have a good relationship and it doesn't mean that you do a good job" Participant 17	
Asking how delivered service/product impacted the business	*"asking how useful it actually was to the customer, you know so how effective it was, so that the customer receive that they are then seeing the benefits that they thought they were going to see in their industry"* Participant 3	5
	"But we need to translate things into an application. And then get a bigger picture. A lot of people are coming up with the ideas for things, solutions to problems that don't necessary exists. And that unfortunately is the lack of experience from industry, from different sectors." Participant 5	
	"I think it would be useful to know how more specifically the customer feels from the outcomes of the project. So the impact, yes, to have a little bit more information available." Participant 9	
	"we could ask how engaging with RC 1 impacted them as a business." Participant 10	
Value for money	*"I think one thing that's maybe missing there is value, value for money perhaps, because even you know all, the quality could be good, the delivery could be on time, the working relationship could be good, we could be responsive, but I think if they paid an arm and a leg for something, that's not, and it's probably they're not going to then be a value to a customer unless all those things have been crossed"* Participant 4	4
	"did they get what they expected out of it, did they get more than what they expected out of it, yes I mean it's a difficult one, obviously we don't want to, we're giving these forms out to everyone and having, getting them to fill in 20 pages, it's quite, so I think probably it's more the description of those are quite queer." Participant 14	
Could we do anything better?	*"So that will form part of the overall improvement project just to say what are we doing just now, can we do it any better?"* Participant 3	3
	"perhaps something that I would add would be how we could have proceed the work, the current project, which would influence better. You know it could be perhaps the quality score or something, or like asking them to put a comment, like if the quality is a bit low, what's their room to improve, you know what we need to do next or what we should have done for example, something like this." Participant 7	
Cost/Time/Quality	*"one of the very good suggestions that one of the guys came up with was as well as talking about did we deliver the project on time and on cost, or at the cost and the hours that we thought we were going to"* Participant 3	3

	"if we're going to measure ourselves on anything it's going to be is what we're doing the right thing, is the quality of what's been received been deemed to be appropriate? Have we done it on time? Have we done it to a reasonable budget?" Participant 4	
	"but are we still delivering on time as well, you know, so as they expect, yes." Participant 6	
Standardised questions	*"I used to just do a summary, just an A4 page summary and we used to send it out to everybody and it said, it used to take us this long to make this component and now it only takes us that long, so we've saved $100 per component, and we would send that out. So that would just, on one page, be a very clear yes, that was successful, that project was good, we did what we said we were going to do and here is the benefit. So that might be something that's quite worthwhile to do as well."* Participant 3	3
	"it would only be again those standard questions that you could start to see trends if they're going up or down, so it becomes a different task to do the analysis on." Participant 13	
Future work with companies	*"it is selling ourselves and it is explaining why we are good at what we do, so it was just an idea."* Participant 3	3
	"I think one thing that might actually be interesting to capture is the future work aspect. Helping us to again classify how engaged they are for the future work to actually occur in those situations, and also yes the proactiveness of that follow up work needs to be more aggressive, more energised, and the hand of course to other teams as well." Participant 12	
N/A	Participant 17	1

Appendix 16:
Table 4.12: Teams' collaboration at the research centre – summary, full version, Chapter 4

Teams' collaboration	Quotes - Example	Frequency
Teams need to see bigger picture	*"In this environment I think we should be working collaboratively. We should always have targets no doubt about it, but I think the targets should be at the centre level and the teams should work together to achieve it rather than have separate targets."* Participant 14	10
Lack of communication/lots of assumptions	*"Yes lack of communication and also the interest, lack of communication"* Participant 2	8
	"I think there's probably an element of forming team and some other team not talking to each other that much. And future forge maybe not talking to each other. So there's probably a breakdown and a room for improvement." Participant 5	
Structure does not encourage the collaboration	*"I think that the structure that's been put in place where (…) every man is an island sort of thing."* Participant 4	8
	"there's certainly an element of compartmentalisation." Participant 8	
Financial targets drive wrong behaviour	*"every team has targets and every team is been driven to targets, financial targets I should say, not necessarily quality, delivery, etc., the targets, the only targets that I have seen that have been imposed on teams, imposed is the right word, have been financial, which perhaps drives the wrong behaviour, because if the behaviour was on quality and delivery, we are likely to get return business, (…) anywhere I think, the realisticness of those financial figures are, in fact they are unrealistic financial figures, and with I think old school, prohibits people from wanting to work together, because everyone wants their piece."* Participant 4	8
	"they would see it from the point of view that they don't want some other team to take their job, because of the financial point of view." Participant 7	
	"because the teams are working towards financial targets set for, so it does impact how people think about it, you know but I would like to have a way of assembling the right teams." Participant 9	
Need for project managers/cross-team coordinators	*"because each team have their team leads and the people working for the project, they're supposed to do one thing, if there was a project manager at the same level with their team leads, that would be less conflict of interest and less, like that would be more hierarchy but it would be easier to maybe organise and see from different perspective, is it prioritised with what is going on."* Participant 1	3
	"there's nobody at the moment who has cross- team responsibility. But I think it would be really helpful to have somebody or a couple of people who have cross-team responsibility. Because, when the enquiries come in, most of them you can tell ok it's for that team and so on, but there are big ones that come in that are cross-team and it's the coordination of that, at the moment I think it's that is lacking." Participant 10	
Inconsistent approach on how teams operate	*"I think because teams you know, especially team leads, they can improve it, for again, I would say that's how the things work, and they're really dependent on team leads."* Participant 7	2
Lack of rules enforced by management	*"team leads and management need to be stronger and rules need to be in place to enable us to do things better, and if there is no level of consistency across the leads, how they operate the teams, none whatsoever, so some team leads would like their teams to be in all at the same time in the morning, some have more flexibility. Flexibility is fine, but I think there needs to be some sort of commonality"* Participant 4	2
Most meetings are not effective	*"because most of rely on meetings, yes, and meetings are not always most effective, they're complicating, so yes sure they can be improved, like even this project management, if we apply project management systems, that may change things drastically."* Participant 1	2

	"I'm not sure about that meeting, that meeting can actually result in people just moaning about things not happening. Now there needs to be like a monthly type meeting that is very very focused on which areas that the different teams can pool together on" Participant 8	
Resource constrains	*"I think we are very busy, again, doing a lot of things, multi-tasking"* Participant 16	2
Need contingency plans when planning a project	*"So there's instances like that where the bare minimum is planned, but there should be some extra in there as contingency, but we don't do that because the customer wouldn't want to pay for it, and that's part of the problem is trying to balance the cost because we are quite expensive with the quality of work that we do."* Participant 13	1
Slow in terms of decision making	*"we tended to be quite slow in terms of decision making, and we're also quite hierarchical with our decision making processes (…)it would help with the inter team activities for sure, and just because people would feel more empowered to basically make a decision that this is what you and I have discussed this, we're going to do this, and then they know they've got the confidence that that's within their remit, and therefore you know they'll then make those decisions more regularly"* Participant 15	1
Lack of interest	"(…) *it's also the interest, people need to be interested in discussion with other people as well, from different team"* Participant 2	1
Collaboration between different teams across centre	*"there is some kind of team where people in different roles are included but also maybe a horizontal fashion in a way, you know there could be collaboration between engineers from different teams, just because the project is technically close for that, I would like somehow to be able quite quickly to harness that interest. I'm not sure it's easy to do, you know I would have to go through a few, you know just like with the project information background for example, company information background, the same with the availability of resource."* Participant 9	1
Team Leads' behaviour/attitude	Participant 7	1
N/A	Participant 3	1

Appendix 17:

Table 5.6 Definition of Capability Maturity Levels, full version, Chapter 5

CML	Descriptor	CML Description
CML 1	Immature Capability	Initial and very generic capability observed at a very low maturity level. Team has little experience in TC and needs to develop their skills and knowledge. Team members have limited number of skills they can perform or only theoretical knowledge about some particular skills. However team knows about basic manufacturing processes related to TC.
		Equipment is not based at the research centre (offshoring) or it has not been used yet. Hence team members have minimal understanding of equipment for this TC.
		No completed projects in this TC.
CML 2	Basic Capability	Basic knowledge and skills demonstrated by team members. Practical skills in need of further development. Knowledge of regulatory issues affecting work and safety in relation to this TC.
		Equipment/machines are placed at the research centre however, those are typical machines that could be found in other research centres. Basic understanding of the equipment has been shown. Process of identifying projects requirements and which projects the equipment could be used for started. Therefore, team has a basic understanding of a few features but it still requires more learning/training in order to use machines on standard projects.
		Small, internal projects with small impact on research centre completed, e.g. basic trials demonstrating concept and application i.e. low impact on the research centre: mainly projects that involve desk work or basic trial demonstrating concept and application, meaning read across from academia. Only one area covered: product requirements, no practical/physical trials started.
CML 3	Defined Capability	Team members demonstrated knowledge but still require more practise to improve their experience. Also, need more training in order to develop practical skills. However, they show good team working skills, organisational and interpersonal skills, i.e. team shows good foundation for maturing process.
		Machines located in the research centre for this TC are somehow specialised but seen in several research established. Team aims to achieve correct standard but is still investigating stability of machines. Hence, there is a good understanding of key features, but the training and further understanding of the machine is still needed.
		Project involved only one stakeholder i.e. directly reporting to one client and only standard work required (i.e. something that was done before, no innovative aspects). Team learns to understand key variables when considering work that is a 'cross-over' from other sector. The completed projects involved work that identified key process variable, understanding effect of parameters' modification etc. Two areas covered: product requirement and manufacturing processes.

CML 4	Intermediate Capability	Team has some experience and proven it by contributing successfully to various projects. Still, certain skills need further development. However, the ability to develop technical skills have been identified and there is a potential to develop advanced level of skills. Team works well together however communication problems might arise, hence team lead need to make sure tasks are properly distributed among team members.
		Equipment placed at the research centre, but it might be also available in different manufacturing centres in the country. Standard features understood and used during several projects, i.e. standard outputs achieved. Team has a clear understanding of how to use the machine in order to deliver standard solutions. Teams makes use of key functionality of the machines but more advanced features still to be understood.
		Small amount of projects completed. Projects mainly involved one stakeholder and standard work with minimal innovative activities. Projects mainly involved trial phases to demonstrate key aspects of fundamental process understanding/ what materials can be tested by the equipment/ verification of the feasibility of achieving acceptable standards. 3 areas covered: product requirement, manufacturing processes and operational.
CML 5	Upper Intermediate Capability	Team members have high level of experience through previous full time employment, i.e. their theoretical knowledge in the general field is quite high. Hence, their skills are developed and can be applied in physical trials i.e. were demonstrated on a variety of projects. Team members do not need much supervision or guidance, they are able to work autonomously given guidance from team lead ot senior management.
		Equipment is based at the research centre and has some non-standard features, which makes it hard to duplicate, but also shows its uniqueness. Understanding of machines is well developed and machines are used in a variety of projects e.g. to confirm optimal specifications for a product/process, i.e. making further contribution to a methodology. The understanding of machines is advanced i.e. standard features are well understood but a further learning process is still needed to understand additional, non-standard features and manage them with confidence.
		Projects involved one or more stakeholders and mostly innovative work has been completed with some standard processes included. Projects delivered key process variables and identified method of control, i.e. projects solidified the methodology process. Hence, it delivered clear guidance of how to repeat process in the future to deliver same results. 4 areas covered: product requirement, manufacturing processes, operational and data & systems.
CML 6	Pre-Advanced Capability	Team members demonstrated successful application of their experience on a variety of projects. Team knows how to apply their knowledge and come up with innovative results. Strong theoretical knowledge and practical skills. Team members can learn from each other and transfer knowledge onto skills others (within the team) who lack those skills. Team members are able to work autonomously with minimal guidance.
		Equipment for this TC has extensive unusual features which makes it more unique and important to research centres. It also allows to apply innovative solutions which has not been demonstrated elsewhere. Machines were used to develop standard outputs (plus at least one-off to production standard). Equipment has been used within full scope of use. Equipment is well understood by the team, and some team members are able to train others and explain standard and non-standard features of those machines.
		Projects had medium impact on UK sectors, but they were collaborative projects. Combination of standard and innovative work was performed. Also projects results were compared with results from other places in order to build a robust methodology for a processes involved. Projects involved work that was completed on representative standard kit, and so process methodology was demonstrated on representative production equipment. 5 areas covered: product requirement, manufacturing processes, operational, data & systems and project management.

CML 7	Advanced Capability	Team members have a broad experience and can be even regarded as experts for this TC. They have advanced/in-depth knowledge and practical skills in a various areas of this TC. Those skills were developed over time and experience have been gained through a variety of projects. Applicability and high level of skills can be observed on a daily basis when team works on their projects. Team members can work autonomously with minimal input from senior management. Some team members know how to manage grant awards and can train others in doing so. Some team members also showed leadership skills which helps when team will be welcoming new members to the team.
		Equipment for this TC is recognised regionally and it is a key local differentiator for the centre. It possesses demo functions at a local level. It was used on a variety of projects, from basic standard activities, to innovative solutions where production standard output (multiple-off) was demonstrated. Machines for this TC are well understood by the team. Fundamental processes as well as additional features were confirmed and demonstrated on a variety of projects, i.e. team has a high level of confidence when using equipment for this TC.
		Projects completed at this level were highly collaborative projects with various stakeholders involved. Completed projects had high impact on UK sector and on companies involved. Projects involved innovative applications with some bits of standard work. Projects also confirmed aspects of new product/process when applied to low rate production trial. Projects also involved early stage or sub-optimal factory production. 6 areas covered: product requirement, manufacturing processes, operational, data & systems, project management and IP.
CML 8	Strategic Capability	Team members with advanced/in-depth knowledge work well together and together lay the foundation of matured TC with international reputation. Team members develop knowledge and skills through various projects in alignment to HVMC strategic direction. Furthermore team members have the ability to influence stakeholders and convey compelling arguments with complex technical information. Team manages projects with high organisational level and resolve any challenges through advanced communication and team working skills
		Team also uses a key piece of equipment which can be also used as demonstration equipment for HVMC. Projects has been completed by and understanding of the machines evolved by conducting innovative test and using machines in non-standard ways. That approach allows to identify new aspects of the machine and create new set of criteria. With the increased usage of equipment the understanding also increased and a defined methodology for new features has been created.
		Having highly performing team and advanced level of understanding of equipment, team has no truble with completing big projects with multiple stakeholders involved. Completed projects are highly innovative and have significant impact on customers. Projects involve knowledge of production processes and team shows extended knowledge in regards to process parameters involved. Those projects also cover 7 project areas (product requirements/manufacturing processes/operational/data and systems/ IP/project management/quality assessment) providing that team has broad understanding of project management and wider view of external factors that are affecting the research centre. Hence, by completing those projects they proved that they have continuous improvement process in place and methodology has been tested and applied trough this TC.

CML 9	Fully Matured Capability	Team members score high, and majority of them have vast experience in TC. Team members can be trusted with managing projects and with supporting others. Team members have a broad spectrum of knowledge and work on implementation of that knowledge and skills in innovative solutions. Team members also show high level of organisation and transferable skills, as well as communication. Team works well together and supports each other when technical challenges arise.
		Team also uses unique equipment that cannot be replicated elsewhere, which has significant impact on a research centre. The knowledge in relation to the equipment is advanced and there is a proven track record within and out of scope of use. Other non-standard test also has delivered satisfying results. Hence, high level of knowledge and understanding of the equipment as well its application in innovative solutions has been proven.
		Having and experienced team and unique equipment gave an opportunity to complete challenging projects that involved major industrial companies. Those projects provide evidence of highly innovative approaches and significant impact created on manufacturing industries. Those projects cover 8 project areas (product requirements/manufacturing processes/operational/data and systems/ IP/project management/quality assessment/supply chain) providing that team has broad understanding of project management and wider view of external factors that are affecting the research centre. Hence, by completing those projects they proved that they have continuous improvement process in place and methodology has been tested and applied trough this TC.

Appendix 18:

Table A7: Technology Capability view – Summary page (III): potential risks and recommendations for each sub-dimension (Example from a TC with CML 6), Chapter 5

Sub-dimension	Potential Risk	Recommendations
D1.1 Experience	If neglected- experience may stay at the same level and when required to improve it, team members might not have interest in or enthusiasm to gain new experience. It is also important to monitor that there is more the one person with key experience in the team, as people might choose to change jobs. Therefore, experience should be equally distributed among team members.	Monitoring that BML for this sub-dimension does not decrease. It is recommended to improve experience of team members (even if it is not required at the moment). Having reached BML 5 means that planning for reaching next BML may start now and it could be organised while completing daily routines. That way team members have time to adjust to new responsibilities and change is not overwhelming for them.
D1.2 Technical Skills	If neglected- various skills might not be developed and when needed, there might not be enough time to apply new knowledge/skills. Also, team members might not have interest in or motivation to improve their skills further. Hence, it is also important to monitor that there is more than one person with key skills/knowledge, in case key person is not available or leaves the research centre. Also, having more than one person with particular skills allows team to address more projects and takes pressure off the only person with required skills.	Monitoring that BML for this sub-dimension does not decrease. It is recommended to improve skills/knowledge of team members (even if it is not required at the moment). More skilful team members can guide and support lower level team members and oversee their progress. Hence, training team members can be organised while completing daily routines, and without time pressure, i.e. steadily. It means that 'weaker' team members have enough time to develop their skills, which gives a team an advantage in regards to TC maturity.
D1.3 Transferable Skills	If neglected- transferable skills may stay at the same level or might even decrease if team members have no motivation to improve them. It is also important to monitor that communication and organisational skills are not decreasing as those might affect technical work. Without effective communication, projects might not be finished on time and/or more conflicts may arise.	Monitoring that BML for this sub-dimension does not decrease. It is recommended to plan for improving transferable skills of team members as early as possible. Effective communication and good level of organisation will allow team to complete projects on time, improve teamwork and avoid potential conflicts. In order to achieve effective communication, team members must feel trust and be able to rely on their team lead. Team lead should objectively recommend most appropriate solutions. Team leads should consider the content of communication as well as the way team members communicate.
D2.1 Uniqueness	If neglected- the importance of equipment might decrease and machine might lose its uniqueness. It is important to learn about machines the team is using for their projects. Understanding various functions and how results can be changed/modified will bring an advantage to the team and to the centre. Understanding machine that is unique in the Catapult network also bring value to the centre and helps with advertising research centre's TCs. The more unique equipment, the more advantage research centre has in that TC.	Having reached BML 9 means that it is important to maintain this BML for this sub-dimension. Planning and organising work in relation to BML 9 should be one of priorities and advantage of this TC. Decision makers should use that as their advantage to promote work at the research centre. By developing their knowledge and applying it to various projects, innovative results can be delivered to clients. Hence, having unique machine is not enough- team needs to understand it and use it in order to maturity this TC.

D2.2 Outcome delivered	If projects are usually the same, it means that team members are not challenged and might not think of innovative solutions that could be applied through available machines. Hence, equipment should not be used only for standard projects but also for innovative ones, or used in non-standard way. It means that knowledge about the equipment is increasing and other sub-dimensions are also positively affected by it.	Monitoring that this BML for this sub-dimension does not decrease. It is recommended to improve experience of team members in relation to equipment and how it is used. By completing more projects that require non-standard application of the equipment, the knowledge about equipment increases and so is the successful rate of applying machines. Such projects could be later used as examples to promote research centre.
D2.3 Level of understanding of the equipment	If neglected- understanding of the equipment might stay at the same level and so team members will not be challenged to apply innovative solutions. It is also important to monitor that there is more than one person that knows how to use the equipment and that the knowledge about the equipment increases and gets distributed among team members. If the only person with valuable knowledge about the machine leaves the research centre, then the maturity level for this sub-dimension will decrease dramatically (which could also affect another sub-dimensions).	Monitoring that BML for this sub-dimension does not decrease. It is recommended to start planning how BML 9 could be reached. As team members have efficient knowledge and are able to reach higher BML that should be encouraged by team lead. Projects that involve improving this BML should be considered and more time dedicated to learning about equipment should be included in team's schedule. Also understanding of standard and non-standard use of equipment should be distributed among team. One person should not be an expert in all the machines but knowledge should be distributed among team members. Training sessions for those who do not have extended knowledge about the equipment should be arranged.
D3.1 Impact and collaboration level	If neglected, the quality of work can decrease and less impact is created by projects completed by the team. Less impact means less collaborations and more repeated work with lower impact. Reviewing lessons learnt and applying those in up-coming projects will take up some time which might affect the team and the maturity level.	Monitoring that BML for this sub-dimension does not decrease. It is recommended to analyse what types of projects have been completed by the team and how successful those were. Also, having reached BML 8 means that planning for reaching next maturity level may start now and it could be organised while completing daily routines. Team leads should also consider to start looking at projects that received lower scores and review lessons learnt in order to apply those in future projects (in order to keep BML 8). As improvement related to past projects and lessons learnt might take a while, it is a good starting point to start this process as soon as possible, or delegate task to a team member to keep a log of projects that scored lower marks and alternative solutions.
D3.2 Outcomes delivered	If neglected- experience may stay at the same level and projects delivered by the team might only focus on lower technological outputs. If team members work on similar work for longer time, they might lose motivation and it will be more difficult to get them to implement innovative solutions. Also, by having to deliver the same types of projects, skills and knowledge do not develop and the probability of applying innovative solutions decreases. That is why more challenging projects are needed to constantly develop team's skills and mature TC.	Monitoring that BML for this sub-dimension does not decrease. It is recommended to improve experience of team members by delivering more challenging projects that require innovative applications. Those team members who have 'immature skills' should be guided by mature team members and develop new skills under their supervision. It is also recommended to start looking at projects that received lower scores and review lessons learnt in order to apply those in future projects. It will be also good to monitor quality of projects delivered and review which team members have mature enough skills to be involved with more challenging projects, where they can apply their new skills.

D3.3 Project areas covered	Potential risks involves team members not wanting to change their work habits and adapt new approaches. Changing behaviour is the most difficult and people often do not want to change their habits, which may cause conflicts. Hence, not completing new tasks (e.g. covering more project management areas) should be highlighted by team lead. Team leads should also explain to teams why this is important and what impact it has on the rest of the research centre. Without monitoring what areas of projects are covered, it is vague what has been done on a project and it is also difficult to identify in which areas teams struggle and where they need help. It means that information like that could support future recruitment as it could highlight problems with specific areas e.g. project management, quality assessment, not enough engineers etc. By not having this info, there is a risk that team will struggle with the same issues and no changes will be apply as there are no evidence of those issues.	9 out of 18 projects need to be reviewed in order to improve the BSL. Results shows that none of the listed areas of project management were covered during those 9 projects. That shows high risk of project management perspective and suggests that better project management approach should be put in place. Decision makers, or team leads, need to ensure that team members involved in projects should know what areas have been covered and which have not been covered, and why they have not been covered. Also, putting minimum effort to improved BSL for this sub-dimension should not be too demanding. It is important to keep monitoring the project management approach among team members.

Appendix 19:
Answers from preliminary results from Small-scale Validation, Survey 1, Chapter 6

8. CMF will be useful to support my role

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Agree

9. CMF provides useful data for TECHNOLOGICAL road-mapping implementation

Participant 1	Participant 2	Participant 3
Strongly Agree	Strongly Agree	Disagree

14. I will be able to access useful and detailed information regarding individuals, equipment and projects through CMF to understand relevant challenges

Participant 1	Participant 2	Participant 3
Strongly Agree	Strongly Agree	Agree

15. I think the Capability Maturity Index with clear definitions will be helpful when communicating our technological progress WITHIN the research centre

Participant 1	Participant 2	Participant 3
Strongly Agree	Strongly Agree	Agree

16. I think the Capability Maturity Index with clear definitions will be helpful when communicating our technological progress OUTSIDE the research centre (e.g. with members or industrial partners)

Participant 1	Participant 2	Participant 3
Strongly Agree	Other (comment included in Future Work)	Agree

17. CMF makes us aware of our own (i.e. centre's) maturity

Participant 1	Participant 2	Participant 3
Strongly Agree	Strongly Agree	Agree

18. CMF will help with aligning Technological Capability with strategy (so there is a clear link between those)

Participant 1	Participant 2	Participant 3
Don't know	Strongly Agree	Agree

19. CMF supports management of technological gaps in the research centre

Participant 1	Participant 2	Participant 3
Strongly Agree	Strongly Agree	Agree

20. CMF provides a good and general overview of the research centre's Technological Capabilities

Participant 1	Participant 2	Participant 3

Strongly Agree	Other (comment included in Future Work)	Agree

21. Our research centre will benefit from using CMF by understanding gaps and strengths (e.g. in relation to skills, experience, application of various machines/software etc.)

Participant 1	Participant 2	Participant 3
Strongly Agree	Strongly Agree	Agree

22. I would like to use the Capability Maturity Framework in the future

Participant 1	Participant 2	Participant 3
Strongly Agree	Strongly Agree	Agree

23. In my opinion there is a need for a standard tool that captures data about research centre's Technological Capabilities

Participant 1	Participant 2	Participant 3
Strongly Agree	Strongly Agree	Agree

24. In my opinion, CMF could become a standard tool for capturing maturity of Technological Capabilities at the research centres

Participant 1	Participant 2	Participant 3
Strongly Agree	Other (comment included in Future work)	Agree

25. CMF could become a standard tool to manage capability maturity across HVMC

Participant 1	Participant 2	Participant 3
Strongly Agree	Strongly Agree	Don’t know

26. CMF will help with increasing awareness about the capability of research centres improving transparency between Catapults

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Don’t know

Appendix 20:

Answers from preliminary results from Small-scale Validation, Survey 2, Chapter 6

9. I think CMF will be useful to identify weaknesses or areas of improvement (e.g. limited understanding of a piece of equipment/machinery, certain skills only demonstrated by 2 team members, etc.)

Participant 1	Participant 2	Participant 3
Strongly Agree	Other (comment included in Future Work)	Agree

10. I will be able to access useful information through CMF in regards to PROGRAMME challenges

Participant 1	Participant 2	Participant 3
Strongly Agree	Strongly Agree	Agree

11. I will be able to access useful information through CMF in regards to TEAM challenges

Participant 1	Participant 2	Participant 3
Strongly Agree	Strongly Agree	Agree

12. CMF will help identify challenges ACROSS different PROGRAMMES/TEAMS

Participant 1	Participant 2	Participant 3
Strongly Agree	Strongly Agree	Agree

13. CMF will provide data in regards to future investment in facilities and manpower

Participant 1	Participant 2	Participant 3
Agree	Strongly Agree	Agree

14. CMF provides objective results regarding the research centre's Technological Capabilities

Participant 1	Participant 2	Participant 3
Agree	Strongly Agree	Agree

16. The process of assigning risk to various aspects/sub-dimensions of Technology Capability is clear and understandable

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Disagree

17. The process of assigning recommendations to sub-dimensions of TC is clear and understandable

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Agree

18. I would like to see more detailed risks/recommendations in order to address capability gaps

Participant 1	Participant 2	Participant 3
Disagree	Other (comment included in Future Work)	Disagree

19. I would like to see results from different HVM Catapults in the future

Participant 1	Participant 2	Participant 3
Strongly Agree	Strongly Agree	Agree

20. The definitions of CMI are clear and understandable

Participant 1	Participant 2	Participant 3
Agree	Agree	Agree

21. The definitions of CMI are accurate

Participant 1	Participant 2	Participant 3
Agree	Agree	Don't know

22. The CMI definitions are reliable

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Don't know

23. The CMI definitions are practical

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Don't know

24. The CMI definitions are feasible and helpful

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Agree

25. CMI definitions reflect Maturity Levels adequately

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Agree

26. The process of creating CMI definitions is clear and understandable

Participant 1	Participant 2	Participant 3
Agree	Agree	Don't know

27. I believe results presented in the presentation show accurate reflection of capability maturity at the research centre

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Don't know

28. Results shown in the presentation are a helpful indication of maturity level and a good starting point for implementing capability maturity process

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Agree

29. Results presented provide a strong foundation for strategy building at the research centre

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Other (comment added to Future Work)

30. Results presented are close to your expectations

Participant 1	Participant 2	Participant 3
Strongly Agree	Strongly Agree	Other: yes at this stage

31. If you had different expectations regarding results presented, could you explain what you were expecting to see (if there isn't enough space below, please e-mail me directly)

Participant 1	Participant 2	Participant 3
n/a	n/a	Good start but some surprising results (e.g. AM) make me question results

32. I would like to use the Capability Maturity Framework in the future

Participant 1	Participant 2	Participant 3
Strongly Agree	Strongly Agree	Agree

33. The presentations showed how data was collected and analysed (i.e. presentations showed transparency of the CMF process)

Participant 1	Participant 2	Participant 3
Agree	Strongly Agree	Other: comment included in immediate work

34. Do you think CMF should include more dimensions/sub-dimensions? If yes- please state which ones should be included

Participant 1	Participant 2	Participant 3
no	n/a	Other: comment included in Future Work

35. CMF and CMI offer consistency of measurement

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Other: comment included in Future Work

36. CMF and CMI offer standardised mechanism to determine Maturity of Technology Capabilities

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Agree

37. The study could deliver similar observations for other Catapults (if they participated in this study)

Participant 1	Participant 2	Participant 3
Agree	Agree	Don't Know

38. The concept of CMF have relevance to other activities of the research centre

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Don't Know

39. There is a clear difference between CMI levels and their definitions and I will have no issue distinguishing between them

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Other: comment added to immediate work

40. If you think certain CMI definitions are too similar and confusing, please state which ones
n/a

41. If you would like to change any CMI definitions which ones would you change? Could you also explain why?
n/a

42. CMF process is 'fit for purpose'

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Other: not yet but could be

43. In my opinion it is clear how each different CMI level is assigned

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Agree

44. CMF provides clear understanding of capability maturity, i.e. it is a prerequisite for TRL/MRL (maturity needs to be achieved before readiness)

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Other: is CMF a prerequisite for TRL/MRL?

45. In my opinion it is clear how risk is assigned to various aspects of CMF

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Disagree

47. In my opinion it is clear how recommendations are assigned

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Other: is this a repeat of Q17?

48. Recommendations proposed by CMF are accurate

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Don't Know

49. Recommendations proposed by CMF are helpful and useful

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Other: they are useful assuming they are accurate

51. Recommendations for Teams and Programmes are helpful and present an adequate indication of what sub-dimensions need improvement WITHIN Team/Programme

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Agree

52. Recommendations for Team and Programmes are objective and show accurate overview of improvements needed ACROSS the research centre

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Agree

53. The results provide a good approximation to the capability gaps in the research centre

Participant 1	Participant 2	Participant 3
Strongly Agree	Agree	Agree

54. This study has included a sufficient number of perspectives

Participant 1	Participant 2	Participant 3
Agree	Agree	Agree

Appendix 21:
Table A8: Final Validation - Survey 1, Chapter 6

1	Are you working at a research centre at the moment? (select one answer only) • Yes- I work at NMIS/AFRC/LMC • Yes- I work at one of the HVMC research centres • Yes- I work for a research centre that is not part of HVMC/NMIS • No- I am working for industry • Other (Please specify)
2	What is your background, i.e. what is your role at the research centre/in your company? If you are not working at the research centre, could you also explain your relationship between your company and the research centre? [space for comments]
3	How many years of experience do you have in this particular role? [space for comments]
4	Could you list some of the well-known tools/frameworks that could be used to manage readiness/maturity? [space for comments]
5	Could you list some of the tools/methods you are currently using (or used before) to manage readiness/maturity? [space for comments]
6	Did you take part in data collection process in 2019? • Yes/No
7	Is your work related to • Technical activities (e.g. manufacturing engineer) • Operational activities (e.g. operations engineer, project manager) • Strategic activities (e.g. team lead, technology officer) • All of the above • Other (Please specify)
8	Research centre needs tools like Capability Maturity Framework to understand and improve their TECHNOLOGICAL capabilities • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
9	The CONTENT in the Capability Maturity Framework is objective • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
10	CMF PROCESS of evaluating Capability Maturity at the research centre is objective • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
11	The structure of CMF (3 dimensions: People, Equipment, Projects) and further 9 sub-dimensions (3 sub-dimensions in each dimension) are a good representation of a research centre's capabilities • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
12	I will be able to access useful and detailed information regarding individuals, equipment and projects through CMF to understand relevant challenges • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
13	A research centre will benefit from using CMF by understanding gaps and strengths/weaknesses of a research centre (e.g. in relation to skills, experience, application of various machines/software etc.) • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
14	CMF provides an appropriate amount of detail to identify capability related gaps • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
15	In my opinion there is A NEED for a standard tool that captures data about research centre's Technological Capabilities

	• Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
16	In my opinion, CMF could become a standard tool for capturing maturity of Technological Capabilities AT A RESEARCH CENTRE • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
17	CMF could become a standard tool to manage capability maturity across HVMC • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
18	CMF will help with improving transparency between HVM Catapults • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
19	I think CMF could help with transferring knowledge and building common strategy between HVM Catapults • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
20	CMF will support TECHNOLOGICAL decision making and/or planning • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
21	CMF supports TECHNOLOGICAL road-mapping implementation • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
22	CMF will support OPERATIONAL decision making and/or planning • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
23	CMF supports identification and management of technological gaps in the research centre • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
24	CMF provides clear understanding of capability maturity (i.e. research centre understands its own weaknesses and strengths) before taking on a project • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
25	I believe CMF provides information that could be used when discussing future projects with members/clients • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
26	CMF process will be useful when guidance in CORE programme development is needed i.e. to understand how successful projects were and what new skills/methodologies were developed • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
27	CMF process will be helpful when considering future investment/manpower decisions • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
28	CMF could be used as diagnostics and capability evaluation tool at the research centre in the future (i.e. to identify weaknesses and areas of improvement e.g. limited undertaking of a piece of software etc.) • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
29	CMF process will be helpful when planning Catapult programme • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
30	CMF could become a consistent approach among NMIS • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
31	Data in the Capability Maturity Framework can only be input by team leads or senior management personnel to protect results from any 'data manipulation' • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
32	In the future, results should be reviewed by senior management or technical director to ensure participants provided objective information • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
33	The transparency about data collection and interpretation has been demonstrated • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
34	The presentations showed how data was collected and analysed (i.e. presentations showed transparency of the CMF process) • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer

35	CMF should include more dimensions/sub-dimensions • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
36	Please use the space below to add your comments/suggestions/concerns/questions [space for comments]
37	Please use the space below to highlight any limitations that you think the CMF presently has [space for comments]

Appendix 22:
Table A9: Final Validation - Survey 2, Chapter 6

1	Are you working at a research centre at the moment? (select one answer only) • Yes- I work at NMIS/AFRC/LMC • Yes- I work at one of the HVMC research centres • Yes- I work for a research centre that is not part of HVMC/NMIS • No- I am working for industry • Other (Please specify)
2	What is your background, i.e. what is your role at the research centre/in your company? If you are not working at the research centre, could you also explain your relationship between your company and the research centre. [space for comments]
3	How many years of experience do you have in this particular role? [space for comments]
4	Could you list some of the well-known tools/frameworks that could be used to manage readiness/maturity? [space for comments]
5	Can you list some of the tools/methods you are currently using (or used before) to manage readiness/maturity? [space for comments]
6	Why are you using those particular tools/methods? [space for comments]
7	Did you take part in data collection process in 2019? • Yes/No
8	Is your work related to • Technical activities (e.g. manufacturing engineer) • Operational activities (e.g. operations engineer, project manager) • Strategic activities (e.g. team lead, technology officer) • All of the above • Other (Please specify)
9	CMF will be useful to support my role • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
10	CMF is informative as it provides current capability maturity levels and gaps • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
11	The CMF will be able to identify PROGRAMME challenges • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
12	The CMF will be able to identify TEAM challenges • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
13	CMF provides a clear and accurate high level overview of the centre • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
14	CMF and TRL-like processes could complement each other (CMF covering what research centre can do, and TRL what product/service needs to be delivered) • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
15	The CMF definitions are (select all answers that you agree with) • Feasible/Helpful/Practical/Accurate/Relevant/True reflection of Maturity Levels/All of the above /Other
16	Recommendations proposed by CMF are helpful and useful • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer

17	Recommendations for Team and Programmes are objective and show accurate overview of improvements needed ACROSS the research centre • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
18	Results showed in Presentation 3 (select all answers that you agree with) • Are accurate • Are relevant • Are helpful • Show a good indication of capability maturity at the research centre • Show transparency of how different Technology Capabilities are used in different Programmes/Teams • Show distribution of various Technology Capabilities (e.g. some Technology Capabilities are used only in one Programme and some are used in 3 or 4 Programmes) • Other
19	In my opinion the process how each CMI level is assigned (select all answers that you agree with) • Logical/Accurate/Relevant/Practical/Clear/All of the above/Other
20	In my opinion definitions of CMI are (select all answers that you agree with) • Clear/Understandable/Logical /Relevant/Practical/Helpful /All of the above/Other
21	There is a clear difference between CMI levels and their definitions and I will have no issue distinguishing between them • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
22	The process of assigning risk is (select all answers that you agree with) • Clear/Understandable/Logical/Relevant/Practical/Helpful/All of the above/Other
23	CMF and CMI offer (select all answers that you agree with) • Standardised mechanism to determine Maturity of Technology Capability • Accuracy of measurement • Consistent approach for a research centre • Good foundation for communicating our technological progress • Transparency • Good approach for building resilience • Identification of skills gaps • Support for decision-making • Connection between technology capabilities and strategic planning • Other
24	Results from CMF provide a strong foundation for strategy building at the research centre • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
25	CMF will support STRATEGIC road-mapping implementation • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
26	CMF will support STRATEGIC decision making and/or planning • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
27	CMF will help with identifying gaps when aligning Technological Capability with Industrial challenges/Cross-sector challenges • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
28	I would like to use the Capability Maturity Framework in the future • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
29	I think CMF will be a valuable addition to the research centre I work at/with • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
30	I would like to see more detailed risks/recommendations in order to address capability gaps • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer

31	I am satisfied with the Capability Maturity Framework at this point and would like to see it developed further • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
32	Why do you think some Technology Capabilities scored better than others? (select all the answers that you agree with) • Some Technology Capabilities are used only in one Programme i.e. scored higher as fewer Programmes depend on them) • Participants had too much confidence in their teams • Technology Capabilities with lower scores were new at the time of data collection • I think results show good reflection of Maturity levels of Technology Capabilities in 2019 (as data collection took place in 2019) • I agree with the results but if data was collected in 2020- the results would have been different • I think data should be collected every year to show progression of maturity of Technology Capability • Other
33	Could you please explain why you agree with the answer(s) in Q31? Could you please explain why you marked those answers? [space for comments]
34	Presented results are close to your expectations • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
35	If you had different expectations regarding results presented, could you explain what you were expecting to see (if there isn't enough space below, please e-mail me directly) [space for comments]
36	This study has included enough examples of Technology Capability to demonstrate potential of Capability Maturity Framework • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
37	In my opinion CMF meets the capability requirements of a research centre • Strongly Agree/Agree/Don't Know/Disagree/Strongly Disagree/Other/No Answer
38	If you think certain CMI definitions are too similar and confusing, please state which ones [space for comments]
39	If you would like to change any CMI definitions which ones would you change? Could you also explain why? [space for comments]
40	Please use the space below to add your comments/suggestions/concerns/questions [space for comments]
41	In your opinion, what steps research centre could implement in order to adopt the CMF? [space for comments]
42	Please use the space below to highlight any limitations that you think the CMF presently has [space for comments]
43	After seeing all 3 presentations - what you would like to add/modify to improve the usefulness of CMF? [space for comments]

Appendix 23:

Table A10: Participants' concerns related to data input and reliability of results, Section 7.11, Chapter 7

Participant	Quote	Category
P111	*You need to explain how data was taken, collected How we can control the input?-need to be clear How was subjectivity controlled?-need to be clear*	Data collection process
P117	*How we rate people as participants – that could be biased but at the same time team leads could also be biased and could not be the best choice to provide data*	Bias/Subjectivity of data
Q27S1 P106	*If it will be possible to prove that this data is reliable*	Reliability
Q10S1 P124	*Agree generally, but, it's also populated by subjective data*	Bias/Subjectivity of data
Q10S1 P121	*I would need to experience the data collection to confirm*	Data collection process
Q24S1 P106	*Maybe, but me personally would trust more to my own experience and knowledge of people, equipment, etc*	Reliability
Q11S2 P106	*Yes, if it will be fed with trustable information, otherwise it can strongly mislead*	Bias/Subjectivity of data Reliability
Q13 S2 P106	*Maybe, but at least results shown in the presentation 3 significantly contradict my knowledge of situation in AFRC... Apparently due to the lack of input data*	Not enough data
Q13 S2 P108	*It doesn't cover all teams or technical themes so not at this time*	Not enough data
Q13 S2 P109	*Due to the initial subjective nature of the assessment, the accuracy of the data could vary significantly. There needs to be appropriate checks and balances to ensure rigorous evaluation of data before it is entered into the CMF*	Bias/Subjectivity of data Review process
Q13 S2 P121	*Not necessarily on its own but coupled with other information and standard marketing media yes*	
Q17 S2 P108	*indicative rather than accurate I would suggest*	Reliability
Q17 S2 P109	*I think that there are some areas that do not appear to reflect reality - e.g. Additive judged to be level 6, yet is still an emerging technology globally; Material Testing level 5, yet this is a very well established set of technologies, and one that the AFRC is considered to be a leader in the HVMC. This confirms my earlier statements on voracity of initial assessment data*	Bias/Subjectivity of data
Q17 S2 P109	*I had my expectations for the results but it doesn't mean that my expectations were right – that's why we need review process*	Review process
Q17 S2 P111	*While the process appears objective and auditable/repeatable, the input data remains subjective*	Bias/Subjectivity of data
Q17 S2 P105	*Will need to look into the input results further*	Review process
Q40 S2 P111	*My greatest reservation is the conflation of subjective input data and objective outputs.*	Bias/Subjectivity of data Reliability
Q40 S2 P117	*need to dehumanise/standardise data input*	Bias/Subjectivity of data
Q42 S2 P115	*Assessment is subjective, does it account for areas of equipment and processes we don't have/use?*	Bias/Subjectivity of data
Q42 S2 P104	*If scored by different team leaders could be optimistic/pessimistic by area.*	Bias/Subjectivity of data
Q43 S2 P101	*How data can be accurately input by more people than project lead, how could this data be collected*	Bias/Subjectivity of data
Q43 S2 P117	*just the data input, methodology is sound and logical*	Bias/Subjectivity of data
Q42 S2 P109	*Voracity of assessment data*	Reliability
Q37 S1 P111	*The subjectivity of the basic inputs remains an issue for me. Perhaps an uncertainty bar in results?*	Bias/Subjectivity of data

Q37 S1 P109	*I think the greatest limitation right now will be the veracity and consistency of initial scoring*	Bias/Subjectivity of data
Q37 S1 P106	*The level of objectivity of the data*	Bias/Subjectivity of data
Q37 S1 P117	*Having people rate themselves and others is difficult to do objectively, may include bias.*	Bias/Subjectivity of data
Q37 S1 P116	*If the assessment is done by in-house staff, the data will not be objective*	Bias/Subjectivity of data
Q37 S1 P107	*Objectivity is not equal to quantification. How to evidence the data so that it is objective*	Bias/Subjectivity of data
Q37 S1 P106	*The level of objectivity of the data*	Bias/Subjectivity of data

Appendix 24:
Table A11: Comments regarding time and effort needed to provided data into CMF, Section 8.6.1., Chapter 8

Participant	Quote
Q19 S2 P108	*risks being time consuming / laborious to maintain*
Q19 S2 P121	*I do think initially the process is tricky to grasp and I needed to review a number of times. I guess I may have benefitted from asking questions. You just need to be careful that the process is a clear and simple as possible for the end user, i.e. do not show them unnecessary detail if not needed.*
Q42 S2 P130	*Interested in understanding how long it takes to complete the framework*
Q42 S2 P129	*Cumbersome*
Q42 S2 P104	*Fairly complex and time consuming to gather data, needs regular review to account for improvements*
Q40 S2 P130	*Process needs simplified. It would take a very long time to assess all of the centres capabilities*
Q40 S2 P120	*All the graphs and tables are quite overwhelming but a good attempt was made at keeping it simple.*
Q37 S1 P125	*Takes LOT of time to complete, comprehensive but hard to internalise difficulty comparing diff techs*
Q37 S1 P120	*Make it as simple as possible so people are more willing to adopt it.*
Q37 S1 P105	*Concern would be amount of effort required to maintain CMF over time*
Q37 S1 P128	*It is a little complex and this could limit uptake*
Q36 S1 P104	*It looks like a relatively intensive process*
Q36 S1 P100	*Appears to be lots of data being collected, don't know if it needs to be as complex to start with*
Q37 S1 P119	*User experience may seem complex to some due to the visualisation method. However, with a simplification of the visualisation of the data much more complex data could be captured to give a more accurate representation for the scoring method*
Q36 S1 P119	*I think though this needs much more complex and deeper data collection points. This is definitely the right route to progress forward with. The visualisation of the data and user experience should be created using principles of simplification*
Q37 S1 P120	*Make it as simple as possible so people are more willing to adopt it.*
P133	*CMF is complex. Try to simplify to departmental level*

Appendix 25:

Table A12: Suggestions regarding modifications to definitions used in CMF, Section 9.2., Chapter 9

Participant	Quote
P100	*someone used the software in the last 0-5 years- that will give more defined definitions*
P100	*Also definitions should show differentiate between industrial or research experience E.g. someone has 30 years of experience – that exceeds PhD as it is applied knowledge or Advanced level that would be PhD or 5 years of experience in industry*
P100	*we could have that much years of experience in this industry that means we can operate in mid TRL levels For example: It would help if we knew if the person worked on TRL 1, TRL 2, etc. – how many years they worked at this position/doing that and when was that experience used (last month/5 years ago, etc.)*
P107	*Definitions needs to be more clear to reviewers : how many bullet points you have to hit to achieve e.g. level 4 – just one bullet point or all bullet points – that should be clearly defined (how person gets to the next level)*
P107	*Uniqueness- it is the USP but you don't have to mature it, and from the definitions it seems like you have to mature it; Terminology could be better – to define uniqueness*
P107	*Stakeholders being involved- it is more important what you are doing on the project than no of collaborators for example We could have very mature capability but we could be working with one client only*
P107	*Impact of what you do on a project – could be a measure of maturity*
P110	*Definitions have to be properly formulated – do we have maturity for all skills or just blocks of skills*
P110	*Need to be careful about whether they need to comply with the whole list or only part*
P115	*I think all 9 are open to interpretation, misuse, being used out of place and some could change order*
P116	*Clear but might be slightly subjective (a 4 or a 5 very similar).*
Q15S2 P100	*need to bounded better - too subjective*
Q15 S2 P106	*logical*
Q15S2 P110	*I think some of these need some work. e.g. why is number of stakeholders important for Capability Maturity when looking at Projects? Impact more important*
Q15S2 P108	*Confusing descriptors on each CMI level, does there need to be 9? Can't there just be 3 to 5? It's open to interpretation and easy to disengage with as so many levels*
Q19S2 P100	*I feel they need to be reduced from 9 to 5. Too much choice, also subjective*
Q19S2 P110	*Some make sense, but not all, so worth further discussion I think*
Q37S1 P100	*Not sure if it can tell me years of experience/level using equipment and what sector applicable*
Q40S2 P110	*Is equipment uniqueness necessary for capability maturity? Some of the definitions suggest so*
Q42 S2 P108	*open to interpretation and misuse*
Q43S2 P100	*Simplify, too much room for subjective opinion*
Q43S2 P110	*Better definitions*

Appendix 26:

Tables from Section 9.6 Additional Comments, Chapter 9

Table A13: Answers to Q37 S1: Please use the space below to highlight any limitations that you think the CMF presently has

Participant	Comment Quote
P104	Some clear keys at the side of tables to indicate the colouring of certain numbers

Table A14: Answers to Q40 S2: Please use the space below to add your comments/suggestions/concerns/questions

Participant	Comment/Quote
P100	Not sure if a requirements document for the project was defined at the outset. This is key.
P115	Accuracy of figures for the CMF is too high. it is a tool for high level analysis and trends

Table A15: Answers to Q42 S2: Please use the space below to highlight any limitations that you think the CMF presently has

Participant	Comment/Quote
P111	Needs to have confidence limits stated with the outputs as the outputs should not be seen as exact.
P120	The CMF is limited by not looking at the performance of the centre on projects
P102	Does it identify improvements in capability? ie last year we had - this year have etc.

Table A16: Answers to Q43 S2: After seeing all 3 presentations - what you would like to add/modify to improve the usefulness of CMF?

Participant	Comment/Quote
P105	Each team will need to develop reference key for each dimension to show how those were evaluated
P120	No immediate suggestions.
P116	Unable to view P2 -sorry!
P114	As mentioned, include assessment of performance of the centre
P131	3D Diagrams could help to visualise the results
P125	Need more than 100 characters to give you meaningful feedback. Needs to be clear and concise
P121	As before I've found it a little tricky to appraise fully having not been involved with data capture