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Future Technology Landscapes

Insights, analysis and implications for defence

Maryse Penny, Tess Hellgren, Matt Bassford

FINAL REPORT

RAND EUROPE

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Prepared for Dstl

The research described in this report was prepared for the Defence Science and Technology Laboratory (Dstl).

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Foreword

With increasing levels of scientific and technological development worldwide, there is a growing volume of primarily civil-related technology that can both potentially impact and be exploited into defence and security capability.

Two studies were commissioned independently from RAND Europe and the Institute of Manufacturing, University of Cambridge to investigate technology landscapes out to 2035 to provide different perspectives and insights into future technology and innovation models which will be relevant to the MOD.

Technology foresight is notoriously poor in 'picking winners'. Rather than do this, the landscaping studies attempt to identify the relevant 'races' that defence and security organisations must address, and the skills and expertise we must develop to exploit or influence emerging winners. In particular, for the UK MOD the studies identify where wider investment (for example, Technology Strategy Board, Research Councils, and other Government investment) can be leveraged or complement future defence science and technology investment.

The studies provide independent views of the technology landscape. Although by necessity both are limited in scope, each has identified a number of valuable insights and recommendations. While we do not endorse all the findings, and indeed highlight that some of the issues identified are already being addressed successfully, we commend this report to all those involved in planning defence and security science and technology.

Alex Churchill
Defence Science & Technology Deputy Head Strategy, Ministry of Defence

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Preface

In January 2013, RAND Europe was commissioned by the Defence Science and Technology Laboratory (Dstl) to conduct a study on the future landscape of defence technology development. The specific objectives of the study were to: identify where MOD and non-MOD investments in research and technology (R&T) are likely to shape future UK technology capability of relevance to defence; and to explore enablers and barriers for the MOD in maximising the impact of its increasingly limited R&T budget.

This research should be of interest to officials of the Ministry of Defence, and more specifically to those involved in forward-looking decisions about technology, investment, acquisition, logistics and strategy. It should also be of interest to stakeholders with involvement in critical technology research, development and funding across government, academia, business and the defence industry.

RAND Europe is an independent not-for-profit policy research organisation that aims to improve policy- and decision-making in the public interest, through research and analysis. RAND Europe's clients include European governments, institutions, NGOs and firms with a need for rigorous, independent, multidisciplinary analysis.

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Summary

1. What were the objectives of the study?

The context for defence innovation has changed significantly recently for two reasons. First, the past five years saw significant declines in both research and development (R&D) and research and technology (R&T) budgets, while sustained austerity is expected to continue to shape available defence spending. The declining investment in defence innovation and technology development presents a particular threat to the long-term sustainability of the defence research base. These changes have reinforced a wider trend in recent decades: the shift of the innovation centre of gravity from defence to the civilian sector. Leveraging civil investment – and ensuring that defence investment is targeted in areas where it can most add value – is critical.

In January 2013 RAND Europe was commissioned by the Defence Science and Technology Laboratory (Dstl) to conduct a study on the future landscape of defence technology development. The primary focus of the study was to help the UK Ministry of Defence (MOD) assess and harness wider investment in relevant UK technology areas. The specific objectives of the study were to:

- Identify where MOD and non-MOD investments in R&T are likely to shape future UK technology capability of relevance to defence
- Explore enablers and barriers for the MOD in maximising the impact of its increasingly limited R&T budget.

We employed a structured methodology involving a range of qualitative and quantitative approaches.

- The first phase of the study was focused on mapping the context within which innovation takes place through stakeholder interviews and conducting a systematic review of publications related to emerging technologies. An inductive approach was developed to review published material on emerging technologies. From this analysis, 16 salient cross-sector technology areas were identified.
- The second phase of the study was designed to explore five emerging technology areas through high-level case studies, namely: additive manufacturing, advanced materials, cybersecurity, small-scale energy storage and synthetic environments.
- The third phase of the study involved more detailed case studies of two technologies: additive manufacturing and synthetic environments.

Findings were drawn from each phase of the study and validated through internal workshops and road-testing with MOD stakeholders.

2. What were the main findings of the study?

Effective exploitation of emerging technologies requires the creation of suitable pathways, relationships and synergies

Innovation does not occur in isolation but relies on interactions between a range of actors within a complex 'ecosystem' comprising dynamic links between actors and rapid knowledge exchange. Our analysis suggests that there are five overarching roles performed by six key groups within the UK's technology landscape. Table 0-1 summarises the principal activities in which UK technology development actors are involved; shaded cells correspond to significant expertise and involvement.

Table 0-1 Primary activities of the main UK technology development actors

	Policy and strategy	Procurement	Funding and investing	Performing	Connecting
Government Departments	X	X	X	X	
Technology Strategy Board	X		X		X
Research Councils UK	X		X	X	X
Higher Education Funding Council			X		
Academia			X	X	X
Businesses		X	X	X	

The UK is generally perceived to be strong at early stage R&D but to have more limited capabilities in commercialising technology. Public sector organisations such as the MOD play a key role in shaping and supporting the wider innovation ecosystem, using both supply-side and demand-side mechanisms to stimulate innovation. It is important that the MOD understands the role that it plays in this regard and the consequences that its actions have. Our analysis suggests that small- and medium-sized enterprises (SMEs) find it very difficult to plug into MOD processes or lack the know-how and resources to enter competitive and uncertain procurement procedures.

In 2011, the UK gross domestic expenditure on R&D (GERD) was £27.4bn, and total R&D expenditure represented 1.79 percent of Gross Domestic Product (GDP). This is significantly below the 2.5 percent target set by the UK government and also below the EU-27 average of 2.0 percent of GDP.

The importance of active engagement from the MOD in stimulating, shaping and translating future technology was highlighted by all interviewees as critical in fostering an ecosystem conducive for defence innovation. Several initiatives were mentioned that contributed towards effective coordination – including the Centre for Defence Enterprise – but there were mixed views on their success to date. However, an overarching theme from our interviews was that the MOD has become increasingly insular in recent years.

MOD's concept of technology innovation is relatively narrow, with a primary focus on new 'things' and a linear model for investment in technology

One major theme that emerged throughout our study is the emphasis that the MOD has tended to place on developing new 'things' as a result of its research spending. Our respondents highlighted the importance of other aspects of the technology landscape such as the ability of technology to help improve processes; logistics, maintenance and support; new modes of training and testing; and in particular the opportunity for technology and innovation to deliver efficiency benefits as well as improved effectiveness.

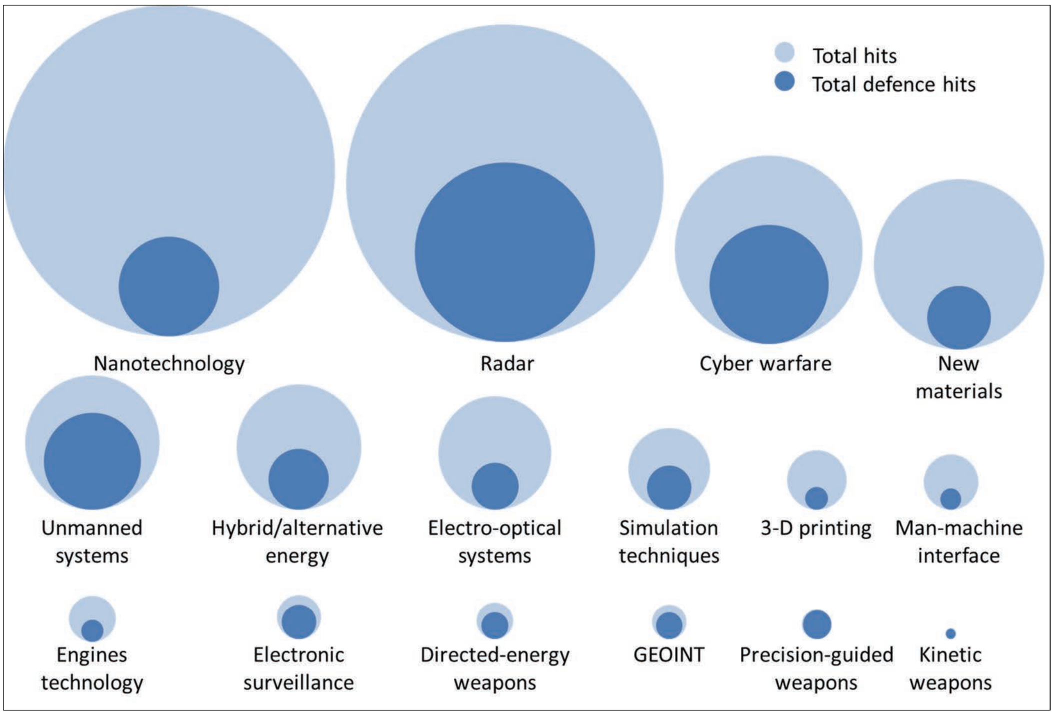
In addition, the MOD typically utilises a focused – but somewhat linear – approach to research investment, with priority given to 'solving problems' through research spending and the use of road-mapping to target relatively short-term research objectives. The rationale was to maximise the outputs from UK defence research spending and focus efforts on those areas of capability in which it was most important to develop or retain an operational advantage.

The interviews and analysis we have conducted suggest that this linear approach is likely to be an inefficient way for the MOD to maximise returns on its investments in terms of future military capability. Not only has the MOD's investment in R&T declined substantially in recent years but other changes have occurred too. The development cycle for new military capabilities has decreased to reflect changes in threats; there is greater application of civilian technologies to defence; and the defence enterprise is becoming increasingly internationalised – on both supply and demand sides.

The relationship between civil and defence interests in emerging technologies varies significantly by technology area

Based on an assessment of over 84 recent publications, we identified 16 emerging cross-sector technologies with particular relevance for defence; these are detailed below in Figure 0-1 which also shows the total publication activity by technology area and the split between overall hits and defence-specific hits. Nanotechnology, radar and cyber warfare were the most prominent technology areas in terms of publication activity, accounting for approximately 70 percent of the sources we identified.

Figure 0-1 Publication activity in salient technology areas



Source: RAND Europe analysis

Technology areas differ significantly from one another in terms of potential, profile and transformative impact

The team performed two in-depth case studies on additive manufacturing (AM) and synthetic environments (SE), using a combination of interviews and analysis of the publicly available evidence base. Those two technology areas were selected due to their relevance to the study objectives, the strength of the UK R&D base and the stakeholder interest.

Additive manufacturing has the potential to have a number of transformative effects. For example: increased customisation of goods, localised production, added functionality and more intricate design. However, how this impact will materialise is uncertain. Therefore, the MOD can do a lot to prepare for the uptake of AM as well as working to understand what this technology means for its business. There are four main aspects for which the MOD should prepare as AM technology matures, namely:

- It is important for the MOD to continue to develop an understanding of the ways in which AM will be most relevant.
- Although the MOD has some clear areas of interest and overlap with AM, it currently has no role in shaping and helping the advancement of AM research.
- It is also essential for the MOD to actively engage with its supply chain in order to understand the uptake of AM and its potential consequences.
- Finally, the MOD should assess how such facilitated manufacturing will impact on long-term capacity planning.

By contrast, not only does MOD currently use **synthetic environments**, it was also an early adopter and indeed pioneered the use of video game technologies within its training programme. However, it seems that following this early push, not only has the MOD lost part of this momentum – especially in comparison with other countries – but it also has been more reluctant to explore and adopt additional possibilities offered by SE. Moreover, in addition to not making full use of SE products, the MOD has also not embraced the organisation-wide changes and efficiencies that SE can facilitate.

This can be explained by the fact that MOD's structure, processes and culture are not adapted to leveraging SE innovation or to influencing the technology area. The MOD's structure and culture limit the adoption of an SE-enabled environment due to the high level of centralisation. Moreover, current MOD processes are inadequate to take full advantage of SE's potential. For instance, SE is a fragmented, fast-changing landscape with a multitude of very innovative SMEs, which seek to sell their products quickly and update them on a regular basis. The MOD's current procurement processes include lengthy lead times and a large bureaucratic burden, making it difficult for SMEs to engage.

However, **AM and SE have in common a transformative impact on the MOD's environment**. Although it is uncertain to what extent the transformative potential of AM will be realised, it is predicted that the technology will have a rippling effect throughout society. For instance, AM was identified as one technology that could partly reverse globalisation by allowing more localised production which could slow or reverse the trend for offshoring. In parallel, the democratisation of manufacturing through AM could affect the nature of conflict and the profiles of adversaries. For defence, AM has a disruptive potential in that it is likely to diffuse the threat, as individuals will be able to produce weapons from blueprints.

Similarly, there are a range of emerging societal trends that have been both enabled and reinforced by SE. These include gamification – the use of games principles outside of a gaming context – and the wider use of serious gaming as a methodology applied to a range of outcomes. More generally, other demographic trends will also have a wide-ranging impact, such as the changing proportion of 'digital natives' to 'digital migrants', which present a risk to the MOD: if it does not adapt internally to a more digitally enabled culture, the gap between its structure and processes and its staff's habits and expectations will widen. On the operational side, the easier and wider use of SE technologies can have a disruptive impact on current MOD doctrines and operations. For instance, the increasing use of machines is likely to change the character of conflicts and the way in which troops position themselves as part of wider capabilities.

3. What conclusions and policy recommendations can be drawn?

First, the MOD should adopt some good practices from the commercial world to leverage commercial technologies

In the future R&D environment, the MOD will largely be a minority actor, while the driving forces for innovation will be increasingly found in the commercial sector. Civilian organisations and investment dominate innovation and technology development, a situation reflected in the proportion of civilian and defence involvement in the five technology areas we scoped.

Although the MOD has different priorities and drivers than a commercial organisation, there are similarities when thinking about research, technology and innovation. We found that the current culture of the MOD makes it ill-equipped to interact with and navigate the current commercial environment to its best advantage. In order to leverage commercial technology, the MOD should adopt commercial ways of working and thinking, in particular:

- **A greater willingness to take considered risks as part of a portfolio of decisions.** This is especially relevant in an age when technology development relies increasingly on international developments and the civil sector, and in which greater information fluidity and considered risk-taking is essential.
- **Identifying key parts of the value chain and innovating/investing there.** It is questionable whether the MOD should seek to 'pick winners' in terms of the future commercial potential of technology investments. However, the MOD should have an appreciation of trends in future technology markets – and in the part of the value chain in which the MOD would seek to benefit by investment.
- **Adopting the language of the technology area.** Defence is a jargon-rich environment with a unique lexicon. Many of our stakeholder interviews stressed the importance of tailoring language and terminology to the community involved.
- **Transitioning to a networked, decentralised structure** that encourages and enables innovation where it is needed. Open innovation and crowd sourcing are increasingly used across sectors to solve tightly defined problems. In the world of the app, accessing the power of wide networks is crucial.

Second, the MOD should facilitate connections and culture as key enabling factors

Most interviewees mentioned either directly or indirectly the importance of personal relationships and experience in technology development. When prompted on the factors required to identify promising technologies or market gaps, interviewees stressed the importance of personal interaction to improve understanding of future requirements.

However, in practice this coordination could be more effective. There is significant scope for the MOD to **develop a more sophisticated and strategic understanding of the impact of its actions on the technology landscape**. However, the MOD's culture may inhibit rather than enable due to its instinctive insularity and a tendency to emphasise the uniqueness of the defence context rather than seeking areas of commonality.

Third, the MOD should better target its engagement with its supply chain

In the future, the MOD will have much more limited scope to influence the development of technologies as it seeks to leverage commercial investments. Our research on developments in synthetic environments revealed that to interact effectively with the large number of innovative small companies in the sector would require different procurement processes, different systems and new relationships. It also revealed that the traditional model of engaging primarily with primes prevents the MOD from interacting directly with its full technology development base, especially SMEs. Within this model, not only does the MOD have an already filtered view of its wider ecosystem, it also loses the ability to select the technologies it may want to sponsor at their earlier stages of development.

Therefore, the MOD should **adapt its procurement processes to enable effective engagement with all actors of the current innovation landscape, as well as across the different types of technology areas**. Generally, initiatives such as the Centre for Defence Enterprise were thought by interviewees to be headed in the right direction in terms of better interaction with SMEs, but were still associated with a number of difficulties. The MOD could also consider whether there are lessons that could be learned from other actors in the UK landscapes. For instance, the Technology Strategy Board (TSB) has considered carefully how best to interact with its key stakeholders and reflected this on the profile of recruited individuals. Also, despite being part of the Department for Business, Innovation and Skills (BIS), it is central to the TSB's identity to be staffed by individuals from a business background. **Holding a similar reflection could help the MOD identify how it wants to situate itself within its ecosystem and make conscious choices as to how it interacts with every actor of the technology development landscape**.

Finally, the MOD should assess how it currently prioritises its investments

The innovations taking place in the commercial sector are seen in products, concepts and processes. The MOD should assess how it currently prioritises its investment in emerging technologies:

- The MOD should **envisage adopting a more probabilistic approach to technology development** to better account for the risks inherent to science and technology (S&T).
- The MOD needs to think about **how best to preserve an option to play in some technology areas and through which avenues it can best influence potential outcomes** – by helping shape a high-level strategy for the technology area, by funding research jointly with a wider government funder, or procuring research directly.
- It is currently unclear **how the MOD prioritises between small-scale investments with large transformative potential and large investments with more niche impact**.

In the current technology development landscape, the MOD may only have a small role to play in the maturing of a specific technology area. This is the case for additive manufacturing, for instance, where market forces and interest from a large number of players ensure sufficient investment for maturation. In such cases, therefore, although the best strategy may be to 'wait and see', this should mean **investing in the in-house competences to be an intelligent customer** when a technology becomes both relevant and economically interesting for the MOD.

Acknowledgements

This report would not have been completed without the support of many organisations and individuals. The authors would first like to thank Alex Churchill, Deputy Head of S&T Strategy in UK MOD as well as Richard Biers and Joseph Capitelli from the Defence Science and Technology Laboratory, for their sponsorship of this study and providing contacts within the Ministry of Defence.

We are also indebted to numerous other individuals who contributed to this study. We would like to thank the many people who contributed to our understanding of the UK's technology development landscape through interviews and workshops over the course of the project. A full list of these individuals and their contributions is provided in Appendix A. In addition to sharing their own expertise, Katie Daniel (EPSRC) and Steve Gale (TSB) also provided valuable connections throughout their respective organisations and helped us gain a stronger sense of the stakeholder landscape.

We would like to thank the research team from the University of Cambridge Institute of Manufacturing, Andrew Gill and Jonathan Hughes, for the insights gained from their feedback and parallel study approach. We are also particularly grateful for his advice and contribution, as well as to Richard Leaver (Greybrook Limited) for his continued consultation throughout all three phases of the study.

Finally, we are indebted to our RAND Europe reviewers Catriona Manville, Dan Jenkins and Luke Gribbon for their thoughtful comments and suggestions, which greatly improved the final document. Within RAND, we are also grateful to Alex Hall for her contributions to the in-depth case studies, and Ben Baruch, Kate Robertson, and Alex Hull for their support in drafting the report. We would also like to acknowledge the support of the Innovation and Technology Policy research team, several members of which assisted the team in this project.

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Abbreviations

AHRC	Arts and Humanities Research Council
AM	Additive Manufacturing
AR	Augmented Reality
BBSRC	Biotechnology and Biological Sciences Research Council
BIS	Department for Business, Innovation & Skills
BRIC	Brazil, Russia, India and China
C4ISTAR	Command, Control, Communications, Computers, Information/ Intelligence, Surveillance, Targeting Acquisition and Reconnaissance
CAGR	Compound Annual Growth Rate
CDE	Centre for Defence Enterprise
COTS	Commercial Off-The-Shelf
DCDC	Development, Concepts and Doctrine Centre
DECC	Department of Energy & Climate Change
DIS	*Defence Industrial Strategy*
DLOD	Defence Line of Development
DoD	US Department of Defense
Dstl	Defence Science and Technology Laboratory
DSP	Defence Strategy and Priorities
DTS	*Defence Technology Strategy*
EPSRC	Engineering and Physical Sciences Research Council
GDP	Gross Domestic Product
GEOINT	Geospatial Intelligence
GERD	Gross Domestic Expenditure on Research and Development
GOCO	Government-Owned, Contractor-Operated
HEFCs	Higher Education Funding Councils
ICT	Information and Communication Technologies
IP	Intellectual Property
IPRs	Intellectual Property Rights
IT	Information Technology
ITAR	International Traffic in Arms Regulation
KTN	Knowledge Transfer Network
KTP	Knowledge Transfer Partnership

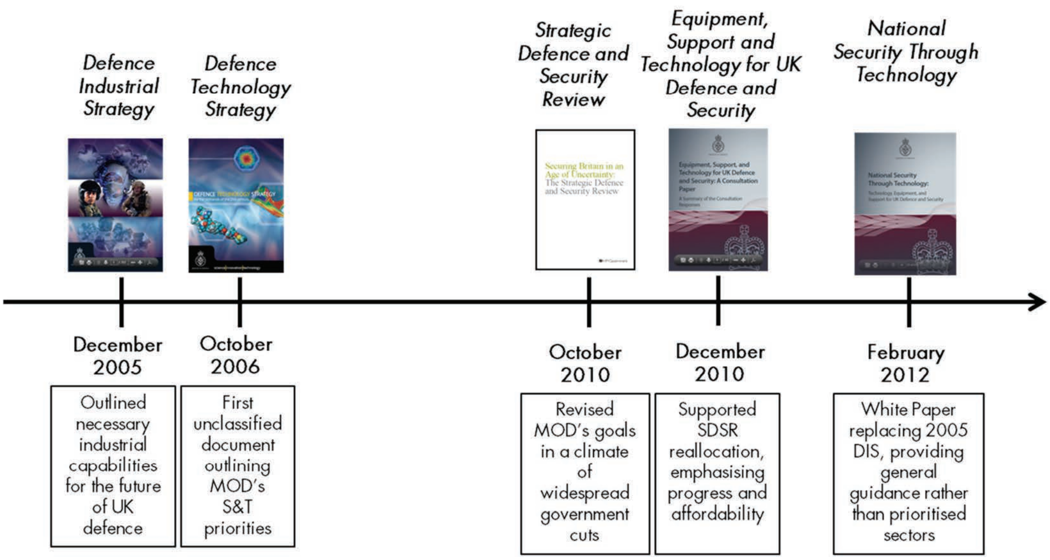
MAS	Manufacturing Advisory Service
MALE	Medium-Altitude Long-Endurance
MRC	Medical Research Council
MOD	UK Ministry of Defence
Nano-UAS	Nano-Unmanned Aerial Systems
NERC	Natural Environment Research Council
R&D	Research and Development
R&T	Research and Technology
RCUK	Research Councils UK
REA	Rapid Evidence Assessment
R/T&D	Research, Technology & Development
RUSI	Royal United Services Institute
S&T	Science and Technology
SBRI	Small Business Research Initiative
SDSR	*Strategic Defence and Security Review*
SE	Synthetic Environments
SME	Small and Medium-Sized Enterprise
TRL	Technology Readiness Level
TSB	Technology Strategy Board
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UCAV	Unmanned Combat Aerial Vehicle
VEC	Virtual Engineering Centre

CHAPTER 1 Study objectives and methodology

1.1 Defence S&T policy is evolving from specifying areas of development to a more enabling role

Over the last decade, defence science and technology (S&T) policy has changed significantly. In particular, it has evolved from highlighting specific areas for technology development in line with military requirements to defining the processes that facilitate innovation, as outlined in Figure 1-1. The 2005 *Defence Industrial Strategy* (DIS) reinforced the importance of S&T in terms of moving UK defence forward, while the 2006 *Defence Technology Strategy* (DTS) aimed to direct defence research into critical domains by identifying priority areas of national interest.[1,2]

Figure 1-1 Timeline of defence policy context



More recent policy documents – the 2010 *Strategic Defence and Security Review* (SDSR), *Equipment, Support and Technology for UK Defence and Security* and the 2012 White Paper *National Security Through Technology* – also reiterate the important role of research and development (R&D), but are much more general in tone and do not prioritise sectors of critical interest.[3] Instead, these documents focus on the need to maintain bilateral relationships, prioritise S&T investment, support open competition and encourage collaboration with small and medium-sized enterprises (SMEs).[4]

[1] UK Ministry of Defence (UK MOD) (2005)
[2] UK MOD (2006)
[3] UK MOD (2010); UK MOD (2011); UK MOD (2012)
[4] UK MOD (2012)

The next SDSR in 2015 is likely to focus on similar areas, as austerity is expected to continue to shape public spending. The challenge for the updated policy will be to build upon the 2012 White Paper to support open competition, maximise the return on defence S&T investment and emphasise value-for-money at every level of technology policy.

1.2 This study aims to maximise the impact of the MOD's increasingly limited resources

This study was commissioned by the Defence Science and Technology Laboratory (Dstl) to inform its future strategy for technological development. To this end, it aims to identify the circumstances required for effective development, the key decisions necessary throughout the process and the points at which investment is necessary.

A key aspect of the study is to explore how to make best use of civilian developments taking place in parallel with UK defence R&D. The study will address how to combine developments in new ways, looking at business models that facilitate development and evolving technologies.

Stakeholder engagement is therefore an important component of the study and appropriate communication mediums will be critical to ensure that stakeholder groups have efficient access to key messages. The statement of work toward which the project team worked is illustrated below.

STATEMENT OF WORK

This future landscapes study on defence technology development aims to assist the Ministry of Defence (MOD) in assessing and harnessing wider investment in relevant UK technology development. By considering where MOD and non-MOD investments in research and technology (R&T) are likely to shape future UK technology capability of relevance to defence, findings should help ensure that the MOD's future technology investment is targeted as efficiently as possible.

The RAND Europe project team has identified three tactical objectives for this study:

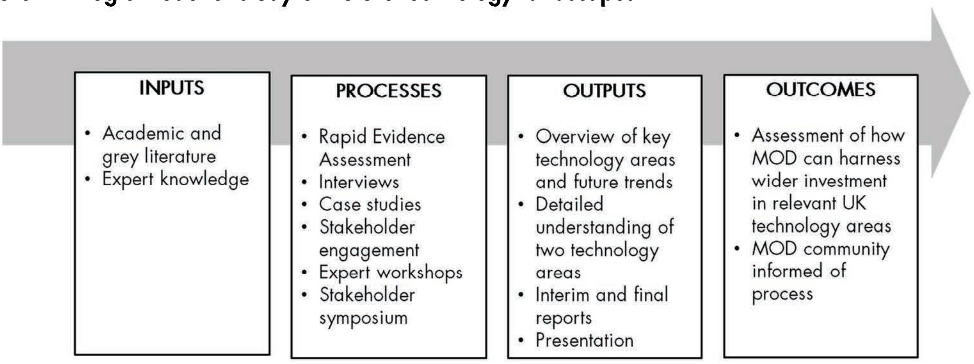
1. To inform the MOD on how to target future investments in technology to complement and leverage other R&T spending (by the MOD, other government sources and the private sector).

2. To identify the key drivers, barriers and enablers to technology development and innovation through data collection, analysis and validation, both for the wider context and within two specific technology areas.

3. To engage with the MOD's S&T stakeholder community to inform key stakeholders of the study objectives and findings.

The RAND Europe project team devised a methodology to meet the MOD's expectations, as outlined in our original proposal. The logic model in Figure 1-2 summarises the key inputs, processes, outputs and outcomes of the study.

Figure 1-2 Logic model of study on future technology landscapes



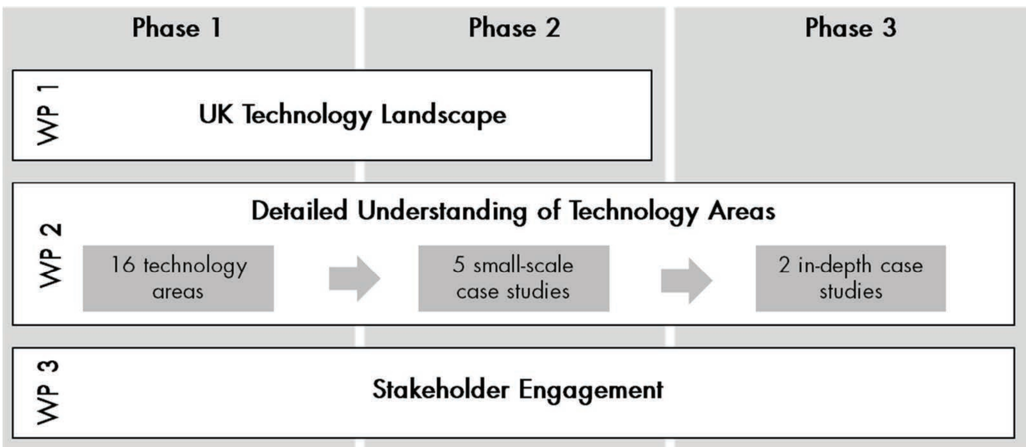
1.3 The project team applied a structured methodology to meet the study objectives

1.3.1 The study was organised in three phases to enable incremental identification and refinement of findings

The study took place between February and August 2013 and was organised in three phases, which enabled several refinements of the analysis and findings (as illustrated in Figure 1-3):

- The first phase of the project focused on understanding the wider context and gathering evidence on factors with the potential to influence future defence technology landscapes. The RAND Europe research team performed an analysis of the key issues in innovation and technology development, and had structured engagement with a range of relevant stakeholders from the civilian environment.
- The second phase of the study was designed to analyse the defence technology landscape and enable the selection of two in-depth case studies. It aimed to narrow the scope of research and was composed of two parallel tasks: firstly, an initial exploration of the five technology areas shortlisted as part of Phase 1; and secondly, an analysis of the innovation and technology development landscape.
- The third phase of the study focused on the two in-depth case studies, additive manufacturing and synthetic environments, which were selected for further exploration by the MOD project sponsor. After the case studies were completed, the team also engaged with different stakeholders to help refine and test findings and recommendations.

Figure 1-3 Overview of study methodology



1.3.2 The team designed a structured approach of three work packages to achieve the study objectives

The team designed a work stream around each objective of the study and to address the different dimensions of technology development. These were:

- An analysis of the UK technology and innovation landscape. The team identified key issues in innovation through a targeted literature review and interviews with internal experts, before conducting a granular analysis of the different actors in the technology development landscape.
- The identification and prioritisation of the technology areas most relevant to defence. The team first performed a Rapid Evidence Assessment (REA) to scope the defence technology landscape and from which 16 technology areas were identified. We used criteria to select a sub-group of five, for which we performed an overview analysis. We then selected two of these areas, additive manufacturing and synthetic environments, for in-depth analysis.
- Finally, the team engaged with a range of stakeholders both to better understand the wider context in which the study was performed, and to gather data and evidence. We also tested and refined study findings through stakeholder engagement with the Defence Strategies and Priorities Unit and the Development, Concepts and Doctrine Centre (DCDC).

A more detailed explanation of the methodology used for each task is included at the start of relevant chapters and in the appendices.

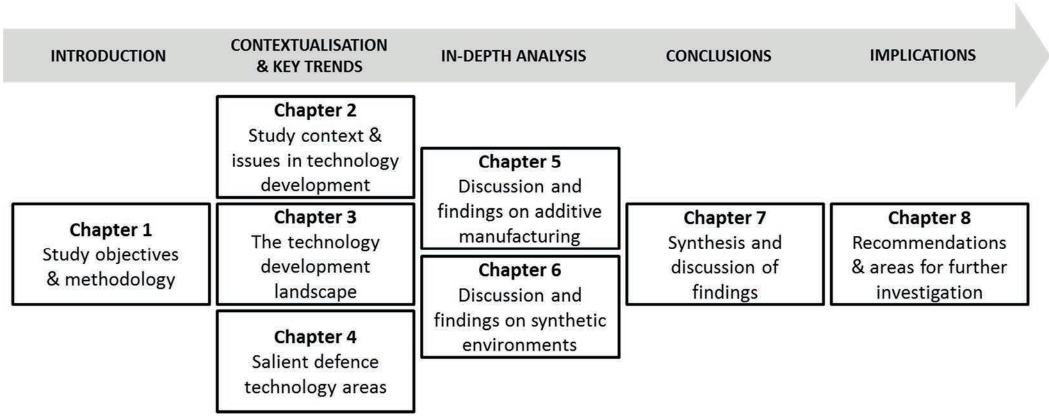
1.4 Structure of the report

This report is structured as follows:

- **CHAPTER 2** presents the context and key concepts of the study, from the current defence technology development context to key issues in innovation.
- **CHAPTER 3** covers the analysis and description of the innovation and technology development landscape.
- **CHAPTER 4** contains the scoping of the defence technology landscape and an analysis of the key trends in technology development.
- **CHAPTER 5** and **CHAPTER 6** include an overview and the team's key findings of the two in-depth case studies, additive manufacturing and synthetic environments.
- **CHAPTER 7** synthesises and discusses the findings of the project.
- **CHAPTER 8** discusses the implications for defence and outlines our final recommendations.

The relationship between the different chapters can be seen in Figure 1-4.

Figure 1-4 Outline of report structure



Supporting evidence and information can be found in the set of appendices:

- **Appendix A** contains a list of individuals with whom the team engaged throughout the project, both as part of the wider stakeholder engagement and also for the in-depth case studies.
- **Appendix B** presents additional information and descriptions of key actors and their role in the innovation and technology development landscape.
- **Appendix C** is a description of the methodology used to conduct the REA.
- **Appendix D** includes details of the analysis of defence publication numbers.
- **Appendix E** presents a list of the emerging technologies identified in the first phase of the study.
- **Appendix F** contains the case-study assessment of the identified technology areas; it also includes a description of the selection process for the five potential case studies.

This report is accompanied by a supporting document, *Future Technology Landscapes: Insights, Analysis and Implications for Defence – Case Study Documentation*, which includes a detailed description of the five technology areas analysed as part of the study. It presents the data gathered for the two in-depth case studies, additive manufacturing and synthetic environments, as well as for the three small-scale case studies, namely advanced materials, cybersecurity and small-scale energy storage.

CHAPTER 2 Study context and key issues in technology development

This chapter presents the key themes of the study by introducing the current context of defence innovation and technology development. It also provides an overview of wider themes in innovation theory. It concludes with a reflection on the recent evolution of defence innovation.

2.1 The study team identified key issues in innovation through a targeted literature review and expert interviews

In order to define the context for this study, the project team leveraged its knowledge and previous experience in defence, and used publicly available data on defence R&D spending and forecasts. In parallel, the project team sought to identify the key issues in the field of innovation through a review of the state of the art in innovation theory. We also obtained input from internal experts from the Innovation and Technology Policy programme at RAND Europe, Jonathan Grant and Steve Wooding, to gain an overview of the key issues and ideas currently informing innovation science.

This engagement allowed us to target our review of the literature on innovation through the identification of key documents. It was also instrumental in helping us better understand the specificities of innovation and technology development in defence, when compared with other industrial sectors. In parallel, the team engaged with a range of stakeholders both to better understand the wider context in which the study was performed, and to gather data and evidence.

2.2 The context for defence innovation has changed significantly in the past five years

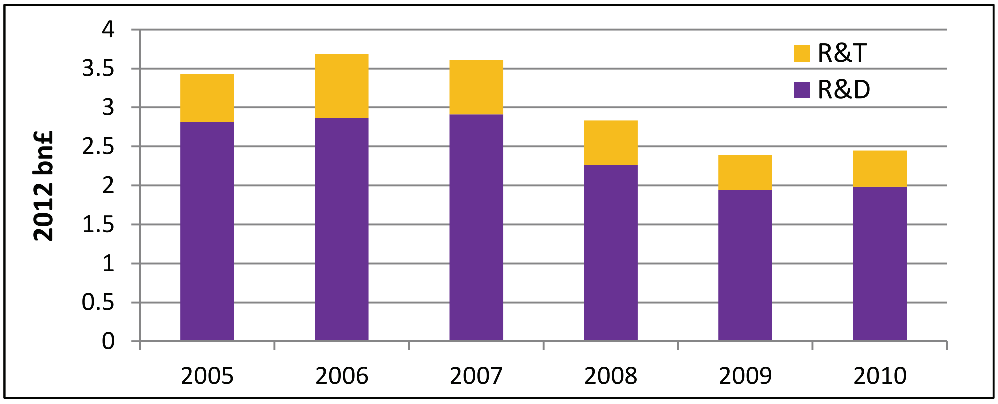
Innovation and technology development are critical to ensure operational supremacy as well as the sustainability and competitiveness of the defence industry in the international market. However, the technology development context has changed rapidly in recent years in three interrelated ways: research, technology and development (R/T&D) budgets have declined significantly due to austerity measures; innovation foci have shifted from defence to the civil sector; and the international dimension has become increasingly important.

2.2.1 R/T&D budgets have declined significantly and austerity is expected to continue to shape available funds

Defence research spending has been substantially reduced in the period since 2007 due to a reduction in overall government spending, the overheated defence equipment programme and the relative flexibility of research budgets compared with other areas of defence spending.

Recent research conducted by RAND Europe has shown that, at a European level, R/T&D spending was the second most impacted by austerity measures since the 2008 economic downturn, after personnel expenditures.[5] This contrasts with equipment spending, where long-term commitments limit the structural flexibility to make short-term adjustments. As a result, and as shown in Figure 2-1, UK R/T&D real-term spending decreased from £3.4 to £2.4 billion between 2005 and 2010, representing a decline from 8.8 percent of the overall defence budget to 6.6 percent over the period.[6] However, R&D and R&T spending were not affected in the same way: R&D spending decreased by a compound annual growth rate (CAGR) of -5.7 percent, while R&T CAGR decreased by -4.5 percent.

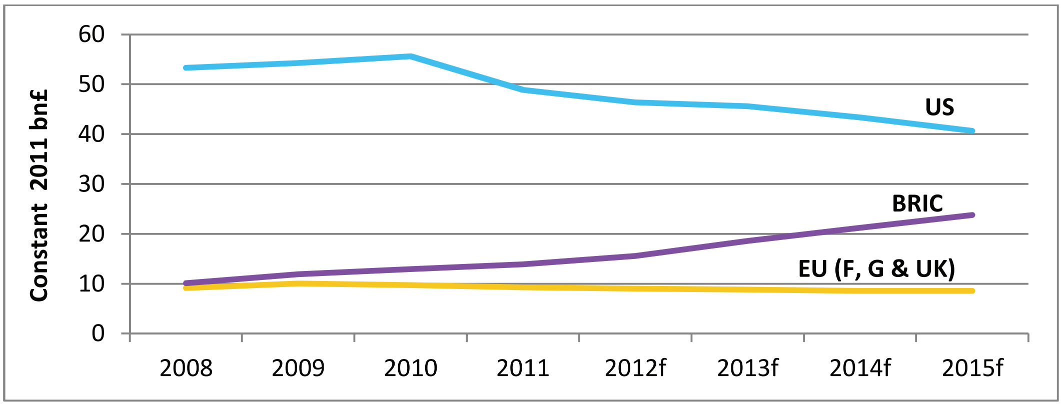
Figure 2-1 UK R/T&D spending, 2005–2010 (2012 bn£)



Source: RAND Europe analysis of EDA data

This trend of declining R&D spending is not only seen within the UK but also more generally at a European level and especially in the US. Figure 2-2 illustrates R&D spending forecasts for the US, BRIC states (Brazil, Russia, India and China) and France, Germany and the UK combined, which represent 90 percent of European R&D spending.[7] It shows that not only is the absolute level of R&D spending in the EU and the US declining, but also the relative difference in comparison to emerging actors is getting smaller.

Figure 2-2 EU (France, Germany & UK), US and BRIC R&D spending forecast to 2015 (2012 bn£)



Source: Anderson (2011)

[5] Penny et al. (2013)
[6] Figures here are in constant 2012£
[7] Penny et al. (2013)

2.2.2 The declining investment in defence innovation and technology development presents a particular threat to the long-term sustainability of the defence sector

Exports to non-European markets represent a significant proportion of defence industry revenue shares and have been an important contributor to the health of the sector. In 2011, non-European sales represented 55 percent of the top 15 defence suppliers' sales. An analysis of their strategies highlighted that consolidating their international footprint constituted one of four axes for growth, along with moving towards a servicing and through-life approach, growing their presence in non-defence markets, and investing in competitive and growing areas.[8] This trend is also found at a lower level in the supply chain. The analysis of the revenue distribution of the six major national defence industry associations, illustrated in Figure 2-3, indicated that 38 percent of sales were non-EU exports, 40 percent were to non-domestic EU markets and 22 percent were domestic.[9] It is expected that exports will continue to present opportunities for European suppliers, especially as this contributes to offsetting the reductions in Member States' demand.

Figure 2-3 Distribution of military revenues of the six major national defence industry associations, 2011

Source: ASD (2012)

However, exports are reliant on the development of systems for domestic customers, as importing markets require products to be operationally proven. The nature of the defence sector – characterised by long development cycles and capital intensiveness – leads to a time lag of up to 20 years between initial investment in R&D and in-service capability.

Therefore, current cuts to defence R/T&D, although having little direct impact on today's capability, present a significant challenge for both the future sustainability of the defence industry and the effectiveness of military capability. This is also linked to the sustainability of skills and competences, as was highlighted by the UK House of Commons Defence Select Committee's statement that the '*Government's emphasis on off-the-shelf procurement and open competition offers a serious threat to the technical skills base, specifically although not exclusively to the defence skills base*'.[10]

[8] RAND Europe analysis of defence companies' annual reports. The top 15 defence suppliers are BAE Systems, EADS, Finmeccanica, Thales, MBDA, Safran, Rolls-Royce, DCNS, Saab, Babcock, Rheinmetall, Cobham, CEA, Serco and Navantia

[9] Aerospace and Defence Industries Association of Europe (ASD) (2012). The six national defence industry associations are AIAD (Italy), ADS (United Kingdom), BDLI, GIFAS (France), SAI (Sweden) and TEDAE (Spain)

[10] UK House of Commons Defence Committee (2013)

2.3 Innovation relies on dynamic ecosystems and adaptive sponsoring mechanisms

2.3.1 Innovation does not occur in isolation, but relies on interactions between actors within a complex ecosystem

Innovation is a '*complex and interactive process involving multiple feedbacks between different services and functions as well as manifold interactions with customers and suppliers*'.[11] The main driver for this complexity is the requirement for many fluid interactions and connections between different actors that enables the diffusion of information and innovation. Lord Sainsbury's review, *The Race to the Top: A review of science and innovation policies*,[12] lists some of the multiplicity of players in the UK's innovation ecosystem. These include industry, government departments, academia, knowledge transfer organisations, institutions governing intellectual property and standards, investors and training institutions.[13]

A key concept in the innovation literature is absorptive capacity, which refers to the ability to '*systematically identify, capture, interpret, share, reframe and re-codify new knowledge; to link it with its existing knowledge base; and to put it to appropriate use*'.[14] Absorptive capacity relies on an existing organisational knowledge and skill base; a '*"learning organisation" culture; and proactive leadership directed towards evidence sharing*'.[15]

Innovation therefore requires a combination of complexity and knowledge exchange. This involves creating the culture, curiosity, incentives and leadership that encourage complex dynamic links to be formed between individuals and groups, leading to the rapid and fluid knowledge exchange that breeds innovation.[16] Top-down management may be ineffective when attempting to create and control complex phenomena, such as innovation, in a shifting environment, such as that of defence. Management should instead aim to create an ecosystem that encourages interactions and links between entities. These entities would then create self-organising, emergent networks that are resilient in the face of changing demands and a changing environment.[17]

2.3.2 Promoting innovation relies on an appropriate balance of supply and demand mechanisms

Public sector organisations such as the MOD play a key role in shaping and supporting the wider innovation ecosystem. The mechanisms through which they can stimulate innovations are traditionally divided into two categories: supply and demand. Supply-side mechanisms focus on sponsoring the ecosystem's capacity to produce innovation. Examples of this include:

- Direct funding, such as grants and subsidies
- Training sponsorship, such as scholarships or funding of PhDs
- Financing of facilities or positions within institutions.

Demand-side mechanisms focus on providing a specific solution to a problem that has been both identified and defined, irrespective of how this solution is designed. These include:

[11] NESTA (2007)
[12] Lord Sainsbury of Turville (2007)
[13] Lord Sainsbury of Turville (2007), p. 4
[14] Greenhalgh et al. (2004)
[15] Greenhalgh et al. (2004)
[16] Bray (2007)
[17] Wood (2000)

- R&D procurement, used as for other goods or services
- Prizes, such as the Longitude Prize offered by the British Government in 1714 for the design of an accurate method to measure longitude
- R&D tax credits, which allow both SMEs and larger companies to deduct a percentage of qualifying expenditure on R&D activities when calculating profit for tax purposes
- Crowd-sourcing, which relies on the contributions of a large number of individuals when addressing a single problem.

The balance between supply and demand mechanisms is important. An exclusive focus on demand mechanisms may lead to being more prescriptive about specific requirements and expected outcomes, when innovation also requires flexibility and greater risk-taking. Similarly, sponsoring the supply of innovation without ensuring that it relates directly to existing or emerging challenges can lead to irrelevant or untimely development. Finally, these mechanisms differ regarding the ways in which intellectual property rights (IPRs) are used as incentives. This is critical as IPRs grant innovators a temporary monopoly and thus the potential to recoup their investment costs.

2.4 Defence innovation has to combine strategic and operational requirements, but has recently undergone profound shifts

2.4.1 Defence technology development is changing through the greater role of the civilian sector and of internationalisation

Innovation increasingly takes place in the civilian sector

In recent decades, the innovation centre of gravity has shifted from defence to the civilian sector. This is due, in part, to the increasing importance of information and communication technologies (ICT) in all systems relying on commercial off-the-shelf (COTS) developments, such as mobile and handheld command-and-control computing capabilities.[18] In addition to integrating civilian technologies, there are also greater opportunities to work jointly with the civil sector due to the closing gap between defence and security. This can be seen, for instance, in a project whereby small communications satellites will be attached to more substantial commercial satellites in the future.[19]

Transfers of civilian innovations to the defence context can be seen across the equipment spectrum, but specific areas are more prone to this than others. Aerospace is particularly conducive to civil spin-ins to the defence sphere, given the similar technology of the commercial and defence sectors in this domain.[20] Data processing capability and electronic developments have also been critical to the changes in man-machine interface and have enabled the increasing autonomy of unmanned systems. Training has also been greatly influenced by spin-ins from video games, as technology from commercial entertainment is applied to defence simulation programmes.[21] Finally, innovations in engines and hybrid technologies have been imported by the defence sector in order to capitalise on commercial developments for higher speed, efficiency and performance.[22]

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[18] Oberlin (2012)

[19] Cacas (2012), p.63

[20] Jackson (2004)

[21] Nash (2012)

[22] Brown (2012); Dixon (2011), p.84

Defence innovation is increasingly international

Further critical developments in the R&D environment have included the internationalisation of innovation and supply chains, and the increasing importance of international cooperation, which offers one channel to maximise innovative potential while sharing costs. As Peter Luff, former Minister for Defence, Equipment, Support and Technology, asserted last year, '*Technology is changing too fast, and money is too tight – as indeed they both probably always were… The future lies in open systems*'.[23]

The UK has established a number of favoured relationships through which it pursues joint innovation. For instance, the UK and the US have collaborated in a variety of areas across sectors, from nuclear submarines to directed-energy systems.[24] Existing programmes such as the F-35 fighter are avenues for developing technologies together. Since the two countries' 2010 cooperation accord, UK defence collaboration has also been particularly strong with France, with joint efforts in funding and procurement in a number of areas: complex weapons, development of medium-altitude long-endurance (MALE) unmanned aerial systems (UAS), potential for a common unmanned combat aerial vehicle (UCAV), and nuclear testing.[25] An on-going study for the MOD led by MBDA on UK critical technologies is also being conducted with the objective of identifying technologies that could be developed through mutual dependencies.[26]

2.4.2 Technology development priorities are informed by both military capability requirements and political context

Despite the increasing role of the civilian sector and international actors, British defence innovation and technology development still has to meet the same objectives. On the one hand, it has to balance the top-down priorities as they are expressed in the SDSR and, on the other, the bottom-up operational requirements that are both expressed and foreseen.

Technological developments have to align with the strategic environment and resulting operational requirements

In recent decades, there have been major changes in European defence at strategic, political and operational levels. Much of this change has also affected the European defence industrial and technological base, and subsequent technological innovation. Key drivers at the strategic level have included the end of the Cold War, the terrorist attacks of 9/11 and the advent of international terrorism, as well as the emergence of China and other Asian states. Moreover, other trends – such as civilian technological developments and their translation into increasing cybersecurity threats – have widened the range of potential threats, blurring the distinctions between security and defence, and between the national and international spheres.

On the political level, there have been moves towards greater coordination on defence issues at the European level and towards minimising human costs in engagements in which homeland security is not directly threatened. Operationally, changes in the strategic environment, political priorities and technological advances have contributed to significant evolutions in tactics and capability requirements.

[23] Bell (2012)
[24] Scott (2012b); Dixon (2012), p.88; Barrie (2010), p.30
[25] Anderson and Caffrey (2012)
[26] Findings from this study are restricted and therefore not available openly

Technological developments are also informed by service and sector specificities

As military requirements evolve, innovation in each of the equipment sectors – air, land, sea, C4ISTAR[27] and weapons – tends to focus on different areas. Table 2-1 presents some of the key trends and current military capability requirements by industrial sector.

Table 2-1 Military capability priorities by industrial sectors

Sector	Military capability priorities and key trends	Technology examples
Air	- Increased range and use of unmanned systems - Cockpit upgrades	- Rotary-wing UAS - Imaging capabilities and sensors optimised for UAS
Land	- Force modernisation - Increase soldier's ability to access and optimise information and communications technologies	- Electronic countermeasures - Armoured vehicles
Sea	- Type 26 Global Surface Combatant as flagship programme - Increased automation of logistics and ship-based handling systems - The Successor will harness innovation in communications, structural materials and batteries	- Automated munitions handling systems on naval platforms - Noise quieting
C4ISTAR	- Improvements in quality and quantity of information collection and communication - Advances in command-and-control, man-machine interface and graphics capabilities - Demand for increasingly connected operations	- Future Infantry Soldier Programme - Multifunction display screens
Weapons	- Increasingly accurate and lethal weapons - Demand for guided ammunitions - Directed-energy weapons (laser systems and radio-frequency weapons)	- Rifle day and night sight: lightweight, significant magnification, low-power consumption, thermal imaging

Source: RAND Europe analysis

[27] C4ISTAR: Command, Control, Communications, Computers, Information/Intelligence, Surveillance, Targeting Acquisition and Reconnaissance

CHAPTER 3 The innovation and technology development landscape

This chapter presents the innovation and technology landscape, focusing on the role of key actors and R&D investment flows.

3.1 The study team conducted a granular analysis of the different actors in the technology development landscape

As part of the second phase of the study, the research team analysed the innovation and technology development landscape. This analysis had several objectives including developing an understanding of the key role played by each actor; assessing each actor's contribution to the technology development landscape, both qualitatively and quantitatively; and understanding the profile of different investments.

This analysis was mainly based on primary data provided by each actor, such as strategies and annual reports or other publications. The interviews conducted during the first phase of the study were also instrumental in providing a qualitative understanding of the activities and priorities of the different institutions, as well as the links between them.

The list of interviewees can be found in Appendix A, while supporting information on individual actors within the technology landscape is located in Appendix B.

3.2 A range of actors, presenting a complementary set of roles and expertise, are involved in technology development

As part of this study, we analysed the role of the six principal actors in the technology development landscape grouped as follows: academia; private sector; government departments (including the Department for Business, Innovation and Skills (BIS)); the Technology Strategy Board (TSB); Research Councils UK (RCUK) and the Higher Education Funding Councils (HEFCs) of England, Scotland and Wales.

The roles of these actors within the technology landscape are complementary and intertwined, so that their areas of responsibility form a continuum and can also overlap. For instance, although Research Councils are agencies of BIS and are responsible for distributing funding to early stage Technology Readiness Levels (TRLs), some also perform research within in-house centres. Businesses also perform R/T&D in addition to procuring research to support their operations and developments. This procurement occurs in a similar way to that of government departments, which are themselves also responsible for defining strategies and policies framing innovation and technology development.

Our analysis suggests that there are five overarching roles performed within the technology landscape:

- Defining **policy and strategy** provides long-term vision and objectives, and facilitates identification of areas of strength as well as gaps within current capabilities.
- **Procurement** corresponds to actors outsourcing the solution to a specific problem identified as part of their normal operations.
- **Funding and investing** relates to the distribution of funds or grants to others performing the research, whether innovation- or challenge-led. Most of the time, business investment will be characterised by expectations of a return on investment, while this is different for funding and investment from a public actor.
- **Performing** includes all activities relating to innovation, technology development or research.
- **Connecting** includes the activities enabling the flow of information and linking of individuals.

The actors we analysed may perform a number of these roles. However, we found that each actor tended to be most active, or have most expertise, in a small number of specific activities. For instance, government departments both define policy and strategy in technology development, and procure research to support their operations and the delivery of their responsibilities. In contrast, the primary activity of HEFCs is to fund academic organisations. Table 3-1 summarises the principal activities in which UK technology development actors are involved; shaded cells correspond to actors' most significant expertise and involvement.

Table 3-1 Primary activities of the main UK technology development actors

	Policy and strategy	Procurement	Funding and investing	Performing	Connecting
Government Departments	X	X	X	X	
TSB	X		X		X
RCUK	X		X	X[1]	X
HEFCs			X		
Academia			X	X	X
Businesses		X	X	X	

Source: RAND Europe analysis
[1] Within RCUK, only Research Councils that have their own research institutes perform research, such as the Medical Research Council (MRC), the Biotechnology and Biological Sciences Research Council (BBSRC) and the Natural Environment Research Council (NERC).

3.3 Different expertise in the technology development landscape is reflected in different contributions to UK R&D investment

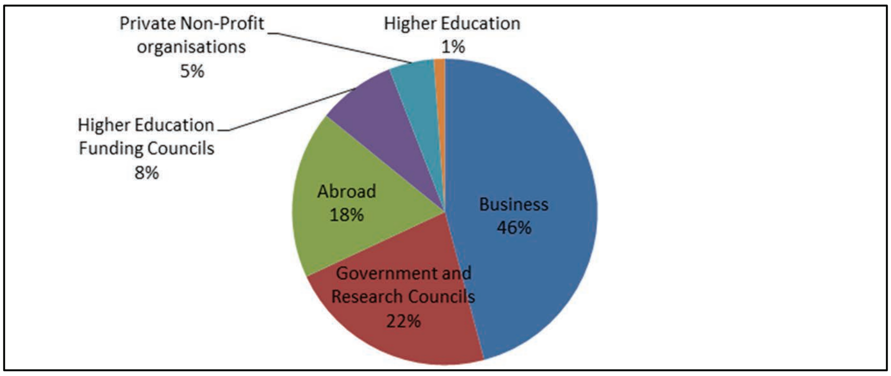
Understanding the relative contribution of each actor will help the MOD prioritise and target its efforts to leverage civilian R&D. In order to ensure consistency in findings, and taking into account the variations in definition used by different organisations, the analysis presented in the following sections focuses on both the high-level picture of R&D investment in the UK, and a granular analysis of investment by business and public organisations. As the project team was not able to collect and analyse data on academic institutions at a granular level within the constraints of this study, our financial R&D contribution is only included as a high-level analysis.

3.3.1 In the overall UK R&D investment landscapes, businesses are the largest investors and performers of research

The Office of National Statistics (ONS) publishes an annual statistical bulletin on UK gross domestic expenditure on R&D (GERD). In 2011, the UK GERD was £27.4bn, and total R&D expenditure represented 1.79 percent of Gross Domestic Product (GDP). This is significantly below the 2.5 percent target level to be achieved by 2014 and set by the UK government in the Science and Innovation Framework 2004–2014.[28] International comparisons show that UK R&D expenditure in 2011 was also below the EU-27 average of 2.03 percent of GDP.[29]

The actors within the UK innovation and technology development landscape contribute to overall R&D expenditure in different proportions, as illustrated in Figure 3-1. In 2011, the business sector provided 46 percent of total UK R&D funding (£12.6bn).[30]

Figure 3-1 Composition of UK R&D by performing sector, 2011



Source: ONS (2013)

3.3.2 British business R&D investment is led by large civilian companies and varies in intensity across industrial sectors

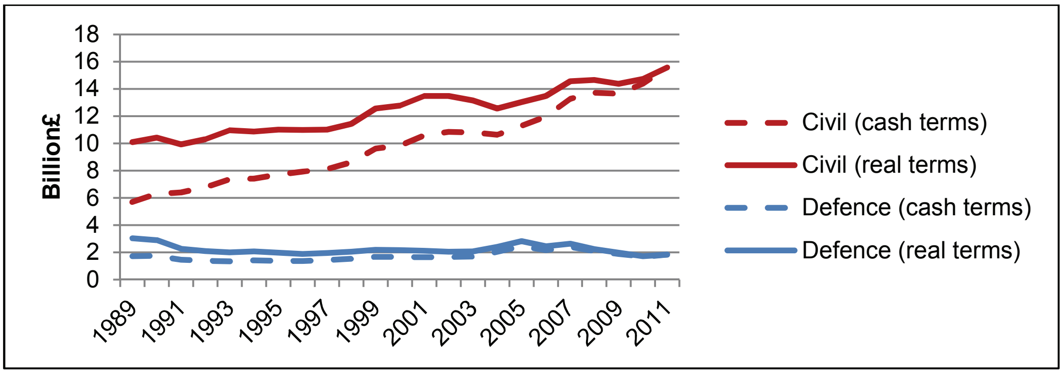
The prominent role of business in the UK R&D landscape makes it especially important to understand the investment priorities and major stakeholders in this diverse sector. Because businesses are a varied group of organisations, we present four different angles from which to analyse business contributions to overall UK R&D investment: trends in business R&D investment over the last two decades; the origin of R&D funds invested by businesses; the contribution of SMEs to R&D investment; and the distribution of business R&D investment by industrial sector.

Firstly, regarding the R&D investment profile of businesses, ONS data shows that from 1989 to date, business R&D spend is increasing, as illustrated in Figure 3-2. For instance, in the 2010–2011 period, it grew by 6 percent in real terms, from £16.4 billion to £17.4 billion.[31] This growth is driven exclusively by increases in civil sector investment, as expenditure on civil R&D has generally increased in both cash and real terms since 1989. In contrast, and reflecting wider trends discussed in Chapter 2, defence R&D is moving in

[28] Office for National Statistic (ONS) (2013), p.4
[29] ONS (2013), p.1
[30] ONS (2013), p.9
[31] ONS (2012), p.3

a different direction: after being relatively stable from 1993 to 2003, defence R&D nearly rose back to 1989 levels by 2005, only to decrease 36 percent by 2011.[32]

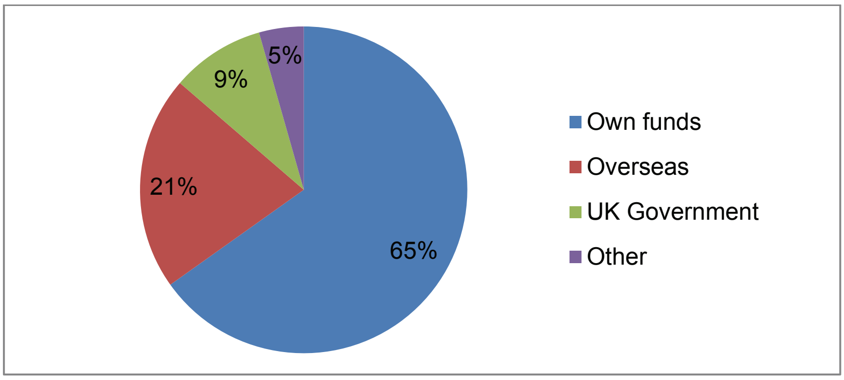
Figure 3-2 Expenditure on civil and defence R&D performed in UK businesses, 1989-2011



Source: ONS (2012)

Secondly, while the public sector engages in many collaborative initiatives with businesses, the majority of R&D activities performed by businesses are self-funded. In-house funding made up 65 percent of business R&D in 2011, as shown in Figure 3-3. The active prioritisation of government–industry partnerships in many technology areas contributes to the 9 percent of business investment originating from UK government. It is also worth noting that a fifth of business investment funding comes from overseas.[33]

Figure 3-3 Funding sources for R&D performed in UK businesses, 2011

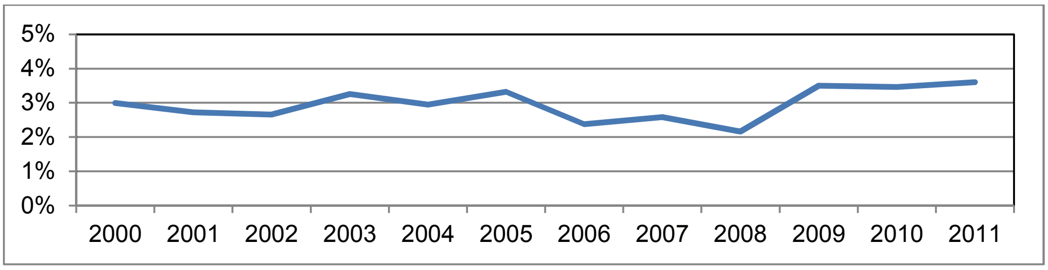


Source: ONS (2012)

Thirdly, large companies contribute the large majority of business R&D investment. Business R&D is motivated by market considerations, and typically falls into one of two models: to develop new products to commercialisation, or to pursue early-stage research that will eventually enable innovation of profitable technologies.[34] The size and scope of individual companies determines the TRL at which individual companies will engage, with large companies having the resources to engage at every TRL. As shown in Figure 3-4, for the past decade R&D expenditure performed by UK SMEs has hovered around 3 percent of that performed by all UK business.[35]

[32] ONS (2012), p.6
[33] ONS (2012), p.11
[34] ONS (2012), p.2
[35] RAND analysis drawn from statistical index Table 26 (Annex) in ONS (2012)

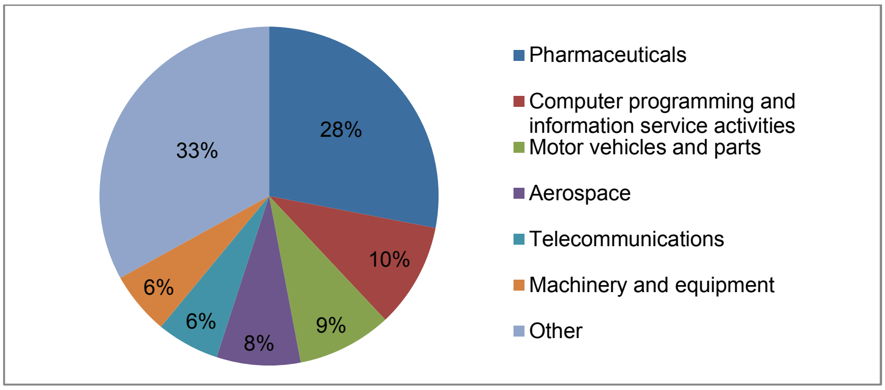
Figure 3-4 R&D expenditure performed by UK SMEs, as percentage of total UK business,2000-2011



Source: RAND analysis of ONS (2012)

Fourthly, some industrial sectors benefit disproportionately from business R&D investment, reflecting specific market structures and dynamics. As shown in Figure 3-5, for instance, over a quarter of business R&D investment is specific to the pharmaceutical sector, which is characterised by both large companies and research intensive products.[36]

Figure 3-5 UK business R&D expenditure by product group, 2011



Source: ONS (2012)

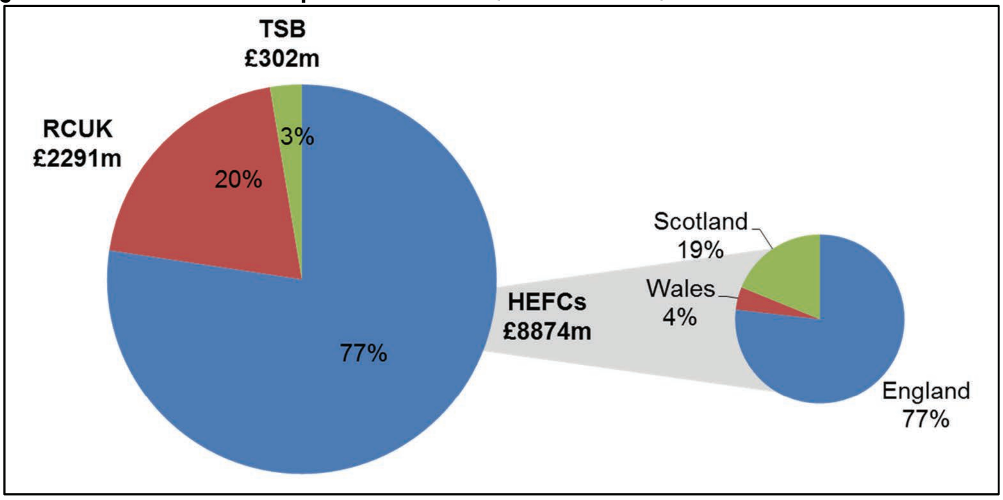
3.3.3 Public sector research funding organisations primarily support academic institutions and contribute by varying degrees to overall R&D investment

The project team also conducted a detailed analysis of the TSB, RCUK and HEFCs as public sector R&D organisations. For this analysis, we used the information published in these organisations' 2012 annual reports – including those of HEFCs and all seven individual Research Councils – and identified all the funding streams directed towards sponsoring the technology development landscape. These activities included: funding research through grants or projects; connecting individuals or organisations and raising research awareness; providing training, development and fellowships; financing research facilities; and other research-related investments. We did not include the procurement and funding of research by government departments in this analysis as we did not have access to sufficiently granular data. We identified three main findings:

- Firstly, the overwhelming majority of R&D investment and research funding from public organisations is directed towards academic institutions, with HEFCs providing over three-quarters of public organisation research-related investment in 2011–2012. Figure 3-6 further illustrates that, as the RCUK represented another 20 percent of research-related spending, the funding provided by the TSB to businesses only represented 3 percent of total research-related expenditure by these public organisations.

[36] ONS (2012), p.5

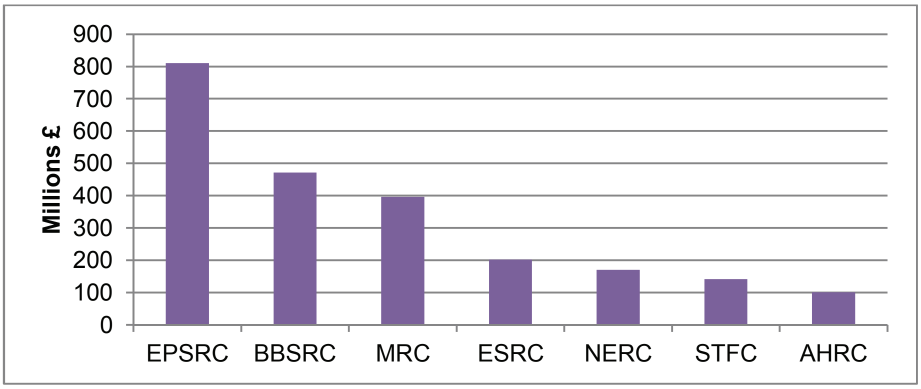
Figure 3-6 Research-related expenditure of HEFCs, RCUK and TSB, 2011–2012



Source: RAND Europe analysis of organisations' annual reports, 2012

- Secondly, the contribution of individual Research Councils and HEFCs varied significantly within their respective groups. Figure 3-6 shows that, for instance, HEFCE, the HEFC for England, contributed over three quarters of the fund distributed by all three HEFCs combined.[37] Similarly, Figure 3-7 highlights the differences in the relative contributions of the individual Research Councils. In 2011–2012, the Engineering and Physical Sciences Research Council (EPSRC) had the largest budget at £810m – more than eight times the budget of the Arts and Humanities Research Council (AHRC), the smallest Council, with a £101m budget. The EPSRC and the Biotechnology and Biological Sciences Research Council (BBSRC) together comprised over half of total RCUK research funding.

Figure 3-7 RCUK research budget by Research Council, 2011–2012



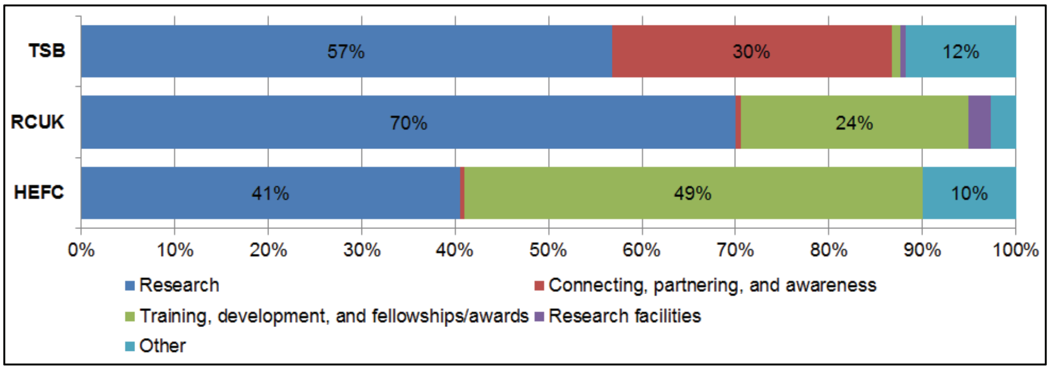
Source: RAND Europe analysis of organisations' annual reports, 2012

- Finally, the spending profile of public organisations' research-related investment varies by organisation type. Figure 3-8 shows the breakdown of TSB, RCUK and HEFCs research-related investment across the five key activities identified. It shows that the majority of research funding across these actors goes towards general research, representing the largest proportion of RCUK's spending at 70 percent. HEFCs have the largest proportion of funding for training, development and fellowships, as this represents nearly half of their research-related spending. In

[37] In Northern Ireland, the Department for Employment and Learning is responsible for distributing funding to the Northern Irish higher education institutions. The research team was not able to gather data on the same level of granularity as was available from the other HEFCs.

comparison, the TSB is the only actor with significant spending in connecting, partnering, and awareness: this category comprises one third of its research-related spending and illustrates the TSB's prioritisation of supporting and encouraging innovation networks, through Knowledge Transfer Networks (KTNs), for example. Specific funding for research facilities is a negligible percentage of all three actors' budgets. These breakdowns for each actor correlate with their priority activities as presented in Table 3-1.

Figure 3-8 TSB, RCUK and HEFCs research-related funding by type of expenditure, 2011–2012



Source: RAND Europe analysis of organisations' annual reports, 2012

CHAPTER 4 Emerging defence technology areas

This chapter describes the literature review undertaken by the research team and provides high-level qualitative and quantitative analyses of trends.

4.1 An inductive approach was developed to review published material on emerging technologies and to identify salient themes

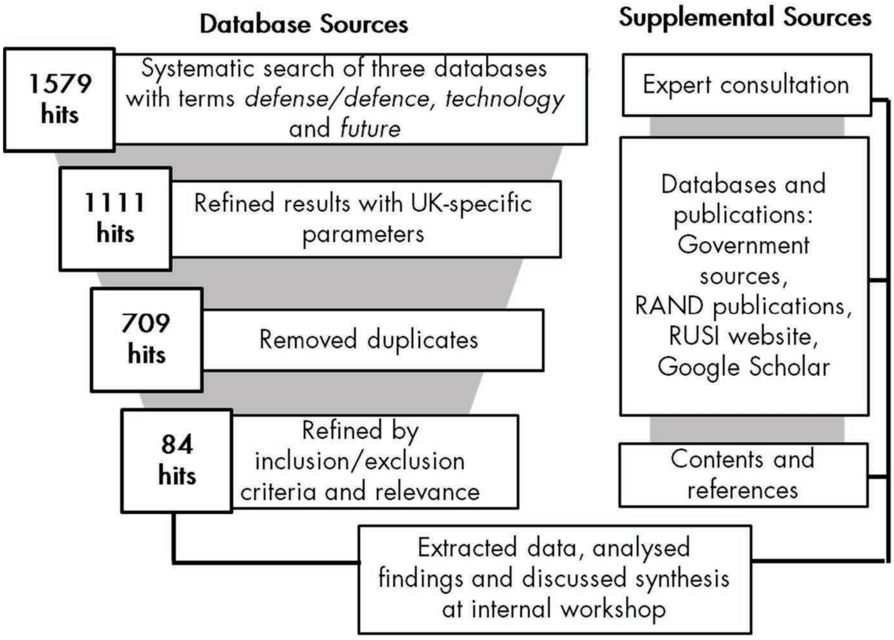
An inductive approach was employed to explore emerging developments in the technology landscape. This involved a technique known as Rapid Evidence Assessment (REA), which is a widely utilised approach in social science research and comprises a structured literature review of the most relevant sources conducted in a thorough, transparent, efficient and replicable manner. This scoping exercise was driven by the research question: *What are the key trends and enablers in the UK's future defence technology landscape to 2035?*

This approach was selected as it provided the broadest possible survey of potential emerging technologies through an efficient and objective process. The alternative approach – structuring the review using an existing MOD taxonomy – may have adversely skewed the results through selection bias, framing bias or confirmation bias.

Our intention was to identify a broad range of published articles, assess these, and use them to develop a set of salient technology areas. This bottom-up approach to developing potentially important areas of future defence technology was intended to be primarily indicative rather than exhaustive. It is important to state that we were not seeking to create a priority list of technology but rather to develop the foundations for later phases of the study. Our understanding is that the MOD has commissioned other investigations into key technologies, such as the MBDA-led work on critical technologies and detailed road-mapping exercises on particular technology strands. However, the outputs from this REA have also been compared with relevant taxonomies and prioritised lists and there is a high level of agreement.

Figure 4-1 outlines the key stages in our REA process. From an initial 1579 hits, upon extensive refinement, our database search yielded 84 relevant sources. Additional articles were located through a supplemental hand search of selected databases (including the Royal United Services Institute (RUSI)), recommendations from expert consultation, and sources in the contents and bibliographies of relevant texts and articles. A more detailed narrative of the methodology is provided in Appendix C.

Figure 4-1 Outline of Rapid Evidence Assessment



Following the collection and analysis of sources, our research team used a structured data extraction template to process source material by subject content. A non-exhaustive list of key technology areas emerged from this bottom-up analysis. These technologies are detailed in the following section, and a breakdown of area-specific trends and examples is also provided in Appendix E.

4.2 Sixteen salient cross-sector technology areas were identified

This section provides an overview of the future landscape of UK defence technologies as scoped in our literature review.

4.2.1 Improvements in automation and digitisation are advancing unmanned systems, weapons and manufacturing

Progress in automation and digitisation across all areas of defence equipment is enabling significant evolution of current technologies. Marked as a UK priority since the 2005 DIS, **unmanned systems** are highly attractive in the air and naval sectors due to their favourable costs, covert nature and lack of associated casualties.[38] They also reduce energy costs and logistical footprints through their lighter structure and heightened fuel efficiency.[39] Developments are underway to improve these systems' autonomy and weaponisation for broader offensive and defensive deployment.[40] Requirements for enhanced surveillance capabilities have also led to novel work on nano-unmanned aerial systems (nano-UAS), individually and as potential components of 'nano-swarms'.[41]

Weapons advances are integrating technological and electronic advances to increase range, lethality, speed, accuracy and stealth.[42] There is a push for weapons technologies to counter

[38] Brown and Lee (2012)
[39] Dixon (2012), p.87
[40] Brown and Lee (2012)
[41] IHS Jane's (2013); Hennigan, (2013), p. B2; Bull, Chitty and Maple (2012); Brown and Lee (2012)
[42] Dowdall, Braddon, and Hartley (2004), p.566

'difficult air targets', such as UAVs and air-to-surface weaponry. Developments are ongoing in such areas as **kinetic, directed-energy** and **precision-guided weaponry**.[43]

Automation and digitisation have also impacted production techniques: **3-D printing** offers a revolutionary manufacturing technology that significantly reduces timescales for every stage of the design and production process. This technique enables quick innovation as well as rapid equipment replacement in an operational context.[44]

4.2.2 Energy and engines technologies are evolving to meet new cost and power requirements

While energy and engines technologies have been evolving for decades, new capability demands are arising due to energy-security concerns, high fuel costs and rising power requirements for new generations of technology.[45] Capitalising on advances from the civil sector, **hybrid and alternative energy sources** are being explored for platform and vehicle systems. Research is underway on solar photovoltaic, biomass, hydrogen and all-electric power possibilities.[46] **Engines technologies** are also capitalising on commercial developments to meet higher speed and efficiency demands. Recent advances show potential for hybrid-electric drive and improvements in high-temperature combustion and turbine systems, as well as distortion-tolerant fans.[47]

4.2.3 Situational awareness and communications capabilities have been heightened by advances in electronics and computing

Improvements in electronics and computing are being integrated to improve the quality, quantity and accessibility of actionable intelligence. Digital **electronic surveillance** is a highly sensitive area of technological development with current research addressing jammers, geolocation techniques, radar and future challenges from engaging in urban theatres.[48] In this context, advances in **geospatial intelligence** (GEOINT) are occurring in the sea and land sectors. GEOINT is benefitting from graphics and computing advances in the commercial electronics industry to enhance 3-D imaging and speed intelligence dissemination.[49]

General interest in **electro-optical systems** reflects the increasing importance of improved visual sensing capabilities and lighter, more sophisticated unmanned vehicles.[50] **Radar** has also improved through integration of related technologies, with 3-D volume search radars capitalising on advances in transmitting and processing, waveform generation, digital beamforming and electronic scanning and stabilisation.[51] These domains are also expected to expand as new detector materials reach maturity, as has been achieved with currently used compounds and micro-bolometers.[52]

To benefit from the heightened volume of intelligence and communications, the **man-machine interface** is becoming increasingly individualised and mobile in order to improve rapid and easy access to information. Future systems are evolving towards making the

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[43] Barrie (2010)
[43] Barrie (2010); Scott (2013b); Bradford (2012)
[44] Bull, Chitty and Maple (2012); *Inside the Army* (2012)
[45] Dixon (2011)
[46] Dixon (2012)
[47] IHS Jane's (2013); Brown (2012); IHS Jane's (2012); Barrie (2009), p.54
[48] Svitak (2012); Scott (2012a)
[49] Batey (2012), p.76
[50] Anderson and Wilson (2012)
[51] Scott (2013a)
[52] Shumaker (2012)

soldier 'an individual C4ISR node on the modern battlefield', equipped with lightweight command, control and communications elements that can be worn on helmets, attached to wrists or used as tablets or smartphones.[53] This is also true at the macro equipment level, an example being the use of commercially inspired touchscreen capabilities in new cockpits.[54] Computing improvements are also enabling the role of **simulation technology** in realistic, cost-effective military training.[55]

4.2.4 Newly emerging technologies may act as key enablers through a wide range of still-unknown applications

A number of emerging technologies in the early stages of development and integration are characterised by both high uncertainty and high potential for cross-sector application. Identifying and applying **new materials** to lighten and strengthen military equipment is a commercial-led area with wide-ranging possibilities. The technology's potential applications include reducing radar visibility, providing vehicular armour, offering coating for jet engine performance, and creating 'smart' materials that react to environmental conditions.[56] **Nanotechnology** is another priority area marked for rapid expansion as a key enabling technology. It has future potential to revolutionise material properties such as strength, weight, cost and conductivity.[57] While **cyber warfare** has also not yet matured, its future offensive and defensive deployment could transform the nature of battle.[58] Reflecting this possibility, cybersecurity concerns continue to influence defence capability needs in C4ISTAR areas of information sharing, intelligence, espionage and 'cyber-situational awareness'.[59]

4.3 The level and growth of publications reflect trends in key technology areas

To supplement the REA results, we conducted a quantitative analysis of the prevalence and growth in online publications on relevant technologies over the past six years. For all 16 technology areas identified in the REA, we recorded the total number of Google Scholar hits, both general and defence-specific, between 2007 and 2012. This data serves as a proxy measurement for the number of online publications, estimating the amount of ongoing civil- and military-led discussion of technology areas. Variations in results may be linked to factors such as technologies' maturity, recent innovation or market potential.

Given the methodological challenges of using search engine hits, these results should be viewed in relative rather than absolute terms, and as indicative rather than conclusive. Lack of transparency in the Google Scholar search algorithm makes it difficult to gauge the accuracy, bias or other confounding factors that may impact upon the numerical estimate of search hits. Fluctuations in the number of hits may also be impacted by a general rise in the number of online publications over the past six years, or by a time lag in uploading more recent publications. The precise wording of search terms may also have influenced results. Extrapolations from the quantitative analysis should be interpreted with these caveats in mind. Limitations of this process, as well as detailed records of our search

[53] Ebbutt (2012a)
[54] Jennings (2012)
[55] Strachan (2011); Ebbutt (2012b); Pengelley (2012); Nash (2012)
[56] Hermann (2008), p.380; Silberglitt et al. (2006) pp.12–13
[57] HM Government (2010); Silberglitt et al. (2006), pp.10–11
[58] Keymer (2012)
[59] Quintana (2012), p.69

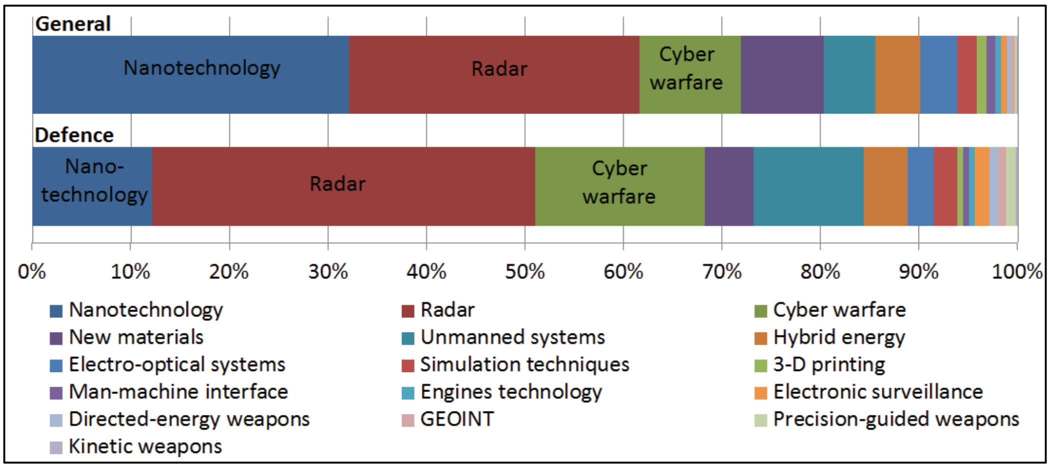
method, are expanded upon in Appendix D. However, despite the caveats listed above the approach serves a useful purpose in illustrating and exploring major trends.

4.3.1 Significant differences exist in the prominence and distribution of technology areas

Technology areas show strong variation in their overall representation in publications, as illustrated in Figure 4-2. Nanotechnology, radar and cyber warfare are the most prominent technology areas in both general and defence-specific online publications. These three areas alone comprise approximately 70 percent of online discussion on the 16 technology areas. This proportion holds across both general and defence-specific publications, although nanotechnology is more prominent in general publications while radar and cyber warfare are more strongly represented in defence-specific discussion.

In contrast, the eight technologies with the fewest online publications comprise less than 10 percent of both general and defence results, indicating lower focus. For weapons technologies and electronic surveillance, lack of discussion may be due to the classified nature of these technologies. Technology categories with low search results may also be discussed in different terms than those used in the search engine analysis.

Figure 4-2 Prominence of key technology areas in online publications, 2007—2012



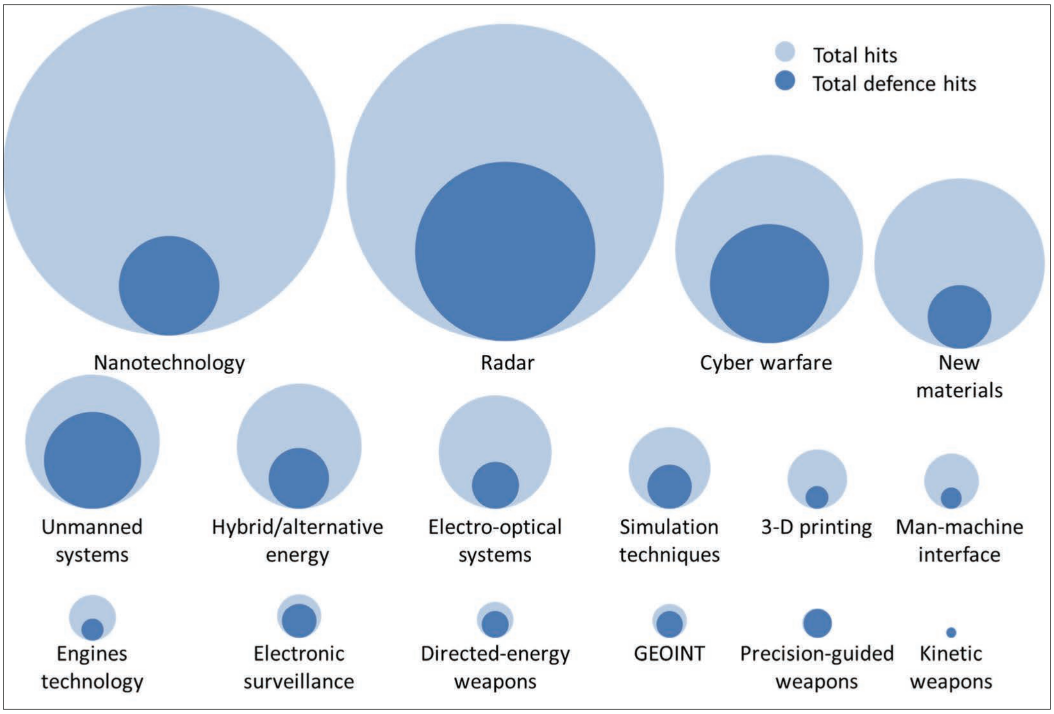
Source: RAND Europe analysis

4.3.2 The proportion of defence to civilian literature varies widely by technology area

Key technology areas show significant differences in their proportion of online literature that is defence-specific, as shown in Figure 4-3. Computing, energy, engines, radar and materials technologies have a low proportion of defence publications (less than 40 percent of their overall online results). Civil developments may be especially important to watch in these areas. Defence publications constitute the majority of online sources for electronic surveillance and kinetic and precision-guided weapons, suggesting a defence lead in interest and development. Directed-energy weapons, cyber warfare, unmanned systems and GEOINT technologies show a relatively even split between defence and general results.

The dominating proportion of defence results for weapons technologies, particularly precision-guided and kinetic weaponry, supports the idea that these areas are more highly classified due to their military nature. This lack of publicly available resources may play a role in the small overall number of online results for weapons technologies.

Figure 4-3 Key technology areas sized by total online discussion, 2007—2012



Source: RAND Europe analysis

4.3.3 Technology areas experienced different rates and directions of change in the 2007–2012 period

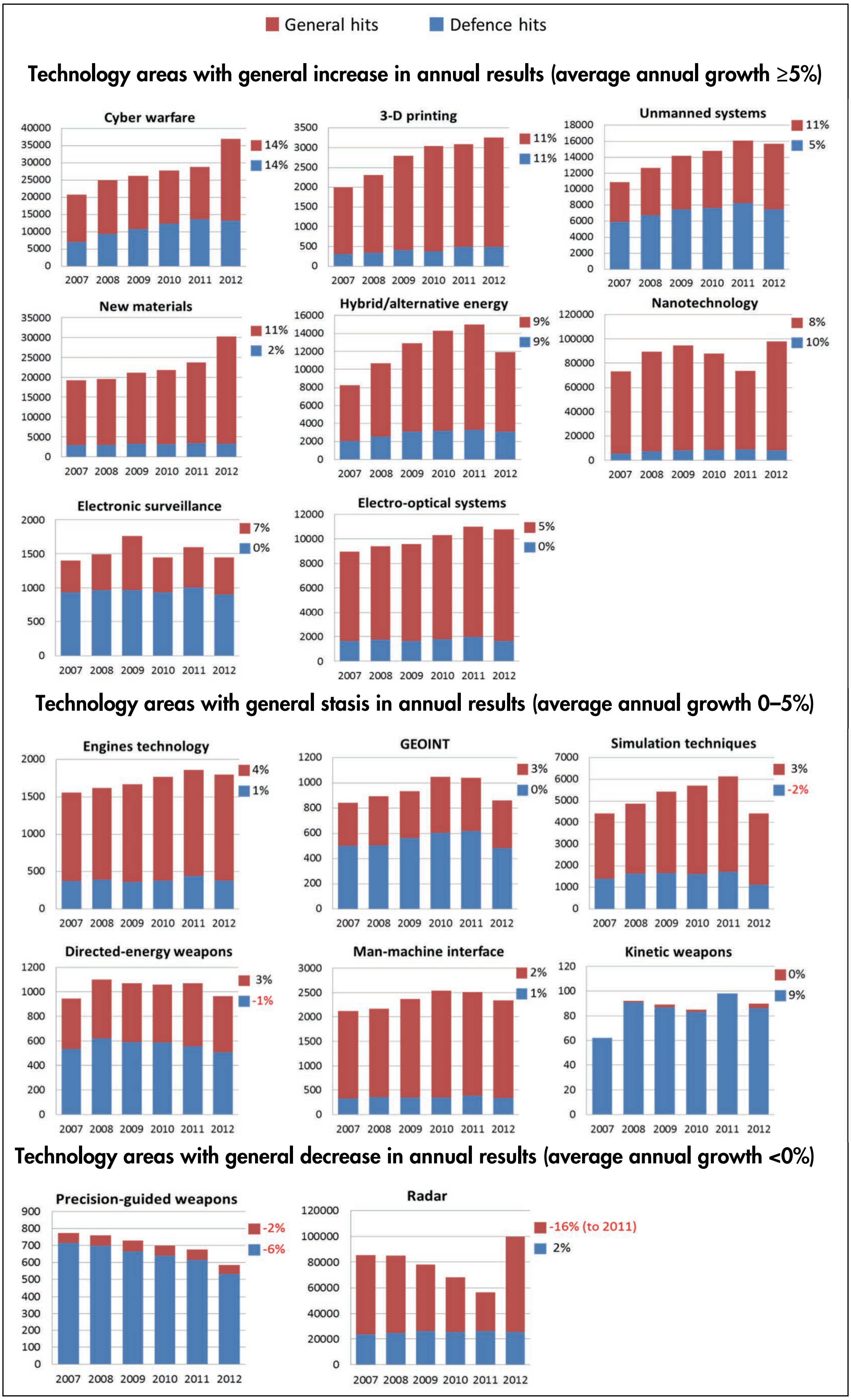
Over the past six years, technology areas have displayed varying trends in terms of the growth or decrease of online publications. For each technology area, Figure 4-4 shows the yearly fluctuations and average annual percentage change in online results.[60]

Publications on energy, electronics, unmanned systems, manufacturing, materials and cyber technology all increased over the 2007–2012 period. This may indicate rising interest in or maturity of these technologies. Engines, computing and kinetic and directed-energy weapons see a relatively stable level of general results (average increase less than 5 percent). Only the area of precision-guided weapons sees a steady decrease over the period, pointing to diminished importance. Radar also sees a steady decrease, with the exception of 2012 data that suggests a resurgence of interest or relevance (although this may be an artefact of the sampling approach).

Defence results for key technology areas are much more stable over the 2007-2012 period. although five technology areas – cyber warfare, 3-D printing, nanotechnology, hybrid energy and kinetic weapons – displayed strong growth of at least 9 percent in average annual defence hits. The rise in publications in these areas suggests growing potential in future years.

[60] The main purpose of this analysis is to identify trends between technology areas: the data are not normalised to account for other factors that may influence the absolute numbers

Figure 4-4 Annual change in online discussion for key technology areas, 2007–2012



Source: RAND Europe analysis

4.4 Summary: technologies differ by impact potential and balance between civilian and military drivers

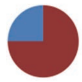
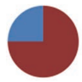
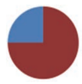
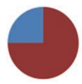
To summarise the findings from both the REA and the analysis of defence technology publications, we have categorised each of the 16 technology areas identified in two ways: by their **impact potential** (based on REA results and expert workshop discussion) and by the **balance between civilian and defence** contributions (based on our quantitative analysis of search engine hits, modified by REA findings and expert consultation). These results are shown in Table 4-1.

Emerging technologies can be characterised as either marginal improvements or game changers, depending on their innovative impact on military capabilities. This impact is achieved through either independent application or integration with current systems. Marginal improvements may come from technologies that advance existing equipment, for example by enhancing speed, power or fuel efficiency. They may also occur through upgrades to the collection, processing and accessibility of information. Game-changing technologies may bring about improvements in similar areas, but their impact is substantial to the point of spurring a new stage in capabilities.

Technology development can be driven primarily either by the military or civilian sectors. Military-led technologies are those that are developed predominantly through defence R&D initiatives. These areas, such as advances in weaponry, are likely to have less relevance to the commercial sector. Civilian-led technologies are developed primarily through commercial R&D. Driven by market demands, these technologies benefit from shorter development timescales and private investment. This commercial sector focus can facilitate rapid advances in defence-relevant technologies. As emphasised by the 2012 White Paper, capitalising on these COTS technologies is especially important in the current climate of Government spending cuts.[61] Adapting and integrating civilian-led developments is critical if the UK is to maintain cutting-edge technologies without bearing the full burden of costs.

[61] MOD (2012)

Table 4-1 Summary table of the 16 most prominent technology areas by impact potential and level of military/civil drivers indicated in literature

Technology	Impact potential	Military- vs civilian-led Civilian-led Military-led
Nanotechnology	Potential unknown, but possibly a game changer	
Radar	Step by step advances from integration of new technologies which are rapidly maturing	
Cyber warfare	Game-changing possibilities for evolving offensive and defensive techniques	
New materials	Wide potential in many applications in both marginal and non-linear changes	
Unmanned systems	Marginal improvements in functionality with some major steps possible in autonomous combat systems; swarms and nano will be a game changer in increasing surveillance and combat capacities without casualties	
Hybrid/ alternative energy sources	Potential game changer but tangible application has been marginal so far	
Electro-optical systems	Step by step improvements as new detector materials reach maturity	
Simulation techniques	Step by step improvements for training programmes	
3-D printing	Game changer if incorporated across defence industrial base	
Man-machine interface	Game-changing advances in usability and accessibility of informational inputs	
Engines technology	Step by step improvements in power and fuel efficiency	
Electronic surveillance	Step by step improvements in surveillance and communications techniques in line with increasing civilian usage	
Directed-energy weapons	Substantial improvements in accuracy, speed, and disruption	
Geospatial intelligence (GEOINT)	Marginal improvements in current mapping capabilities, data fusion and interpretation	
Precision-guided weapons	Substantial improvements in accuracy, range, speed, and lethality	
Kinetic weapons	Substantial improvements in accuracy, range, speed, and lethality	

Source: RAND Europe analysis

CHAPTER 5 Additive manufacturing: discussion and findings

This chapter presents the study team's assessment of the additive manufacturing (AM) technology area. Following an overview of the methodology used, it includes:

- A definition of the technology area
- An assessment of key developments and future trends
- An understanding of the implications for the MOD
- The team's overall findings regarding this technology area.

5.1 The study team conducted an extensive number of interviews in conjunction with further literature analysis

As part of the third phase of the study, the project team performed two in-depth case studies – AM and SE – in order to understand detailed technology landscapes, assess how specific technology areas are expected to evolve, and analyse the profile variations between different technology areas. The process followed by the team to choose these two specific technology areas is detailed in Appendix F.

To perform those detailed case studies, the research team used the overview of AM performed during the previous phase of the study as the starting point for the in-depth analysis outlined in the following sections. Two methodologies were used to conduct this further analysis. Firstly, we conducted an extensive set of interviews with the individuals from the range of actors involved in each technology area. Secondly, we completed those interactions with further desk research, using documents we had not been able to integrate previously or following leads provided by interviewees. An overview of interviews and engagements for the AM case study is shown in Table 5-1.

Table 5-1 Overview of engagements for the AM case study

Case Study	Government	Academia	Defence	Business	Total
Additive Manufacturing	2	7	4	3	**16**

Interviewees were selected through their prominence in the literature used to date, their membership to a representative body of the technological area, or by the suggestions offered by the project sponsors.

The full case study and all the data collected through interviews and case studies can be found in the supporting *Case Study Documentation*. The full lists of interviewees for each case study can be found in Appendix A.

5.2 Additive manufacturing has been branded as the third industrial revolution

AM enables rapid conversion of digital designs into physical form by merging thin layers of heated materials into a 3-D form.[62] AM has many synonyms, of which '3-D printing' is one of the most common derivatives today.[63] While the technology was initially used for prototyping, and most of the 50,000 AM machines in existence around the world still serve this purpose, there has been a shift in interest and potential to AM as a route to direct production.[64] Final products now comprise 20 percent of AM output, and projections suggest that this will rise to 50 percent by 2020.[65]

The potential of AM for the future of manufacturing is perceived to be significant – it has been called the 'Third Industrial Revolution' and its transformative potential has been claimed to be as significant as the advent of the Internet.[66] Indeed, the AM sector has seen double-digit growth over recent years – by nearly 30 percent in 2011 alone – and could exceed a supply chain value of £80 billion annually by 2020.[67] However, a number of non-trivial challenges exist that currently limit widespread application of AM, and the experts we interviewed expressed a range of views about the speed, scope and scale of AM in the future.[68]

5.3 AM shows great potential for niche applications across many commercial sectors but is still at a low maturity level

5.3.1 AM is already being used by several sectors in the UK, which is a European leader in the technology

AM is used to address the needs of multiple industries in four broad markets:[69]

- prototyping
- tooling and casting
- direct part manufacturing
- maintenance and repair.

AM use in UK industries is led by the medical, aerospace and consumer goods sectors. The medical sector is the largest adopter of AM, with applications including such products as cranial implants, hip replacements and dental crowns.[70] Aerospace has also been among the most prevalent users of AM techniques, with Boeing flying approximately 20,000 laser sintered parts, including 32 parts on its 787 Dreamliners.[71] Both high- and low-end consumer goods are another area of major application. Fast-moving consumer goods are

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[62] Sissons & Thompson (2012); Centre for Additive Layer Manufacturing
[63] Other names include advanced manufacturing, 3-D printing, rapid prototyping, rapid tooling, rapid technologies, rapid manufacturing, advanced manufacturing, additive fabrication, additive layer manufacturing, direct digital manufacturing and direct manufacturing. Stratasys, 'Additive Manufacturing 101: How the Future of Product Development and Manufacturing is Changing', presentation
[64] Interviews conducted by RAND Europe, 2013
[65] *The Economist* (2011)
[66] Sissons and Thompson (2012); Campbell et al. (2011), p.9
[67] Hague and Reeves (2013), p. 45
[68] Interviews conducted by RAND Europe, 2013
[69] Scott, J. et al. (2012), p.ii
[70] Hague and Reeves (2013), p.44
[71] InterPRO, website

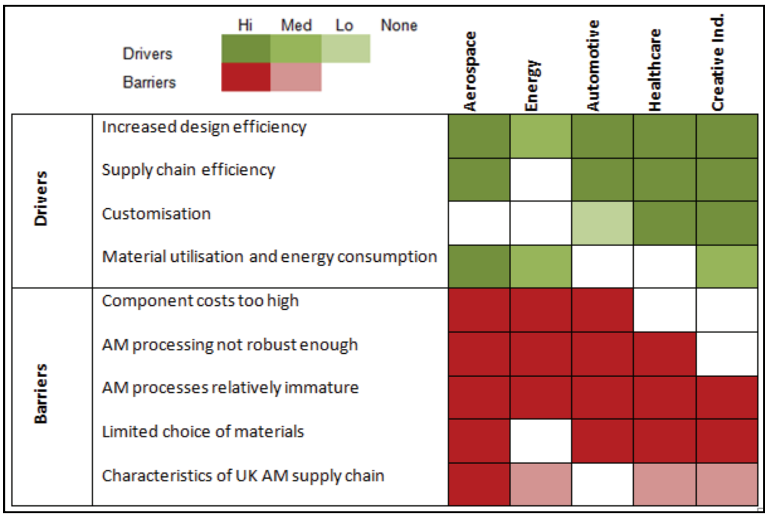
seeing projected growth, with AM used for products from phone cases to lampshades.[72] 3-D production for low-end goods is also a major area of development: from 2007–2011, the sale of personal 3-D printers grew annually by 200–400 percent.[73] Sectors like the creative, motorsport, and automotive industries are also showing interest in AM applications.[74]

The UK is the largest centre for AM research and development in Europe, with investment coming from across government, research, industry and academia.[75] Between 2007 and 2016 the total investment in collaborative or university projects will reach £95.6m.[76] Research institute funding has come from both the TSB, which has committed approximately £13m from 2007–2016, and RCUK, particularly the EPSRC.[77] AM is also supported by a number of university-hosted research institutes collaborating with industry and government partners, such as the EPSRC-funded centre at Nottingham.[78]

5.3.2 AM provides multiple advantages including customisation, design freedom and added functionality

While AM will not replace traditional commercial manufacturing, it is well suited to certain applications. The TSB's AM Special Interest Group has identified four primary drivers in the UK for AM: design freedom, supply chain efficiencies, customisation of products and material utilisation.[79] These priority areas all contribute to accelerating the manufacturing process, reducing costs and supporting innovation. Figure 5-1 shows the importance of these drivers for five major sectors, along with corresponding barriers.

Figure 5-1 Drivers and barriers for UK additive manufacturing



Source: AM SIG (2012), pp.10, 12

AM provides a wide range of benefits, enabling new levels of complexity and reducing costs of entry to the manufacturing process. It enables new opportunities for customisation and design freedom, and enables complex internal structures that can reduce weight, add

[72] Interviews conducted by RAND Europe (2013)
[73] Manyika et al. (2013), p.105
[74] Interviews conducted by RAND Europe, 2013; Freedman (2012)
[75] Thornton (2012)
[76] Additive Manufacturing Special Interest Group (AM SIG) for the Technology Strategy Board (2012), p.17
[77] AM SIG (2012), p.17
[78] EPSRC Centre for Innovative Manufacturing; Hopperton (2012)
[79] AM SIG (2012), p.11

strength and generally increase functionality of products.[80] There is potential in the future to use new materials or combine materials, like electronics and metals, in new ways. AM also eliminates substantial amounts of waste, reducing time and energy needed for production.[81] Additionally, AM enables local manufacturing and encourages innovation by reducing costs of entry and speeding up design-to-product timescales.[82]

5.3.3 AM will need to overcome a number of barriers to achieve its potential

As indicated in Figure 5-1, AM also faces a number of barriers to fulfilling its potential on a large scale. Overwhelmingly, experts point to cost effectiveness as a major priority. Due to limitations in such areas as production speed and available materials, AM is currently much more expensive than conventional manufacturing.[83] Given the immaturity of the technique, the supply chain is also relatively fragmented. Reliability and quality of printed products is another barrier to AM adoption, with 20 percent of AM-produced parts failing before completion and an additional 10 percent completing manufacture with fatal internal flaws.[84] Other challenges include pre- and post-production issues, accuracy of printers, barriers in computer-aided design (CAD), and standardisation of both machines and materials. There are also limitations inherent to the scientific process itself, such as the speed of production and the materials that can be used.[85]

Overcoming these barriers to feasible application is the key priority for wide adoption and commercialisation of AM. Looking ahead, it is difficult to predict which barriers are most likely to be overcome, and at what speed. Investment and research, particularly focussing on the transition from research to application, will be critical.[86] Dealing with intellectual property restrictions, which may impede progress, will also be critical to furthering open research.[87]

5.4 Currently, AM presents limited opportunities to the MOD and wider commercial adoption would be required to overcome barriers

5.4.1 The MOD is currently assessing AM's potential, especially regarding operational logistics and specialised applications

From a defence perspective, AM is an area of substantial but undetermined future potential. The MOD is currently engaged in a number of studies and scoping exercises to determine the feasibility of applying this technology, and to assess the degree to which AM could be a 'game-changer' for defence.[88] The relevance of AM for defence mirrors its commercial priorities of customised/localised production, reduced cost and enhanced opportunities for innovation. In addition to the general benefits of reducing design-to-production timescales and lowering expenditure for producing/replacing equipment, the defence application of these benefits is favourable in a number of specific contexts, summarised in Figure 5-2.[89]

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[80] Manyika et al. (2013), p.106
[81] *The Economist* (2011)
[82] *The Economist* (2011); Sissons and Thompson (2012)
[83] Interviews conducted by RAND Europe, 2013
[84] Interviews conducted by RAND Europe (2013)
[85] Interviews conducted by RAND Europe, 2013
[86] Interviews conducted by RAND Europe, 2013
[87] Interviews conducted by RAND Europe (2013)
[88] Interviews conducted by RAND Europe (2013)
[89] Interviews conducted by RAND Europe (2013)

Figure 5-2 Defence-specific benefits of AM

In-theatre production	Specialised applications (e.g. stealth materials, sensors)
Aircraft, particularly UAVs	Lightening soldiers' carrying loads
Improving energy use	Reducing logistics repairs burden
Modifying equipment design phase	Space premium missions

Source: Interviews conducted by RAND Europe, 2013

For soldiers, vehicles and bases, the MOD is interested in how AM can provide solutions to improve energy use, lighten soldiers' carrying loads, reduce the logistic repairs burden and modify the equipment design phase.[90] AM also has the potential to replace physical with digital inventories on space premium missions, such as submarines.[91]

Defence could also benefit from specialised applications of new properties enabled by AM materials and processes. These uses include embedded sensors, temperature resistant devices, armoured vehicle plating, explosive materials, acoustic absorbency, and even biomedical monitoring applications to ensure soldiers receive the nutrients they need.[92] Lightweight AM products would be useful for defence aircraft, particularly for unmanned aerial vehicles (UAVs) with lower certification requirements.[93] AM's ability to localise manufacturing could also be valuable where immediate, customised production is a tactical asset.[94] In-theatre production can provide spare parts, reducing the need for fuel and convoys, and even create temporary implants for soldiers requiring emergency medical treatment.

Along with these benefits, AM may introduce certain defence and security risks by expanding the ability to design and produce weapons.[95] For example, weapons may be better disguised during manufacturing, with implications including advanced improvised explosive devices (IEDs).[96]

5.4.2 Barriers include cost, reliability, materials and production upscaling – and need to be reduced to give the MOD the confidence and incentive to adopt AM more widely

In some ways, AM is highly suited to defence production, which is often high value, low volume, and involves complex designs. However, defence-specific challenges exist. Lack of precision and reliability in AM processes remains a barrier for defence, for which validated accuracy and repeatability of products is important.[97] Experts noted that rigorous testing of AM materials and methods must occur before the process is trusted and adopted widely.[98]

In forecasting AM's defence potential, the next five years may focus heavily on testing the quality and feasibility of limited AM application.[99] Initial impact for military forces will likely be limited until AM is more developed and its use is more widespread – and until it is shown that AM can be preferable to traditional manufacturing. In the next 15 years, niche

[90] Interviews conducted by RAND Europe (2013)
[91] Wohlers (2011) in Scott, J. et al. (2012), p.15
[92] Interviews conducted by RAND Europe (2013)
[93] Interviews conducted by RAND Europe (2013)
[94] Scott, J. et al. (2012), pp.15–16
[95] Campbell et al. (2011), p.13
[96] Campbell et al. (2011), p.13
[97] Interviews conducted by RAND Europe (2013)
[98] Interviews conducted by RAND Europe (2013)
[99] Interviews conducted by RAND Europe (2013)

applications like stealth coating, self-lubricating metals and the use of recycled materials could occur, with AM use potentially expanding after 2030 if proven effective.[100]

5.5 We identified three findings for the AM case study

5.5.1 AM will have a considerable impact on manufacturing although how this impact will materialise is uncertain due to current economic drivers

The projected market size of AM by 2020 is £86bn while the wider value of AM at that time has been estimated to lie between £160bn and £350bn.[101] Part of the attractiveness of AM is linked to its ability to increase customisation of goods and localised production, which are enabled by wider societal trends, such as the growing cost of labour. AM will also enable unique applications, such as added functionality and more intricate design, which will create new opportunities and products.

However, there is a high level of uncertainty regarding the ways in which AM will develop in the long term and the full size of its impact. AM is a technology at an early TRL with only a limited number of applications and products currently manufactured through this method. Similarly, AM still has to overcome significant barriers before being used more widely in manufacturing processes, and it is currently unclear which of these barriers will be overcome and under what timescales.

The overall view from our diverse stakeholder engagements was that AM's impact will be both incremental and transformative depending on the areas and products for which it is used. Similarly, although the medical and aerospace sectors are currently leading the application of AM, it is unclear how other businesses will take up AM and in what ways they will direct later TRL evolutions and the commercial use of technologies currently in development.

5.5.2 The MOD can do a lot to prepare for the uptake of AM as well as working to understand what this technology means for its business

There are a number of aspects for which the MOD should prepare as AM technology matures:

- Firstly, as it has currently been doing, it is important for the MOD to understand the ways in which AM will be most relevant. Currently, aspects such as reduction of the logistics burden and use for in-theatre medical treatment seem most relevant. It will also be important for the MOD to see how it will be able to leverage further commercial technologies to divert them to defence-only uses, such as the AM application of stealth material, as well as to think through which parts are best suited to AM techniques, in order to begin trialling the technology and considering the logistics impact.
- Secondly, although the MOD has some clear areas of interest and overlap with AM, it currently has no role in shaping and helping the advancement of AM research. Market forces and other funders such as wider government and businesses are the prime actors who will help the area continue to develop. If the MOD were to invest, it is also currently unclear where the MOD's added value would be located and, for instance, in what part of the value chain it should focus its action.

[100] Interviews conducted by RAND Europe (2013)
[101] Manyika et al. (2013)

- Thirdly, it is also essential for the MOD to actively engage with its supply chain in order to understand the uptake of AM and its potential consequences. For instance, as end-user, the MOD will have to be included within the certification process of any piece produced using AM. But AM will also change the relationship to intellectual property (IP), which would come down to data. The MOD should therefore assess how it will define the contractual clauses for access to design characteristics, both of parts produced through AM and of parts that are currently produced through traditional methods but may be transferred to AM in certain circumstances.
- Finally, the MOD should assess how such facilitated manufacturing will impact on long-term capacity planning. For instance, the contingency of having a constant spectrum of equipment could be reviewed if production timescales were to enable more adaptable equipment procurement.

5.5.3 AM will have an impact on the environment in which the MOD will operate in the future

Although it is uncertain to what extent the transformative potential of AM will be realised, it is predicted that the technology will have a rippling effect throughout society. For instance, AM was identified as one technology that could partly reverse globalisation by allowing more localised production which could slow or reverse the trend for offshoring. AM can also both enable and accentuate other trends such as changes in the professional activities individuals want to pursue, the human cost of labour and the advancement of robotics. The convergence of these impacts could significantly change the profile of manufacturing in Western nations.

In parallel, the democratisation of manufacturing through AM could affect the nature of conflict and the profiles of adversaries. For defence, AM has a disruptive potential in that it is likely to diffuse the threat, as individuals will be able to produce weapons from blueprints. This will have three consequences: firstly, armed forces will have a reduced knowledge of potential adversaries and the asymmetric nature of conflict may be enhanced; secondly, the widespread adoption of AM could reinforce the increasing importance of cybersecurity, as operations would emphasise data protection and control; and thirdly, AM will accentuate the need for coordination with other government institutions as it will contributes to the further integration of defence, national security, and law and order.

CHAPTER 6 Synthetic environments: discussion and findings

This chapter presents an assessment of the synthetic environments (SE) technology area. It includes:

- A definition of the technology area
- An assessment of key developments and future trends
- An understanding of the implications for the MOD
- The team's overall findings regarding this technology area.

6.1 The study team conducted an extensive number of interviews in conjunction with further literature analysis

The research team used the same principles and methodologies for this case study as outlined in the previous chapter, apart from also conducting two focus groups with keen gamers. An overview of interviews and engagements is shown in Table 6-1.

Table 6-1 Overview of engagements for SE case study

Case Study	Government	Academia	Defence	Business	Total
Synthetic Environments	2	3	5 (+1 wkshp)	6 (+1 wkshp)	**16** **(+2 wkshps)**

The full case study and all the data collected through interviews and case studies can be found in the supporting *Case Study Documentation*. The full lists of interviewees for each case study can be found in Appendix A.

6.2 SE combines virtual and human elements to provide a simulated experience

SE is a multidisciplinary technology area that may represent either natural or artificial environments, and is capable of modelling complex relationships and interactions between various actors and components of a given system.[102] Closely linked to information technology (IT) developments, SE is not a stand-alone area but rather a transversal technology across sectors and disciplines. Improvements in SE, such as simulation and

[102] University of Manchester Aerospace Research Institute, informational brochure

virtual reality technologies, are informed by the integration of multiple technology areas, including information, communication and visualisation technologies.[103]

SE advances are occurring in the areas of visualisation, interaction and processing technology. New immersive and virtual reality technologies are improving the realism of the simulated experience, for example through 3-D capabilities and augmented reality (AR), which layers information and visualisations on real-world images.[104] Network interoperability – the ability for an SE to connect to other systems during use – is enabling more advanced connectivity, such as in distributed simulations that involve multiple machines.[105] The participant-environment interface is also improving through multiplayer and motion-sensor technologies.[106] These advances are empowered by developments in computing technology, such as graphics processing units (GPUs) that enable realistic visual effects.[107]

6.3 Commercially, SE is widely used for a range of purposes and sectors

6.3.1 SE commercial applications include design, testing, training, facilitated interaction and modelling

Over the past decade, the simulation and modelling domain has been led by commercial rather than defence developments. Key applications include training, education, support to acquisition, and operational analysis. For many industries, simulation technologies are used before the manufacturing process to empower design, testing and evaluation processes.[108] Simulation can also support performance evaluation in supply chain management by helping optimise conditions, analyse decisions, evaluate diagnostics and minimise risks.[109]

Technologies relating to SE are used in disparate sectors for a wide range of applications, from navigation systems to medical training. Real-time simulators are used in industrial applications from power grid protection tests to space-robot integration.[110] SE is also used for transport modelling, and in aerospace for air traffic management and prototyping.[111]

6.3.2 SE is a highly fragmented area led by the IT and games industries

Developments in synthetic environments technologies are particularly driven by advances in the IT sector and in the games industry. In IT, SE is a highly fragmented area divided between large multinationals (such as Apple, Google and Sky) and 'bedroom programmers', who push the boundaries with new apps created at home. The games industry is also a key SE innovator, motivated by competitive market pressures and characterised by high research investment, with UK developers spending an average of 20 percent of turnover on R&D.[112] More widely, SE is used in a variety of commercial settings to create more

[103] University of Manchester Aerospace Research Institute, website
[104] Deloitte (2012), p.45
[105] Interviews conducted by RAND Europe (2013)
[106] Adolph (2011), p.5
[107] Adolph (2011), p.17; Deloitte (2012), p.45
[108] Interviews conducted by RAND Europe (2013)
[109] GoldSim Technology Group LLC (2007)
[110] Dufour, et al. (2010)
[111] Neffendorf, et al. (2007), p.ii; University of Manchester Aerospace Research Institute, informational brochure
[112] TIGA (2013)

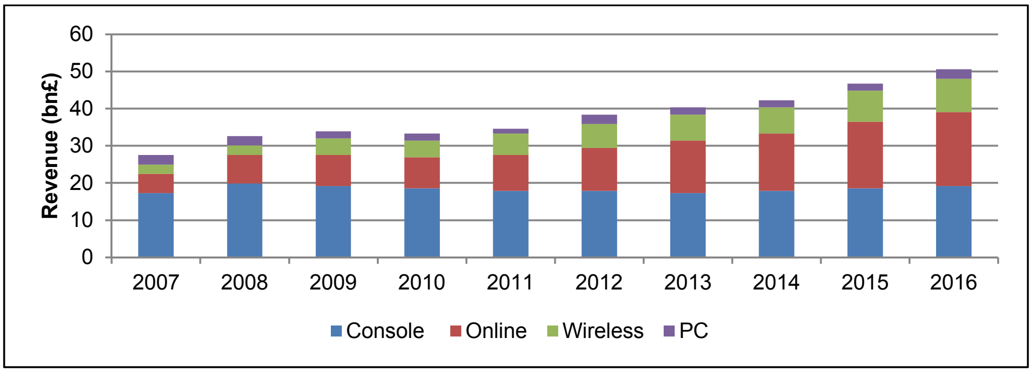
efficient, flexible and effective business models with internal structures being modelled around SE-enabled design processes.[113]

In terms of other stakeholders, government funding for SE tends to come from the TSB and is distributed across a range of research areas.[114] Several UK universities also have SE-focused programmes that receive MOD or industry support – such as Cranfield's Simulation and Synthetic Environment Laboratory and Liverpool's Virtual Engineering Centre.[115]

6.3.3 As SE grows, future developments will blur the reality-simulation boundary

Because the SE market area is diffuse and difficult to measure at the aggregate level, the video games and interactive entertainment industry, as a major driver of SE innovation, serves as a strong proxy. Looking ahead, the global video games market is estimated to grow from £27.5bn in 2007 to £50.6bn in 2016, as shown in Figure 6-1.[116] Recent growth has also been seen in the UK: in 2012, the games sector contributed £947m to UK GDP, a £35m increase from 2010.[117]

Figure 6-1 Global consumer spending on video games, by platform type, 2007–2016



Source: PwC (2013)

Experts predict that the non-defence technology landscape will change dramatically for SE over the next 20 years.[118] Potentially revolutionary developments will come in areas such as increased bandwidth, ray-tracing and 3-D visuals.[119] Across the many uses of SE, there is a continued push towards increasing realism and interactive potential, blurring the boundaries between 'real' and 'simulated' experiences. As processing and display capabilities improve, future constraints may arise around the capacity of the human brain to absorb and respond to the various streams of information that are simultaneously presented.[120]

[113] Interviews conducted by RAND Europe (2013)
[114] Interviews conducted by RAND Europe (2013)
[115] Cranfield University, website; Cunningham (2012), pp.17–18
[116] PricewaterhouseCoopers (2013), p.19
[117] *The Guardian* (2013)
[118] Interviews conducted by RAND Europe (2013)
[119] Interviews conducted by RAND Europe (2013)
[120] Interviews conducted by RAND Europe (2013)

6.4 SE is already used by MOD, but COTS are both one of the key enablers and barriers

6.4.1 SE is primarily used by the MOD for training and acquisition

Defence currently utilises SE technologies in a number of areas, particularly to support training and acquisition operations. SE is a valuable enabler of military training, particularly due to the reduced tempo of modern military operations and the lack of space for live training at a realistic scale.[121] Live, virtual and constructive (LVC) training can be used at all stages of the training process: providing initial learning, preventing skills fade, and delivering post-mission recuperations.[122] The MOD applies SE widely in training efforts, as well as in focused centres like the pilot Defence Simulation Centre (pDSC) at Boscombe Down.[123] The use of SE in training is set to expand, with the MOD announcing in July 2013 a £226m investment in a specialist training school with simulators for both pilots and engineers.[124]

In defence acquisition, SE is useful across the full range of testing and development, from exploring initial concepts through to assessment, demonstration/manufacture and upgrading of equipment. SE enables equipment testing in controlled environments, decreasing the expense and risk of real demonstrations.[125] SE is also useful in modelling disposal scenarios, such as in the UK's recent study on disposal options for a nuclear submarine.[126]

6.4.2 SE reduces key constraints such as cost and enables hypothetical scenarios

SE is valuable for defence testing and training capabilities, both by overcoming challenges of real-life scenarios (such as cost) and by enabling hypothetical situations to be modelled. Experts emphasised that cost presents the major driver for SE in defence training.[127] Simulators cost an average of 10 percent of the actual systems that are being simulated.[128] For example, flight training in the Eurofighter Typhoon costs approximately £70,000 per hour, making live training unfeasible for the entire training pipeline process.[129] SE training can also be adapted in a cost-effective manner to different scales (individuals, teams and joint/collective forces) and intensity levels (generic versus specialised skillsets).[130] SE also overcomes additional constraints to real-life training and testing, for example by cutting down timescales, reducing the need for physical space, eliminating noise concerns and avoiding risky training procedures.[131]

Simulation technology also provides a realistic, immersive experience of potential scenarios that are impossible to model in real life. For example, BAE has a computerised simulation facility for testing UAV platforms, which are currently banned from UK airspace.[132] Virtual

[121] Dobson (2008)
[122] Kirby et al, p.3
[123] LTPA, 'Defence Simulation Centre'
[124] Ministry of Defence, website, 2013
[125] Interviews conducted by RAND Europe (2013)
[126] Jackson, 'Effective Use of Synthetic Environments to Support the Acquisition Life Cycle'
[127] Interviews conducted by RAND Europe (2013)
[128] Kirby et al., p.2
[129] Kirby et al., p.2
[130] Kirby et al., p.6
[131] Interviews conducted by RAND Europe (2013)
[132] Cornford (2012), p.69

environments also enable large-scale training programmes that would otherwise be unfeasible, and can model future technologies that have not yet been developed.[133]

6.4.3 The rapid innovation cycle of SE is the most significant barrier to defence adoption

The most significant barriers to SE integration in the defence context are cost and acquisition timelines.[134] The MOD's lengthy procurement processes have not adapted to the SE sector, which is dominated by fast-moving innovation and involves many SMEs that operate on more rapid timelines.[135] Another barrier for MOD adoption is the short technology lifecycle of SE, in which state-of-the-art technologies may require replacement within 6–9 months. This rapid turnover presents major challenges in planning for future iterations and accounting for new technologies in overall systems design.[136] Testing requirements and compatibility with legacy equipment also pose problems.[137]

The MOD can address barriers to SE integration by focusing on a number of areas. Experts consistently expressed the need for the MOD to move away from bespoke equipment design towards standardisation and generalisation. Standardisation would address a number of challenge areas, such as communications, interoperability, costs and reusability.[138] Improving the flexibility and agility of simulated systems would help adapt technologies to varying requirements, such as the need for different training/playing environments (ranging from snow to harsh terrain).[139] Ensuring interoperability and complementarity of individual SE technologies is also a priority to ensure effective integration.[140] Additionally, thoughtful integration of SE may require the MOD to address a cultural bias towards live training.[141]

6.4.4 The MOD faces both opportunities and challenges in integrating COTS solutions

COTS options offer cost-effective and deployable SE opportunities for defence from sectors such as computer graphics, gaming technologies and mobile devices. Presently, COTS technology is mainly used on the periphery of the MOD's activities where useful, while most of the core systems and software for SE are made in-house.[142] There are a number of challenges to COTS integration, particularly the high level of the MOD's required specifications and the disconnect between military and commercial priorities (i.e. quality improvements vs. cost reductions).[143]

Looking ahead, defence needs to stay informed and take full advantage of opportunities to integrate commercial SE technologies at lower cost. The games industry provides particular potential for COTS collaboration, with gaming technology such as Virtual Battlespace 2 (VBS2) – shown in Figure 6-2 – already used as a battlefield simulation tool to train soldiers.[144] The MOD is already engaging in a number of initiatives to maintain continuous

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[133] Stoker (2013)
[134] Interviews conducted by RAND Europe (2013)
[135] Interviews conducted by RAND Europe (2013)
[136] Interviews conducted by RAND Europe (2013)
[137] Interviews conducted by RAND Europe (2013)
[138] Interviews conducted by RAND Europe (2013)
[139] Interviews conducted by RAND Europe (2013)
[140] Interviews conducted by RAND Europe (2013)
[141] Kirby et al., p.9
[142] Interviews conducted by RAND Europe (2013)
[143] Interviews conducted by RAND Europe (2013)
[144] Bohemia Interactive, 'VBS2 overview'

dialogue with elements of the commercial sphere to ensure that when it is in a position to procure, a mature specification and shared understanding exists.[145]

Figure 6-2 Snapshot image of VBS2 technology

Source: Bohemia Interactive

6.4.5 SE has the potential to improve defence operations in many areas and could have a transformative impact on the MOD as a whole

In the future, SE could find valuable applications in a range of defence uses beyond its current training and testing manifestations. For example, the MOD could integrate mobile technologies into its architecture to make better use of these for both training and operations, to improve troops' situational awareness or for mission rehearsal.[146] SE could also play a much more significant role in the MOD's operations if steps are taken to holistically adopt the technology. The example of companies such as MBDA and Bentley, which have used SE to restructure their businesses internally, could be valuable to the MOD, providing an opportunity to reduce costs while increasing capabilities.[147]

6.5 The project team identified four key findings of the SE case study

6.5.1 Although the MOD currently uses SE, it does not leverage its full potential

The MOD was an early adopter of SE and pioneered the use of video game technologies within its training programme. Similarly, in the late 1990s it started investigating how virtual reality, simulation and modelling could be used as part of its procurement processes and introduced SE-based acquisition (SEBA) to help better define requirements.

However, it seems that following this early push, not only has the MOD lost part of this momentum – especially in comparison with other countries – but it also has been more reluctant to explore and adopt additional possibilities offered by SE. The MOD has not pushed to leverage SE in other lines of development, despite SE having potential applications and uses throughout all the defence lines of development (DLODs). For instance, the MOD has been slow to recognise how mobile technologies could be leveraged

[145] Interviews conducted by RAND Europe (2013)
[146] Interviews conducted by RAND Europe (2013)
[147] Interviews conducted by RAND Europe (2013)

throughout its operations, such as in theatre where specifically designed apps could enhance situational awareness or help with mission rehearsal.

In addition to not making full use of SE products, the MOD has also not embraced the organisation-wide changes and efficiencies that SE can facilitate. Organisations such as Bentley and MBDA have introduced SE to enhance parts of their operations, with a strong top-down strategy to update and streamline their internal processes. Significantly, these organisations have also reported a change in the overall mindset of their staff, as SE has helped achieve greater dialogue, synergies and coordination between different parts of their companies. Therefore, even with a limited investment, SE can have a disproportional and transformative impact on an organisation.

6.5.2 The MOD's structure, processes and culture are not adapted to leveraging SE innovation or to influencing the technology area

The MOD's structure and culture are relatively static and closed

The MOD's structure and culture limit the adoption of an SE-enabled environment due to the high level of centralisation. Interviewees described the MOD as being silo-ed between its different agencies, with little information exchange and a high level of inertia. In comparison, an SE-enabled environment fosters a culture that accommodates both top-down and bottom-up forces and initiatives. However, the MOD is currently having difficulties managing the greater level of agency made possible by, for instance, mobile communications, and it is likely that this would be reinforced through greater integration of different parts of the organisation. Moreover, although SE is relevant to all DLODs, its applications and implications would vary across the different lines. Therefore, the MOD would have to adapt its use of SE across the different parts of its organisation in a modular way, while still being able to manage SE integration at an organisational level.

The MOD's procurement and personnel processes are misaligned with the SE technology area

Current MOD processes are inadequate to take full advantage of SE's potential. SE is a fragmented, fast-changing landscape with a multitude of very innovative SMEs, which seek to sell their products quickly and update them on a regular basis. The MOD's current procurement processes include lengthy lead times and a large bureaucratic burden, making it difficult for SMEs to engage. This situation is seen in the challenges that the MOD faces in including COTS products within its architecture. Similarly, a large proportion of innovation in SE leverages the potential provided by open source technologies, which the MOD does not currently utilise to the extent that it could. Finally, SE is used transversally across a number of sectors, from entertainment to medicine and weather forecasting, making it difficult to identify the innovations most relevant to the MOD and multiplying the number of informal interactions required to keep informed of developments in the whole area.

The MOD also uses a very specific language that in some cases may prevent it from being fully understood by commercial actors. For instance, when conducting interviews with non-MOD actors, the project team shifted to referring to SE by more commonly used phrases such as 'virtual reality' or 'simulation'. Some MOD interviewees also indicated that they had moved from the term 'synthetic environment' to other expressions – such as 'simulation' or 'virtual reality' technologies – that were more directly meaningful to their stakeholder community.

Regarding skills, SE requires a high level of customisation, as the structure and modules used are individually adapted to the intended outcomes. For instance, the specific end-user interface and depth of simulation will influence both the hardware and software required, and may necessitate varying levels of specifically developed elements. Interviewees across sectors suggested that, although they relied on COTS technology where possible, a large proportion of their SE was purpose-built, mostly in-house but also outsourced where possible.[148] It is essential for the MOD to recruit, develop and retain in-house expertise, and invest internally to be a smart buyer, user, developer and integrator of SE innovation and technology. In order to achieve this goal, reform needs to take place in areas such as human resources, where policies were thought to be inadequate to compete with a more attractive commercial sector.[149]

6.5.3 Assessing both the implications and limitations of SE is essential to effective adoption and implementation of its innovations

As SE will be a large part of the future, it is important for the MOD to fully assess the limitations and also the implications of the wider use of SE. As mentioned previously, other organisations that have integrated SE within one part of their business found that it had rippling effects throughout their operations and processes. Therefore, if the MOD were to move towards being an SE-enabled structure, it would be essential to fully understand the consequences – both intended and unintended – as it does so.

Although SE offers great potential for the MOD, it should also be stressed that SE presents some limitations with equally relevant implications. Firstly, there are some applications of SE that are unique to defence, such as the modelling and training of counter-IED measures, for which there is no commercial market that the MOD could uptake. Secondly, SE can only reproduce what it has been programmed to do, which, for example, makes it inadequate to train for certain contingencies. Finally, certain dimensions of SE need to be better developed before becoming more widely applicable. For instance, the human factor is not yet fully accounted for, with the cognitive side of training through SE still in development.

6.5.4 SE both results from and enables societal trends, which will contribute to changing the MOD's societal and operational context

There are a range of emerging societal trends that have been both enabled and reinforced by SE. These include gamification – the use of games principles outside of a gaming context – and the wider use of serious gaming as a methodology applied to a range of outcomes. One interviewee indicated that these trends are partially due to the fact that the generation entering the job market over the last decade, some of whom now occupy middle-management positions, has spent more time playing video games than watching television.

More generally, other demographic trends will also have a wide-ranging impact. For instance, the proportion of 'digital natives' to 'digital migrants' – individuals who were born in the digital age and those who were not – will increase naturally with time, bringing into the workforce individuals with different expectations regarding communications, the fluidity between various platforms, and the depth of experience enabled by SE. Therefore, there is a risk that if the MOD does not adapt internally to a more digitally enabled

[148] Interviews conducted by RAND Europe (2013)
[149] Interviews conducted by RAND Europe (2013)

culture, the gap between its structure and processes and its staff's habits and expectations will widen.

On the operational side, the easier and wider use of SE technologies can have a disruptive impact on current MOD doctrines and operations. For instance, the increasing use of machines is likely to change the character of conflicts and the way in which troops position themselves as part of wider capabilities. This also opens new ethical questions regarding the rights of machines and how these can be used in the context of military operations. Regarding adversaries, more distributed networks and a wider use of mobile technologies will affect the tactics of opponent groups and facilitate decentralised and asymmetric engagements. Similarly to the way in which the Internet is being monitored to assess the information sharing of adversaries, adapting the MOD's operations to encompass the disruptive aspects of opponents' SE-enabled tactics is essential.

CHAPTER 7 Synthesis and discussion of findings

The purpose of this chapter is to present the current challenges and opportunities for the MOD in understanding the future technology landscape and how to be an intelligent agent in shaping and leveraging this future. These findings draw from all phases of the study: literature review, stakeholder engagement and case study analysis.

7.1 The defence innovation and technology base is part of a wider ecosystem

A number of institutions are involved in funding research and the commercialisation of research. For instance, the Research Councils, the TSB and BIS all play a role in sustaining projects and individuals through grants, training and coaching. Complementing this sponsoring role, business angels and venture capitalists contribute to furthering the development of technologies through the provision of funds required to commercialise technology into products and services.

To an extent, the MOD takes part in all these activities, as it performs some research in-house, funds research through procurement, and sustains innovation through grants and other training programmes. In principle, the levers available to the MOD are complementary to those of other actors in the UK technology landscape. Its understanding and close relationship with the UK supply chain and defence research providers mean that the MOD has the ability to play both a coordinating and customer role in shaping the future landscape. This role is distinctly different from that of other actors. Moreover, our interviewees confirmed that the defence innovation base is inherently different from others, due to:

- The size of the institution and its associated bureaucratic and static nature
- The symbiotic relationship between the MOD and industry
- Security of supply issues that limit the attractiveness of procuring from SMEs
- The sensitivity of issues that limit information flow and the type and number of individuals working in this area.

An overarching theme evident from our study is that the MOD has become increasingly insular in recent years. However, the importance of the MOD's active engagement in stimulating, shaping and translating future technology was highlighted by all of our interviewees as critical in fostering an ecosystem that is conducive for defence innovation. Several initiatives were also mentioned that contributed towards better coordination with the MOD, including the Centre for Defence Enterprise (CDE), although there were mixed views as to their success to date.

The innovation ecosystem is not a coherent whole working in symbiosis towards a single objective. On the contrary, it comprises a range of actors each with its own objectives and interests. They are, however, interconnected and the depth of each connection is related to the alignment of organisations' goals. For instance, the link between the Research Councils and academia is extremely close and well established. Similarly, the TSB aims to link with SMEs through a range of initiatives focusing on facilitating information flows. Weaker ties are also important in the diffusion of information, which is critical to innovation.[150]

7.2 Effective exploitation of emerging technologies relies on creating suitable pathways and effective coordination

Another key theme identified during the study was the combination of factors and pathways required to ensure effective conceptualisation, development and exploitation of innovation. Although the UK has a strong web of innovative organisations, including academia and SMEs, internationally it was perceived in our study to have more limited capabilities and a lower success rate in exploiting and commercialising technologies. Difficulties in crossing this 'valley of death' are related to the fact that technology development requires the involvement of different actors and the presence of different incentives depending on its development stage. A number of factors were mentioned by interviewees:

- Firstly, it was stressed that different actors in the technology development ecosystem work on different timelines, which compromises their ability to interact or coordinate effectively. For instance, SMEs find it very difficult to plug into MOD processes, which are driven by long-term programmes, or to have the know-how and resources to go through competitive and uncertain procurement procedures. It was mentioned that, at around 15 percent, the CDE hit rate was too low to attract SMEs with limited sales and marketing resources and a greater need for liquidity. Overall, it was highlighted that more could be done to enable and harness the innovation potential of SMEs.
- Secondly, although all actors in the technology development ecosystem rely on one another, this interdependence is unbalanced. In the relationship between SMEs and primes or the MOD, SMEs tend to be the more dependent partner as they operate on much shorter timescales.
- Thirdly, the value of the MOD processes was recognised, but improvements were thought to be necessary to ensure greater coordination or information flow between actors, as well as to maximise their value. For instance, processes such as horizon scanning can be effective, but they are being carried out with mixed results. Interviewees pointed out the lack of coordination between the horizon scanning performed by the three services and Dstl, as these currently take place independently from each other, while delays associated with processing the information also limit its value.
- Finally, current practices with respect to IPR, traditionally owned by the MOD at the end of projects, were criticised by several actors as limiting the attractiveness of investment and obstructing effective collaboration between actors.

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[150] Social network theory emphasises informal as well as formal links between people in the diffusion of information. See, for example, Granovetter, Mark, 'The strength of weak ties', *American Journal of Sociology* 78:6, 1973

7.3 The MOD's concept of technology innovation is relatively narrow, with a primary focus on new 'things'

One major theme that emerged throughout our study is the emphasis that the MOD has tended to place on developing new 'things' as a result of its research spending. Our respondents highlighted the importance of other aspects of the technology landscape such as the ability of technology to help improve processes; logistics, maintenance and support; new modes of training and testing; and in particular the opportunity for technology and innovation to deliver efficiency benefits as well as improved effectiveness.

For instance, the MOD perceives the potential of synthetic environments to be primarily around the tangible and quantifiable benefits it can provide, rather than the transformative impact it could have on the MOD's organisation. Currently, the two primary MOD applications of SE focus on training and SE-based acquisition. However, the MOD has been reluctant to explore and implement how it could also use SE to streamline its operations and facilitate information sharing across the different parts of its organisation.

In other technology areas, logistics and maintenance are often relegated to 'Cinderella' status in discussions about technology innovation as, although they are recognised as being important, they do not benefit from the same level of regard or interest.

Moreover, many of our interviewees suggested that existing MOD processes emphasise a solution-led approach, and that more could be done to focus on the benefits of a challenge-led approach. The inherent risk is that the MOD over-specifies its requirements because of its solution-led approach. This significantly narrows the scope and range of potential solutions, and reduces the likelihood of introducing innovations that may come from completely unrelated domains – or in processes rather than technology.

7.4 A linear model for investment in technology appears increasingly outdated

Historically, the MOD was able to commission the bespoke design, manufacture and construction of military capability, all underpinned and enabled by a substantial research programme in both basic and applied science. The MOD's industrial partners were incentivised to invest in future technologies, as there was an implicit or explicit market for those technologies from the Ministry.[151] Defence research was viewed as an exciting place for talented scientists and engineers to enter, due to the opportunity to work on novel technologies and challenging problems. During the Cold War era, defence technology was cutting edge and UK innovation was often at the vanguard.

In the early 21st century, a more focused – but somewhat linear – approach to research investment was adopted by the MOD, with priority given to 'solving problems' through research spending and the use of road-mapping to target relatively short-term research objectives. The rationale was to maximise the outputs from UK defence research spending and focus efforts on those areas of capability in which it was most important to develop or retain an operational advantage.

The interviews and analysis we have conducted suggest that this linear approach is likely to be an inefficient way for the MOD to maximise returns on its investments in terms of future military capability. Not only has the MOD's investment in research and technology

[151] Interviews conducted by RAND Europe (2013)

declined substantially in the period since 2007, with UK R/T&D real-term spending decreasing from £3.6 to £2.4 billion between 2007 and 2010,[152] but other changes have occurred too. The development cycle for new military capabilities has decreased to reflect changes in threats; there is greater application of civilian technologies to defence; and the defence enterprise is becoming increasingly internationalised – on both supply and demand sides.

Moreover, the investment model should be adapted to the profile of different technology areas. For instance, the varying speed of innovation in different technology fields needs to be reflected in thinking about future developments. It would be relatively straightforward to make long-term predictions on how developments in certain technology areas may be leveraged by defence, but in other fields that might be more difficult.

In the study objectives articulated by the MOD and Dstl, the importance of civil and export markets for UK technology was emphasised. This was also a major theme of the White Paper on *National Security through Technology*.[153] This has been confirmed by our research to date. It is clear that the MOD does not have the budget required to be the sole customer for any but a very few selected technologies. Investment from other sources (venture capital, industry investment, equity investments) is also unlikely without a viable business case and the prospect of future revenues from a range of customers.

7.5 There is no 'one size fits all' approach to leveraging civil investments in technology

The five technology areas that have been scoped in this study exhibit a wide range of differences in three dimensions – although it is likely that these characteristics exist along a continuum rather than being mutually contradictory. Consequently, it is important to consider both individual and structural factors:

- Technology areas differ by the degree of fragmentation of the technologies covered, stakeholders involved and levels of demand and supply. For instance, although advanced materials are treated as one technology area in many government strategies, it is a heterogeneous group bringing together sectors from pharmaceuticals to building and IT. This is similar for cybersecurity, which includes software, hardware and a human component.
- Technology areas differ by their transformative potential. Some of the areas we scoped were characterised as enabling technologies, so that their integration into existing practices would increase further innovation or existing capabilities disproportionately. These include the cyber area and related information technology, which has revolutionised modern society in recent decades. Similarly, advanced materials such as graphene are perceived to have had a large transformative impact – and receive large investment as a result. Technology development in other areas, however, is expected to produce only incremental changes to existing solutions. This is the case for small-scale energy storage, for which research improves existing solutions, as well as synthetic environments in which new technologies improve realism and immersion.
- Technology areas differ by maturity level and innovation rate. Some technology areas have benefitted from long-term research and have reached a significant level

[152] RAND Europe analysis of EDA data

[153] UK MOD (2012)

of commercialisation; in additive manufacturing, for example, where the research focus is currently on adding functions to the materials used. Others, however, have a significant proportion of early stage development; examples include advanced materials and cybersecurity. Similarly, the length of time between innovation, commercialisation and integration will vary across technology areas. Being IT-based, synthetic environments and cybersecurity cycles are much quicker than those of small-scale energy storage or additive manufacturing.

These significant differences between the technology areas have two consequences. Firstly, the conceptualisation of each technology area, and the way in which each one interacts with the different actors, requires in-depth understanding and investment, while at the same time it is necessary to arbitrate across technologies and identify priorities. One of our interviewees within a funding body stressed the balancing act performed by the organisation between the different areas it sponsored, and emphasised the complementarity of area-specific experts and higher-level councils of advisors. Secondly, the level of long-term visibility achievable will vary by technology area. For instance, development in cybersecurity is highly reactive to new types of threats that are difficult to predict, while long-term visibility will be easier to obtain in small-scale energy storage due to longer development cycles.

In addition, it may be helpful to define how technology areas differ from one another at the high level, to help set strategy. A number of frameworks can help conceptualise how elements differ from one another. The matrix in Figure 7-1 is influenced by project management theory and is based on the idea that, depending on the type of projects one is involved with, the skills, techniques, risk management and expectations should be adapted.[154] For instance, a project where the objective is known but the way to reach it is unclear is different from another for which both are tightly defined.

These types of frameworks could also be used to understand how technology areas differ from one another and the most appropriate type of approach. In this sense, AM would be located in the upper right-hand corner of the matrix, 'direction setting', as it is currently unclear how AM can be best used within the MOD, but the process currently followed internally is the same as that followed for other new technologies. In comparison, the transversal aspects of SE are located in the bottom right-hand corner, 'concrete creation', as the MOD has not yet fully explored the possibility of being an SE-enabled organisation, nor is the process to get there understood due to security limitations.

Figure 7-1 Example of conceptualisation framework

		Is the objective defined?	
		Yes	**No**
Is the process understood?	**Yes**	Operational management	Direction setting
	No	Process development	Concept creation

Source: Adapted from Obeng (1994)

[154] Adapted from Obeng (1994)

7.6 Summarising drivers, enablers and barriers to technology development in the UK

Our analysis has highlighted a number of good practices in innovation and technology development. Firstly, effective innovation requires careful identification and definition of the problem – not the solution. Secondly, effective exploitation of emerging technologies relies on creating suitable pathways and effective coordination. Thirdly, individuals' skills and experience are essential enablers of innovation – but connections and culture are equally important.

Finally, stakeholders mentioned a number of drivers, enablers and barriers to technology innovation and development. Table 7-1 includes a list of those that were referred to by several interviewees, or that confirmed findings from the literature.

Table 7-1 Summary table of drivers, enablers and barriers gathered through stakeholder engagement

Drivers	Enablers	Barriers
• Military requirements • Nature of the threat • Operations • Strategy • Entrepreneurship	• Information sharing within ecosystem • Appropriate contracting mechanisms • Complementary innovations • Synergies between all actors (value chain, innovation ecosystem, other armed forces…) • Competencies and absorptive capacity • Challenge-led approach • Risk-taking culture • Exports	• Austerity and decrease in funding • Inefficiencies and lack of coordination between numerous actors • Complexity of innovation to exploitation processes • Static nature of the MOD • Difference in timeline between SMEs and MOD/primes • Government-owned intellectual property rights

Source: RAND Europe analysis

CHAPTER 8 Recommendations and areas for further investigation

This final chapter outlines the high-level recommendations identified by the study team. Potential areas for further investigation are also outlined at the end of the chapter.

8.1 The study team used iterative workshops to identify, refine and contextualise recommendations

The study team identified the recommendations outlined in this chapter through successive workshops. Firstly, the team conducted two internal workshops to discuss the findings from the case studies and study as a whole, as well as to identify the implications for the MOD and possible recommendations. Secondly, we tested and refined those recommendations through stakeholder engagement with the Defence Strategies and Priorities Unit and DCDC. Discussing our thinking with different MOD communities was particularly helpful in contextualising the recommendations within the wider MOD initiatives currently taking place.

8.2 The project team identified four high level recommendations

8.2.1 The MOD should adopt some good practices from the commercial world to leverage commercial technologies

In the current and future R&D environment, the MOD, and defence more generally, will be a minority actor, while the driving forces for innovation will be increasingly found in the commercial sector. This is reflected in the proportion of civilian and defence involvement in the five technology areas scoped by this study: the key actors within each of these areas were civilian and most of the technology development performed reflected civilian priorities. Similarly, in the case of AM for instance, the maturation of the technology will be driven almost exclusively by civilian sector.

However, the priorities and interests of defence differ significantly across technology areas. For instance, in cybersecurity, defence priorities are similar to those of any other organisation or business: data and networks need to be secure. This means that a solution developed for large corporations, such as Shell, GSK or Volkswagen, will be just as relevant to the MOD. In other areas however, the MOD will have specific requirements for which it will have to invest directly, whether to fill a gap or to adapt civilian developments. This is the case for composite materials in aircrafts or small-scale energy storage solutions. For SE specifically, as these are usually developed to specific requirements, these will always combine COTS technologies with custom-made hard- and software.

In addition, innovation in technology areas may be relevant to different elements of the MOD's lifecycle phases or processes. Developments in cyber technologies will impact the MOD's general IT equipment just as much as they will impact theatre-specific material for defence. In opposition, the impact of AM is expected to focus on logistical aspects of operations. Similarly, the ways in which the MOD should harness innovation will differ, depending on whether it has a specific requirement not met by innovation in the civilian sector, or whether it can leverage civilian innovation but use it in a different way. For instance, training has benefitted significantly from SE developments that adapt civilian innovation to defence-specific needs.

Although the MOD is a government organisation and is responsible for ensuring the protection of UK citizens and their way of life, there are many similarities between it and large commercial entities. However, our analysis suggests that the current culture of the MOD makes it poorly equipped to interact with the commercial environment and leverage civil technologies to its best advantage.

Therefore, in order to leverage commercial technology the MOD needs to adopt commercial ways of working and thinking, in particular:

- **A greater willingness to take considered risks as part of a portfolio of decisions.** Both the increasing insularity of the MOD and the move towards reduced risk-taking inhibit the identification, development and adoption of innovation. This is especially relevant in an age when technology development relies increasingly on international developments and the civil sector, and in which greater information fluidity and risk-taking is essential.
- **Identifying key parts of the value chain and innovating/investing there.** It is questionable whether the MOD should seek to 'pick winners' in terms of the future commercial potential of technology investments. Not only do governments typically have a poor track record in this regard – and it is unlikely that the MOD has the competence to do this – it could also serve to create perverse incentives for both the MOD and the beneficiaries of its research investment. However, there is no doubt that the MOD should have an appreciation of trends in future technology markets – and of the part of the value chain in which it would seek to benefit by investment. This is important in enabling the MOD to understand the likelihood of being able to access technologies from future global commercial markets. It is also critical in thinking about the sustainability of UK firms that are important suppliers of technology to the MOD.
- **Adopting the language of the technology area.** Defence is a jargon-rich environment with a unique lexicon – for instance the term SE is only used by the MOD as the wider community refers generally to simulation technologies. Many of our stakeholder interviews stressed the importance of tailoring language and terminology to the community involved. This is a particular issue with SMEs who are at the fringes of the MOD's ecosystem. It was mentioned that, despite regular collaboration with the MOD, interviewees have found interactions difficult due to very basic barriers such as the widespread use of acronyms. In this context, it was confirmed that visualisations are effective ways of communicating, but only if the recipient of the visualisation is identified prior to creation and the data supports a well-articulated message. The TSB has a policy of recruiting technology leads from the commercial sector which helps in this regard.

- **Transitioning to a networked, decentralised structure** that encourages and enables innovation where it is needed. The MOD should identify new opportunities, not only with respect to specific emerging technologies, but also in the mechanisms it could use to harness those technologies. For instance, open innovation and crowd sourcing have been key recent developments in procurement strategies and are increasingly used across sectors to solve tightly defined problems. In the world of the app, accessing the power of wide networks is crucial.

8.2.2 The MOD should facilitate connections and culture as critical enabling factors

Most interviewees, from the innovation ecosystem and specific technology areas, mentioned either directly or indirectly the importance of personal relationships and experience in technology development. This refers to the large range of interaction, both formal and informal, between every actor involved in technology development. One interviewee used the phrase 'liquid networks', where constituents are mobile but semi-structured. The dynamism of the sector, encouraging career moves from the public sector to industry and SMEs, was seen to help develop those relationships. For instance, when prompted on the factors required to identify promising technologies or market gaps, interviewees answered that this was mostly based on their personal experience, rather than through any defined process. These interactions could also be facilitated by specifically sponsored networks, such as TSB's KTNs and KTPs, or by the funding organisations provide.

Another interviewee referred to the skills required to identify promising innovations or gaps in the market. Primes have a key role in identifying and integrating technology developments. As such, they interact with a wide network of SMEs to identify the latest technology developments, with the objective to fund some of them until they reach sufficient maturity and can be integrated. The interviewees stressed the importance of personal interaction, both within the SME/academia web as well as within the MOD, in improving understanding of future requirements.

However, in practice this coordination could be more effective. There is significant scope for the MOD to develop a more sophisticated and strategic understanding of the impact of its actions on the technology landscape. One of our interviewees commented that the MOD research community had a 'very small gene pool', which when combined with an instinctive insularity meant that the capacity to coordinate was limited. It was also mentioned that stakeholders within the MOD often appear reluctant to engage in the drafting and establishment of joint strategies for technology development, both at high level and within specific technology areas. Although this was usually due to a lack of capacity rather than willingness, our interviewees highlighted this as a missed opportunity to influence the future technology landscape.

In addition, elements of the MOD culture – and in particular its instinctive institutional insularity – can act to inhibit rather than enable the pull-through of technology. Firstly, it limits the level of information exchange across different parts of the organisation. In the example of synthetic environment for instance, in order to avoid taking any risk regarding the diffusion of sensitive information, the different entities connected may only be able to communicate on the least sensitive aspects, thus using a lowest common denominator approach. In such cases, the traditional communication routes may still be required so that, for example, not only does SE introduce additional resource requirements, but it also does not fulfil its transformative potential. Secondly, it encourages the MOD to perceive itself as having a unique set of challenges and constraints, at the expense of identifying and leveraging the similarities it has with other organisations. Our interaction with businesses throughout the project, but also more widely, suggests that the way in which security breach concerns are framed and conceptualised are very similar – despite the consequences being different. For instance, information security and encryption were mentioned to be as essential to protect the livelihood of businesses as it is to the MOD's operations.

8.2.3 The MOD should adapt how it engages with its supply chain

Regarding the ways in which the MOD interacts with its supply chain, the change in the R&D environment means that the MOD will have a more limited scope to influence the development of technologies. This is due to the fact that the MOD will tend to be a minority actor across most sectors, but also because highly relevant sectors may also have a profile for which the MOD procurement system is not adapted. This is seen for instance in the challenges that the MOD currently faces in interacting with the large number of innovative small companies in SE.

Therefore, the MOD should adapt its procurement processes to be better aligned with the current landscape, as well as with the different types of technology areas. Generally, initiatives such as the CDE were thought to be in the right direction in terms of better interaction with SMEs, but they still were associated with a number of difficulties. Similarly, the MOD should interact with suppliers, including in a prospective manner, to understand how to balance the share between primes and SMEs.

Organisations such as the TSB have also led a wider reflection on how to interact with their key stakeholders, with a direct impact on the profile of individuals recruited. Despite being part of the BIS, it is central to the organisation's identity to be staffed by individuals from a business background and with strong technology development experience, thus favouring fruitful interactions with businesses. The MOD should consider how to best leverage the skills of individuals with a business background in its recruitment process, especially for those involved in procurement process.

8.2.4 The MOD should assess how it currently prioritises its investments

The innovations taking place in the commercial sector are seen in products, concepts and processes. The MOD currently uses a limited concept of innovation with a focus on 'things'. For instance, the adoption of SE has focused on training hard- and software, as well as acquisition models, rather than for the potential it displays on transforming its internal processes. The MOD should, therefore, assess how it currently prioritises its investment in emerging technologies:

- Firstly, the MOD should envisage adopting a more probabilistic approach to its technology portfolio to better account for the risks inherent to S&T.
- Secondly, the MOD needs to think about how best to preserve an option to play in some technology areas and through which avenues it can best influence potential outcomes. This may involve helping to shape a high-level strategy for the technology area, by funding research jointly with a wider government funder, or directly investing in research.
- Thirdly, it is currently unclear how the MOD prioritises between small-scale investments with large transformative potential and large investment with more niche impact.

In the current technology development landscape, the MOD may only have a small role to play in the maturing of a specific technology area. This is the case for AM, for instance, where market forces and interests from a large number of players ensures sufficient investment for maturation. In such cases, therefore, although the best strategy may be to 'wait and see', this should mean investing in the in-house competences to be an intelligent customer when a technology becomes both relevant and economically interesting to the MOD.

8.3 Areas for further investigation

Throughout the data collection and analysis, the project team identified a number of areas which were relevant to the study, but that it were not possible to explore in great depths within the constraints of this study. Further exploration of these areas would contribute to a wider understanding of the issues analysed as part of this study.

Analyse the UK's position within the wider international innovation ecosystem

The increasingly international dimension of innovation emerged from the research throughout the complementary research streams, and would thus benefit from being explored further. This includes questions such as:

- What are the innovation nodes the UK engages with the most and how do these differ across technology areas?
- Which non-UK organisations invest in the UK, why, and how do these investments vary over time?
- What are the key enablers, drivers and barriers to international innovation?

Assess the interaction between and overlap across individual technology areas

Although analysing specific technology areas can help define strategies and prioritise investment, this also hides the strong interactions and overlap across individual technology areas.

- How does investment in individual technologies affect development in other technology areas?
- How does innovation in cross-cutting and enabling technologies transform the landscape?
- How can R&D strategies be tailored to address the dynamics across technology areas at different granularity levels?

While performing the analysis, the research team also identified a number of specific areas which would contribute to taking further the findings from this study. Additional analysis on those areas would also help the MOD in preparing for and implementing changes in its R&D strategy.

Identify best practices from other organisations and assess their relevance and transferability

Our interactions with actors across the innovation ecosystem revealed that the challenges currently faced by the MOD are found across organisations, from businesses to other government institutions, while other nations, such as France and Australia, are also having to reconsider their R&D strategies in the current environment. Focusing on the similarities between the UK MOD and other organisations would help identify best practice and ensure that these can be adapted to the MOD's specificities.

- How are other Ministries of Defence addressing the shift towards civilian-led innovation?
- What commercial practices are relevant to the MOD and how could these be transferred to the public sector?
- How do other countries balance defence and civilian technology development?

Evaluate the impact and implications of emerging innovation models

As new trends in innovation are gaining increasing momentum, such as open innovation for instance, it will be crucial for the MOD to understand the potential of these mechanisms, as well as the circumstances under which they are most effective. Moreover, as the MOD integrates these models, understanding their implications will be key to their effective introduction. For instance, as the MOD outsources an increasing proportion of its innovation, it should also define a strategy to develop the required level of in-house skills to be a smart customer.

- What are the emerging innovation models and in which circumstances are they most useful?
- What are the resources and knowledge required to effectively leverage these innovation models?
- What are the long term implications of the more widespread use of different innovation models?

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Appendix A: Stakeholder engagement and interviews

Throughout the course of the study, the project team engaged with a range of stakeholders both to better understand the wider context in which the study was performed, and to gather data and evidence. This appendix outlines the types of engagement that occurred for each project phase, with complete lists of involved stakeholders.

To contextualise the study and findings, the team engaged with actors from both the broad UK technology landscape and the MOD

In the first stage of the study, the project team engaged with 17 individuals who either take an active role in technology development in the UK and/or have expertise in the domain. Table A-1 is a list of people interviewed by the team. These interviews were conducted to better understand the overall UK technology landscape and the involvement of government, academia, business and defence.

Table A-1 List of stakeholders interviewed by the project team in Phase 1

Name	Organisation	Date
Derek Barter	QinetiQ – Technical Director	26th Feb 2013
Chris Bollinghaus	Digital Barriers – Executive Manager	11th Mar 2013
David Bott	TSB – Director of Innovation Programme	20th Mar 2013
Stephen Browning	TSB – Head of SBRI and Smart	20th Ma r 2013
Paul Crawley	MBDA – Special Advisor UK	20th Mar 2013
Katie Daniel	EPSRC – Senior Manager, Shaping Capability	21st Mar & 1st May 2013
Steve Gale	TSB – Leader of Defence Special Interest Group	25th Mar 2013
Mark Glover	TSB – Director of Business Planning	20th Mar 2013
Prof. Lorraine Dodd	Cranfield University and Defence Academy – Director of Research at the Centre for Applied Systems Studies	19th Feb 2013
Prof. Andrew Dorman	Kings College London and Defence Academy – Professor of International Security	20th Feb 2013
Dr Richard Leaver	Greybrook Limited – CEO	24th Feb & 17th Apr 2013
Ruth Mallors	Aerospace, Aviation & Defence KTN – Director	25th Mar 2013
Richard Malvern	Business Development, United Technologies Inc (formerly) Goodrich ISR	21st Feb 2013
Sir Paul Newton	Exeter University – Chair of Security and Strategy	28th Feb 2013
Simon Schneider	Omnicompete – Head and Founder of Global Security Challenge	20th Mar 2013
Huw Walters	BIS – Director of Aerospace, Marine and Defence	14th Mar 2013
Richard Wileman	Business Development, United Technologies Inc (formerly) Goodrich ISR	21st Feb 2013

We also tested and refined study findings through engagement with stakeholders at the strategic level. After completing and synthesising our final two in-depth case studies, we engaged with external stakeholders from the MOD' Defence Strategy and Priorities (DSP) unit and the Doctrine and Concept Development Centre (DCDC) to further test and refine our findings. The individuals with whom we engaged are listed in Table A-2.

Table A-2 DSP and DCDC workshop participants

Name	Organisation	Date
Seb Pollington	MOD DSP – Strategy Unit Land	13th Aug 2013
Chris Evett	DCDC	15th Aug 2013
Chris Haber	DCDC, Tech GST5	15th Aug 2013
Jes Odedra	DCDC, DAR Science and Technology	15th Aug 2013
Andrew Middleton	Dstl	15th Aug 2013

The team performed an extensive number of interviews to gather data and test findings for two in-depth case studies

Throughout the last phase of the study, the project team focused on the analysis of the two technology areas selected for further exploration by the MOD project sponsor: AM and SE. In order to gather data and test findings, we conducted an extensive set of interviews with individuals from the range of actors involved in each technology area. A breakdown of these interviews is shown in Table A-3.

Table A-3 Breakdown of interactions for AM and SE case studies

Case Study	Government	Academia	Defence	Business	Total
Additive Manufacturing	2	7	4	3	**16**
Synthetic Environments	2	3	5	6	**16**
			(+1 wkshp)	(+1 wkshp)	**(+2 wkshps)**

Interviewees were selected through their prominence in the literature used to date, their membership in a representative body of the technological area, or by the suggestions offered by the project sponsors. For the SE case study specifically, we also conducted two focus groups with keen gamers. The full lists of interviewees for each case study can be found in Tables A-4 and A-5.

Table A-4 Interviewees for the AM case study

Name	Organisation	Date
Dr Tony Chapman	EPSRC – Manufacturing Theme	25th Jun 2013
Dr Martin Baumers	University of Nottingham Additive Manufacturing and 3D Printing Research Group – EPSRC Centre for Additive Layer Manufacturing Research Coordinator	27th Jun 2013
James Bradbury	University of Exeter Centre for Additive Layer Manufacturing – Research and Application Engineer	28th Jun 2013
Prof David Wimpenny	HVM Catapult/MTC, AM SIG Advisory Group – Leader for AM & Net Shape	2nd Jul 2013
Neil Hopkinson	University of Sheffield, Centre for Advanced Additive Manufacturing (AdAM) – Centre Director	2nd Jul 2013
Prof Russ Harris	Loughborough University – Professor of Medical Engineering and Advanced Manufacturing	2nd Jul 2013
Dr Phil Reeves	Econolyst Ltd – Managing Director	3rd Jul 2013
Dr David Whittaker	AM SIG Working Group – Technology Expert, Materials KTN	8th Jul 2013
Stuart MacLachlan	AM SIG Working Group – Sector Leader Powders, Materials KTN,	8th Jul 2013
David Fry	Dstl – Principal Analyst, Land Battlespace Department	10th Jul 2013
Fiona McCue	Dstl – Programme Leader Logistics, Land & Joint Logistics Domain	11th Jul 2013
Prof Richard Hague	EPSRC National Centre for Innovative Manufacturing in Additive Manufacturing, University of Nottingham – Director, Additive Manufacturing and 3D Printing Research Group	11th Jul 2013
John Hunt	Dstl	12th Jul 2013
Laura Jones	Dstl – Platform Sciences Group, Functional & Non-metallic Materials	12th Jul 2013
Andrew Middleton	Dstl – Exploitation Lead, Dstl Knowledge Innovation & Futures Enterprise	12th Jul 2013
Robin Wilson	TSB – Lead Technologist, High Value Manufacturing	18th Jul 2013
Prof Ian Hutchings	University of Cambridge Institute for Manufacturing, Ink Jet Research Centre – GKN Professor of Manufacturing Engineering	18th Jul 2013
Dr Graham Martin	University of Cambridge Institute for Manufacturing, Ink Jet Research Centre – Director	18th Jul 2013

Table A-5 Interviewees for the SE case study

Name	Organisation	Date
Prof Jeremy Smith	Cranfield University –Head of Simulation and Analytics	1st Jul 2013
Mark Newton	Flight Simulation and Synthetic Trainers PT – Project Manager of DOTC(A)	2nd Jul 2013
Doug Stewart	Flight Simulation and Synthetic Trainers PT – Technology Project Manager	2nd Jul 2013
Dr Gillian Murray	Virtual Engineering Centre, University of Liverpool – Director	4th Jul 2013
Dr Charles Patchett	Virtual Engineering Centre, University of Liverpool – Technical Manager	4th Jul 2013
David Bowman	Virtual Engineering Centre, University of Liverpool	4th Jul 2013
Bharat Patel	Dstl – Senior Capability Advisor, Simulation Training and Evaluation, Policy and Capability Studies Department	5th Jul 2013
Andy Fawkes	Former MOD – Head of Synthetic Environments Co-ordination Office	10th Jul 2013
Mike Raettig	TRL Consulting	11th Jul 2013
Dr Zoe Webster	TSB – Head of Technology	12th Jul 2013
Tom Laws	Dstl – Microbiology, Biomedical Sciences	15th Jul 2013
Richard Leaver	Greybrook Limited - CEO	15th Jul 2013
Dave Harrhy	Dstl	16th Jul 2013
Rob Smith	MBDA – Head of Weapon System Simulation & Experimentation	17th Jul 2013
Zoe Brown	EPSRC – Portfolio Manager, Information and Communication Technologies	18th Jul 2013
Dr Chris Yapp	Independent Consultant in technology and futures thinking – Former Head of public sector innovation at Microsoft	22nd Jul 2013
Sue O'Hare	Former Reading University, The Enterprise Office – Director	25th Jul 2013
George Mallea	Sky Go - Managing Editor	25th Jul 2013
Lars Hoffman	Lars Hoffmann Spil - Learning Games Developer	31st Jul 2013
Michael Poindexter	Serving military troops	6th Aug 2013
Nicona Bryan	Serving military troops	6th Aug 2013
Cody Camp	Serving military troops	6th Aug 2013
Nicolas Aguilar	Serving military troops	6th Aug 2013
Finn Grimwood	Solarflare – Programmer	7th Aug 2013
David Russel	Solarflare – Programmer	7th Aug 2013
Oliver Ray	Solarflare – Programmer	7th Aug 2013
Johnathan Cooper	Solarflare – Programmer	7th Aug 2013

Appendix B: The innovation and technology development landscape

This appendix includes supporting data and analysis for the findings on the innovation and technology development landscape presented in Chapter 3. It also provides background information on each of the actors discussed, including government departments, public funding bodies, academic institutions and businesses. We have deliberately reproduced diagrams and figures from each of these actors where relevant, as we see them as an important indicator of how actors present themselves.

Government departments are involved at the strategic and operational levels, with BIS playing a unique role with responsibility for research funding

Government departments have two key roles as they both contribute to defining strategies for research investment and procure research for their own operations

Government departments have two roles regarding innovation and technology development. Firstly, within their own areas of competence, they are responsible for advancing national competencies, protecting and developing UK markets, and producing informed policy solutions. Departments develop long-term strategies at different levels, which can be either cross-departmental, with the objective of framing the vision for future capacities at national level, such as the 2011 *UK Cyber Security Strategy*, or department-specific, such as the 2006 *Defence Technology Strategy*, which identified future requirements specific to defence.

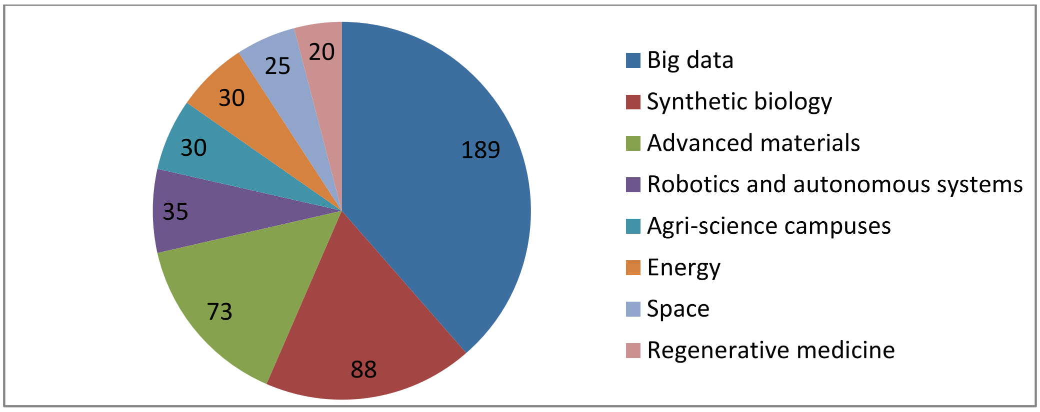
Within this role, government departments also decide on the allocation of research and technology innovation funds in areas of critical importance or provide targeted research grants. In addition, they can allocate funding to national priority areas outside of, but in coordination with, any strategies, as took place in January 2013 when the 'eight great technologies' received £650m of investment. Figure B-1 illustrates the distribution of funding between these technology areas.

In parallel, government also engages in regular independent reviews to assess challenges and opportunities for strategies to be implemented successfully. For instance, in the case of business-university research collaboration, a number of government-commissioned reviews have aimed to assess the best ways to enhance R&D and research exploitation.[155] Most recently, the July 2013 Witty review explored how universities can productively engage with Local Enterprise Partnerships to promote economic growth through research applications at a local level, including in partnership with SMEs.[156]

[155] Wilson (2012)

[156] Witty (2013)

Figure B-1 Distribution of £650m investment in the 'Eight Great Technologies', January 2013 (m£)



Source: Willetts (2013)

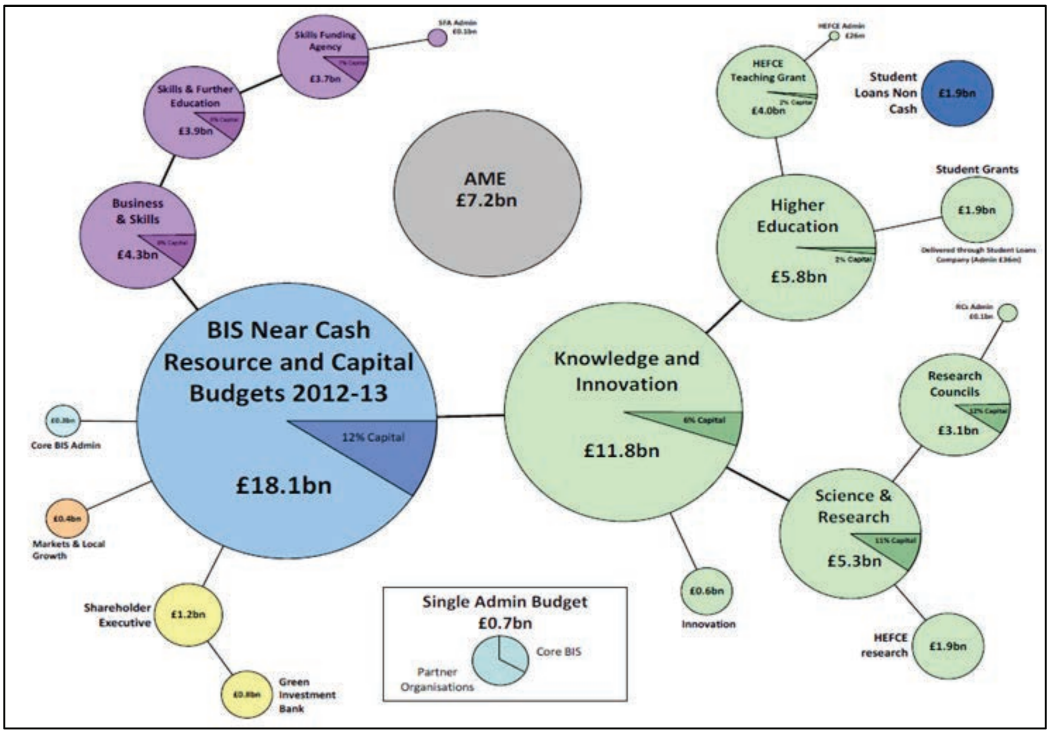
Secondly, government departments procure suppliers to perform research and technology development in order to contribute to the operations under their responsibilities. Often, departments have agencies specialising in monitoring and procuring research (such as Dstl in the Ministry of Defence and the National Institute for Health Research in the Department of Health). Investment made by a department may be innovation-led, if an area is identified as being particularly relevant and promising as a long-term priority, but more frequently it is pursued as part of existing project or programme in which a problem has been identified. Over the last 15 to 20 years, many departments have privatised their R&D agencies, moving towards outsourcing their R&D rather than performing it in-house. This was the case for the Department for Transport, which privatised the Transport Research Laboratory in 1996, and also for the MOD in 2001, when it divided the Defence Evaluation Research Agency into Dstl, which remained internal to the department, and Qinetiq, which was privatised.

BIS holds a unique position in being responsible for investing in skills, boosting innovation and helping individuals to start and grow businesses

In comparison with other government departments, BIS holds the unique responsibility for encouraging innovation across all UK sectors. It is the central supporter of research and innovation, and works with 49 agencies and public bodies to invest in skills and education to empower innovation and trade.[157] BIS has two specific agencies, the TSB and RCUK. These are responsible for distributing funding to performers of research in business and academia respectively, and are described in more detail below. As shown in Figure B-2, BIS is a significant investor in knowledge and innovation, providing £11.8 billion in funding in 2012–2013 for RCUK, HEFC, universities, and broader innovation projects.[158] This includes £100m in funding to long-term research projects at universities.[159] In parallel, BIS contributes at a policy and strategy level to promote opportunities for research and innovation. For example, it was instrumental in lowering barriers to business creation and forming a single Manufacturing Advisory Service (MAS) to provide sector-specific support.[160]

[157] Department for Business, Innovation & Skills (BIS), 'What we do'
[158] BIS (2012), p.23
[159] BIS, 'What we do'
[160] BIS, 'What we do'

Figure B-2 BIS budget allocation and detail regarding allocation for FY2012/13 across programmes and activities



Source: BIS (2012)

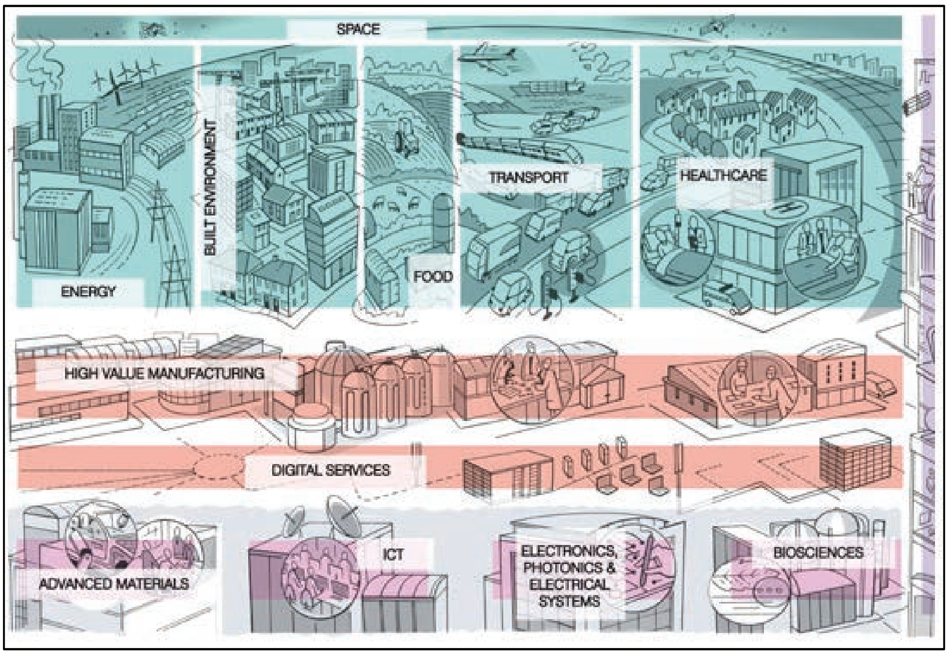
The TSB engages primarily with businesses and allocates funding to develop technologies from TRL 3–7

The TSB was founded in 2007 as a public sector organisation whose role is to '*stimulate technology-enabled innovation in the areas which offer the greatest scope for boosting UK growth and productivity*'.[161] It supports technology areas where there is greatest market potential, focusing particularly on removing barriers to innovation and application. Figure B-3 summarises the priority areas identified in the organisation's business strategy.[162] These include areas of technology, such as biosciences, advanced materials and high-value manufacturing, and areas of technology application, including space, energy and food.

Although it aims to encourage and invest in R&D across the full range of the technology life cycle, the TSB mostly focuses on TRL 3–7. As such, businesses are its prime customer – especially SMEs, for whom the TSB helps bridge the research funding gap between early stage innovation (often funded by academia) and late stage commercialisation (often funded by capital investors). The TSB receives most of its investment funds from BIS but others – such as other government departments, the devolved administrations and RCUK – also contribute.

[161] TSB, 'About us'
[162] TSB (2012d)

Figure B-3 TSB's 12 focus areas



Source: TSB (2012)

The TSB has three key ways of stimulating the innovation and technology development landscape. Firstly, it funds research projects and grants, either in an innovation-led or challenge-led manner, as well as investing in research facilities. For instance, Smart provides pre start-ups, start-ups, micro businesses and SMEs with access to grants to enable them to assess potential markets and invest in R&D and innovation. Similarly, the Small Business Research Initiative (SBRI) provides businesses with public sector procurement contracts to research and develop new products and services to address public sector challenges.[163] Secondly, the TSB offers training and support to innovators in order to maximise the success and viability of the businesses it supports. Finally, the TSB facilitates the flow of information within the research and technology development landscape through a range of platforms and tools, connecting stakeholders across business, academia and government. The TSB's online community hosts KTNs, which aim accelerate business innovation by enabling people to share knowledge, ideas and opportunities within and between specific sectors. Similarly, KTPs aim to stimulate business innovation by drawing on the expertise in UK universities, colleges and other knowledge providers, and transferring knowledge.[164]

RCUK engages primarily with academia and focus on early stage development (TRL 1–3)

RCUK is complementary to the TSB and also invests public research funding to promote knowledge and innovation with the aim of benefitting the economy and society.[165] Research Councils receive funding from the government's Science Budget, which is administered through BIS.[166] In addition to performing their own research, RCUK funds projects, fellowships, grants and facilities across a wide range of research disciplines either in an innovator-led or challenge-led way. Part of this funding includes Research Council-only funds, but some can also be used in partnership with businesses or government departments if the Council has identified an emerging area of research of particular interest to them. RCUK investment supports over 50,000 researchers in UK universities and in the

163 TSB, 'Funding and support'

164 TSB, 'Funding and support'

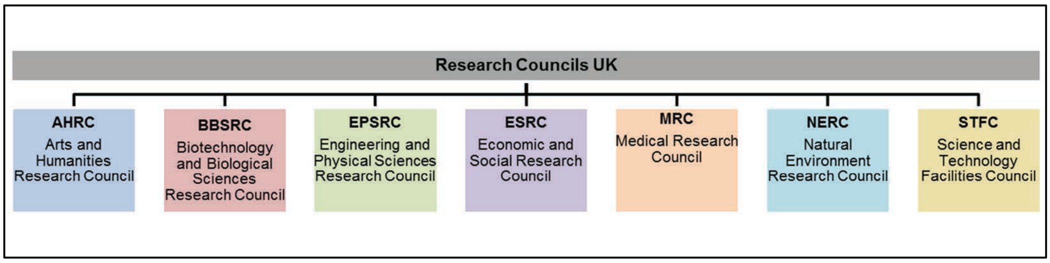
165 Research Councils UK, 'About the Research Councils'

166 Research Councils UK, 'About the Research Councils'

Councils' own Research Institutes.[167] Finally, RCUK also supports research and innovation training, and works to share research through public engagement and knowledge exchange.

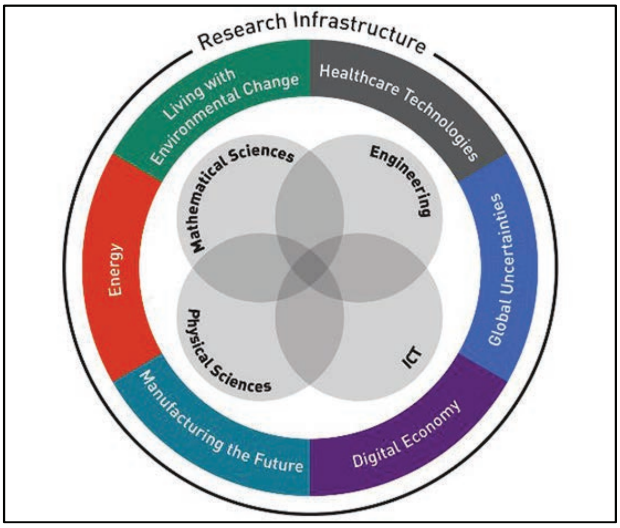
Seven different Research Councils represent the full spectrum of academic disciplines
RCUK is organised at two different levels. Firstly, there are seven complementary Research Councils organised in coherent research areas, from the Arts and Humanities Research Council (AHRC), to the Medical Research Council (MRC), the Natural Environment Research Council (NERC), and the Engineering and Physical Sciences Research Council (EPSRC). Each research council is responsible for a defined budget and is tasked with identifying priority areas and sponsoring individual technology areas. Figure B-4 illustrates the seven different Research Councils.

Figure B-4 The seven Research Councils that make up RCUK



The EPSRC, for instance, has 113 research areas cutting across 10 research themes – including digital economy, engineering, global uncertainties, manufacturing the future and living with environmental change. For each financial year, a strategic decision is made whether to increase, maintain or reduce the amount of funding received by each technology area. The key criteria used by the EPSRC in reaching those decisions are the quality and importance of the research area, as well as the necessity to maintain a balanced research portfolio. As the EPSRC sponsors very early stage development, part of its mission is to ensure that sufficient prominence is given to a range of topics and technology areas. Figure B-5 shows the EPSRC's priority research areas in interaction with RCUK's cross-cutting themes.[168]

Figure B-5 The EPSRC's portfolio of research and priority areas



Source: EPSRC (2013)

[167] Research Councils UK, 'About the Research Councils'
[168] Engineering and Physical Sciences Research Council (EPSRC), 'Our Portfolio'

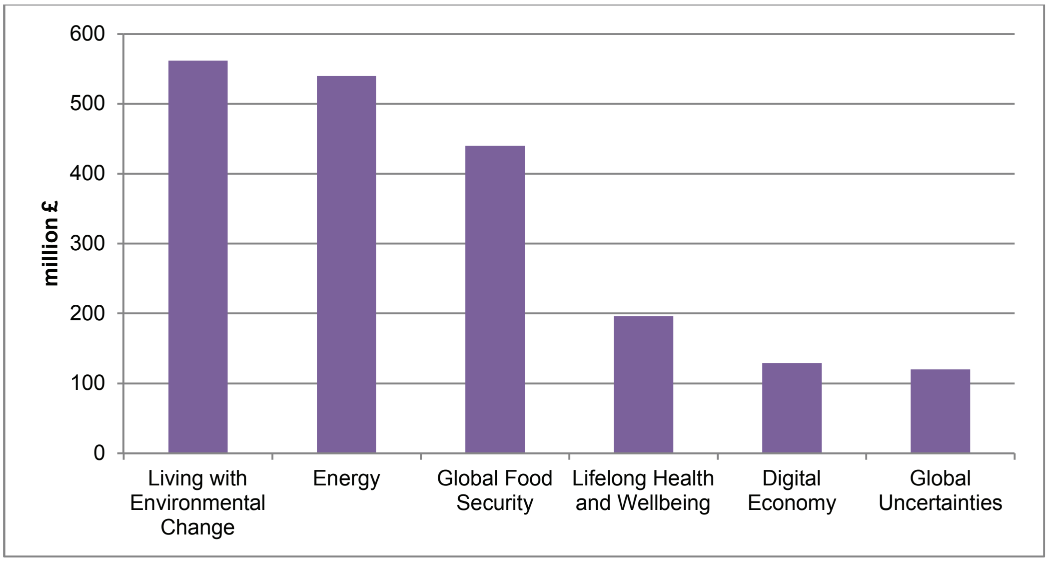
This range of work makes the EPSRC a critical funder for many important UK industries. Sectors dependent on this investment comprise 30 percent of UK GDP and 88 percent of manufacturing efforts.[169] Like all of RCUK, the EPSRC provides funding in a number of ways, including support of approximately 8,000 academic researchers and over 12,000 highly skilled postgraduates working in industry and the public sector.[170] A large proportion of the EPSRC's work emphasises the value of cross-sector collaborations, and it is engaged in initiatives with over 2,300 companies and 100 public bodies including government departments.[171]

RCUK bridges the Research Councils at strategic level and coordinates efforts in six cross-cutting priority areas

At a strategic level, the seven individual Councils are bridged by RCUK, which was established in 2002 as an umbrella organisation to enable the individual Councils to work together more effectively to enhance the overall impact and effectiveness of their research, training and innovation activities, and contribute to the delivery of the government's objectives for science and innovation.[172] As such, RCUK is not responsible for one overarching funding budget, but rather helps to coordinate the budgets of individual research councils to maximise their combined impact.

RCUK also identifies themes for priority investment across the seven individual Councils, for which it coordinates the delivery of multidisciplinary research. Each of the six priority themes is important in terms of the knowledge and skilled people that will be generated, and has significant potential for delivering economic impact. Effective coordination of the programmes through RCUK will accelerate delivery of benefits and economic impact. Figure B-6 indicates the key cross-council themes and the spend for each from 2011–2015.[173]

Figure B-6 RCUK spend by priority programme, 2011–2015 (m£)



Source: BIS (2010)

[169] EPSRC, *Strategic Plan 2010*

[170] EPSRC, *Strategic Plan 2010*

[171] EPSRC, *Strategic Plan 2010*

[172] Research Councils UK, 'About the Research Councils'

[173] BIS (2010), p.9

Higher Education Funding Councils focus on supporting academic institutions and individual students or academics

Higher Education Funding Councils (HEFCs) are public sector entities that distribute funding to universities and colleges across the UK. There are three HEFCs with regional remits for England, Scotland, and Wales – the Northern Irish equivalent is subsumed within the Department for Employment and Learning. Similarly to the TSB and RCUK, HEFCs receive their funding from BIS to support a range of higher education activities, primarily in the areas of teaching and research, through grants and fellowships.[174] HEFCs also fund selected cross-cutting initiatives associated with higher education, for example Scotland's Colleges Energy Industry partnership.[175]

Academia focuses on performing research, usually at the earliest stages of development

The 300+ UK universities and academic institutions are key performers of technology research, and are major recipients of targeted funding from both the private and public sectors. Academia is particularly strong in conducting and disseminating research. Universities may also host research facilities that bring together cross-sector partners to support innovation through to commercialisation. However, because academic research is not tied to market concerns, universities are significant providers of early stage technology research (TRL 1–3) that may be particularly high risk and high reward. Critically, universities are also responsible for teaching and training the experts who will apply their skills to research and development across the public and private sectors.

Businesses perform, procure and invest in research

Finally, businesses play a key role in the technology development landscape and tend to focus on TRL 4–9. This is because, in contrast to public sector organisations and academic institutions, business research is highly driven by market concerns and has to be commercially viable within a measurable future. The innovation rate varies across sector and type of private sector organisation. For instance, the ICT sector is characterised by a fast innovation rate, due to both the type of technologies and the competitiveness of the sector, while aerospace experiences a much slower innovation rate, due to the cost of developments and the market structure. Similarly, SMEs are characterised by smaller budgets and shorter market timescales, which may limit or focus research capacity. In contrast, primes can afford to support dedicated research budgets with longer timelines, and often procure research from relevant SMEs.[176] This interface between big industry and SMEs is a critical enabler for industrial collaboration on technological development.[177]

Businesses contribute to research as performers, procurers and investors. Firstly, businesses conduct research in-house. This may occur either as part of a dedicated department or processes, such as in large pharmaceutical companies, or as the business's main activity, as is the case for innovative SMEs. This research can occur after replying to another organisation's call for tender or as part of their innovation programme designed to increase or maintain their competitive advantage. Secondly, businesses contract out research if they cannot perform it in-house or if it may be more cost effective. Lastly, big business or capital investors may invest in SMEs they find of interest and on which they plan for a return on their investment. Alternatively, they may provide small grants or fund fellowships.

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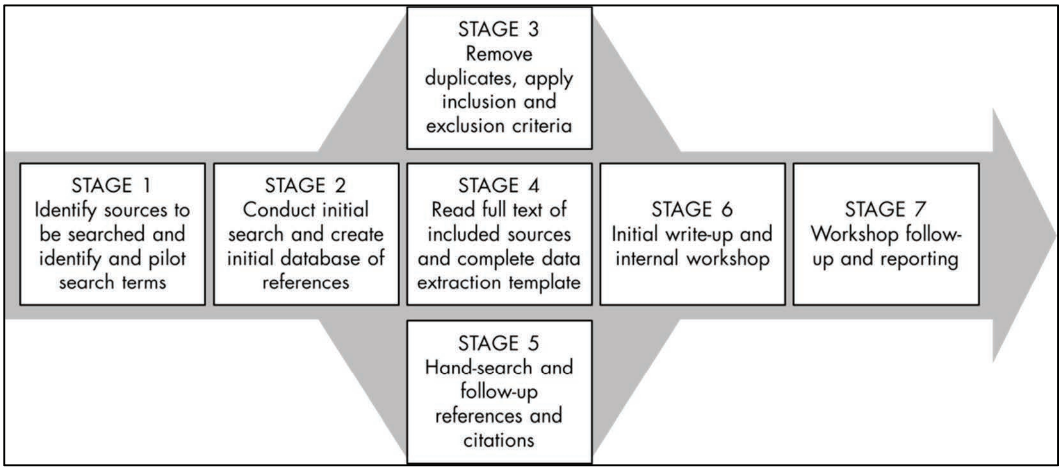
[174] Higher Education Funding Council for England (HEFCE) (2012), p.4
[175] Scottish Funding Council (2012), p.10
[176] Interview conducted by RAND Europe, 21 February 2013
[177] Interview conducted by RAND Europe, 21 February 2013

Appendix C: Methodology of the Rapid Evidence Assessment

Appendix C describes in detail the methodology and results of individual stages of the REA, as described in Chapter 3. The overarching steps of our REA process are outlined in Figure C-1 and elaborated below.

Figure C-1 General stages of the REA process



Stage 1: Identify sources to be searched and identify and pilot search terms
Three databases were selected to be searched based on their comprehensive scope, relevance and usability:

- Military Collection (ProQuest)
- Inside Defense
- IHS Jane's.

Search terms were developed, in consultation with Dstl, and piloted. The final search terms varied slightly by database depending upon the level of search engine detail available, as determined during the pilot search.

Stage 2: Conduct initial search and create initial database of references
Search terms were entered into each of the identified databases. The research team kept detailed notes of how the search terms were entered into the databases to ensure transparency and reproducibility of the approach.

Stage 3: Remove duplicates, apply inclusion/exclusion criteria by reading title and abstract
Depending on the format of search results, duplicates were removed manually or by importing references into Endnote and using the 'remove duplicates' function. A member

of the research team then screened all references by title and abstract, applying the initial inclusion and exclusion criteria. These included the following:

- Published from 2008–2013
- In English
- Both peer-reviewed and non-peer-reviewed sources
- Only sources that reference the UK, either focusing particularly on UK developments or discussing relevant technological trends in an international context.

Database search terms and results are summarised in Table C-1. A total of 84 sources were identified.

Table C-1 Search documentation of the REA

ProQuest Military Collection

Search Terms	Inclusion/Exclusion Criteria	Resulting number of hits
Abstract includes *defence* OR *defense, technolog*, new* OR *futur** OR *emerg** OR *develop**	Publications including crime OR history OR climat* OR social OR human rights OR health OR democracy; titles including elder* OR terror* English, 2008–2013; restricted by type of relevant documents	543
	+ united kingdom OR U.K. OR UK OR britain	75
	Excluded duplicates/contracts, reduced by title/abstract/relevance	**26**

Inside Defense

Search Terms	Inclusion/Exclusion Criteria	Resulting number of hits
All text includes *defense, technology, future, united kingdom*	2008–2013; daily news and documents searched	107
	Excluded duplicates/contracts, reduced by title/abstract/relevance	**5**
All text includes *defence, technology, future*	2008–2013; daily news and documents searched	87
	Excluded duplicates/contracts, reduced by title/abstract/relevance	**3**

IHS Jane's

Search Terms	Inclusion/Exclusion Criteria	Resulting number of hits
All text includes *defense* OR *defence, technology, future*	2008–2013, United Kingdom as 'country'	842
	Duplicates removed	675
	Removed all articles purely describing capabilities	549
	Removed articles based on title	296
	Excluded to 2012–2013	65
	Excluded by relevance	**50**

Source: RAND Europe analysis

Stage 4: Read full text of included sources and complete data extraction template

Where accessible, research team members read the full text of the references that met the inclusion criteria. On reading some sources, it became clear that they did not meet the inclusion criteria after all, and such references were excluded at this stage.

In addition to recording bibliographic information, subject-relevant content was extracted from each source in a data extraction template, using the criteria shown in Table C-2. This template allowed the relevant source material to be arranged thematically.

Table C-2 Data extraction template categories

What types of technology are emerging/evolving?	Sector-specific and/or cross-sector trends
	Engineering/design elements
	Capability needs/achievements
What models of research and development are contributing to technological growth?	International collaboration
	Spin-in from civil/commercial technologies
	Coordination with industry, academia, etc.
	Supply chain implications
How does the changing technology landscape reflect or inform the UK's evolving technology strategy?	Policy evolutions
	Budget concerns
	Military priorities

Source: RAND Europe analysis

Stage 5: Hand-search and follow-up references and citations

The systematic search of databases and specialist websites was supplemented by hand-searching identified websites and databases. These included:

- RUSI website
- Google Scholar
- RAND publications database
- Selected UK government websites.

Additional sources were also located through the contents and bibliographies of relevant texts and articles, or via the recommendation of expert advisors. Supplementing the central database search, this hand-search element provided the research team with confidence that the key texts and studies in the relevant fields have been included (or at least considered and excluded if they did not meet the inclusion criteria).

Stage 6: Initial write-up and internal workshop

Information processed in the data extraction template was analysed in draft format. The structure and content of this initial output was discussed and revised by the research team at a half-day internal workshop.

Stage 7: Workshop follow-up and reporting

The data extracted from the studies and revised outputs from the internal workshop were used to write the final report.

Appendix D: Quantitative search documentation

This appendix records the search documentation for our quantitative analysis of Google Scholar hits, as described in Chapter 4. Table D-1 provides the general and defence search terms for each technology area, as well as a yearly breakdown of search engine hits.

Interpretation of our results is caveated by methodological limitations. Lack of transparency in the Google Scholar search algorithm makes it difficult to gauge the accuracy, bias or other confounding factors that may impact on the numerical estimate of search hits. For example, our results strongly suggest that numbers of hits were often rounded to three significant figures. Fluctuations in number of hits may also reflect a general rise in online publications over the past six years, or lag time in uploading more recent publications. Precise wording of search terms may also have influenced results.

Table D-1 Search documentation of quantitative analysis

	Search terms	2007	2008	2009	2010	2011	2012
Unmanned systems	'unmanned system' OR vehicle OR technology	10900	12700	14200	14800	16100	15700
	+military OR defence OR defense OR warfare OR weapon	5950	6750	7470	7670	8250	7510
Electronic surveillance	'electronic surveillance'	1400	1490	1760	1450	1600	1450
	+military OR defence OR defense OR warfare OR weapon	933	969	966	936	1010	903
GEOINT	'geospatial intelligence' OR 'geospatial-intelligence' OR geoint	844	895	934	1050	1040	862
	+military OR defence OR defense OR warfare OR weapon	502	505	564	605	617	484
Man–machine interface	'man-machine interface'	2120	2170	2370	2540	2510	2340
	+military OR defence OR defense OR warfare OR weapon	327	352	346	343	385	341
Electro-optical systems	electro-optical	8960	9390	9590	10300	11000	10800
	+military OR defence OR defense OR warfare OR weapon	1630	1730	1640	1780	1950	1620
Radar	radar	85400	85200	78200	68100	56500	99700
	+military OR defence OR defense OR warfare OR weapon	23500	24800	26000	25300	26000	25500
Cyber warfare	cyber	20800	24900	26200	27800	28800	37000
	+military OR defence OR defense OR warfare OR weapon	7150	9380	10900	12400	13700	13300
Kinetic weapons	'kinetic weapon' OR 'kinetic weapons' OR 'kinetic weaponry'	62	92	89	85	98	90
	+military OR defence OR defense OR warfare OR weapon	62	91	87	83	98	86

	Search terms	2007	2008	2009	2010	2011	2012
Directed-energy weapons	‘directed energy’ OR ‘directed-energy’	946	1100	1070	1060	1070	965
	+military OR defence OR defense OR warfare OR weapon	535	620	590	586	555	506
Precision-guided weapons	precision-guided technology	775	761	731	700	678	586
	+military OR defence OR defense OR warfare OR weapon	715	700	665	642	617	532
Hybrid energy	‘hybrid energy’ OR ‘alternate energy’ OR ‘alternative energy’	8230	10700	12900	14300	15000	11900
	+military OR defence OR defense OR warfare OR weapon	2030	2530	3110	3200	3310	3090
Engines technology	engine technology	1560	1620	1670	1770	1860	1800
	+military OR defence OR defense OR warfare OR weapon	378	395	361	384	445	379
Simulation techniques	‘simulation technology’ OR ‘simulation technologies’	4420	4870	5430	5700	6130	4430
	+military OR defence OR defense OR warfare OR weapon	1400	1630	1670	1620	1720	1130
New materials	new materials	19200	19600	21200	21800	23700	30200
	+military OR defence OR defense OR warfare OR weapon	2950	2930	3250	3230	3470	3270
3-D printing	3-D printing OR 3D printing OR digital manufacturing	1990	2310	2800	3040	3090	3260
	+military OR defence OR defense OR warfare OR weapon	307	340	411	375	488	494
Nanotechnology	nanotechnology OR nano-technology	73400	89300	94700	87800	73500	97900
	+military OR defence OR defense OR warfare OR weapon	5480	7350	8210	8670	9050	8390

Source: RAND Europe analysis

Appendix E: Summary of key technology areas

This appendix gives an overview of our REA results for each of the 16 technology areas described in Chapter 4. Table E-1 provides examples, comments and references for each technology area.

Table E-1 Summary of REA findings by technology area

Technology Area	Examples	Comments	References
New materials	- Reducing radar visibility - Vehicular armour - Jet engine coating - Fabrics incorporating power sources - 'Smart' materials that react to environmental conditions	- Used for lightening/strengthening equipment and optimising performance - Opportunity to capitalise on civil sector interest from commercial aircraft industry - Integrates advances in many scientific fields	- Hermann (2008), p. 380. - Silberglitt et al. (2006), pp.12–13.
3-D printing	- Small drone can be designed in days and manufactured in minutes - Nano-UAVs printed cheaply and quickly from carbon fibre and plastic sheets - US military has showed successful use in portable lab in Afghanistan - M16 rifle parts can be printed in polymer	- Rapid turn-around period for virtual design, simulation and testing - Saves time and cost in manufacturing Could be revolutionary to defence industry models if widely adopted for on-the-ground manufacturing	- *Inside the Army* (2012) - Bull et al. (2012) - Doctorow (2011)
Nanotechnology	- Coatings can reduce weight, cost, and coefficient of water drag resistance for aircraft	- Still in very early development, with significant unknowns - Strong civil market developments - Globally, UK has considerable commercial strength, particularly in nano-optics and nanoscale materials	- Cole (2010), pp. 26–27; quoted in HM Government (2010b) - TSB (2009b); quoted in HM Government (2010b), p.6. - TSB (2009b); quoted in HM Government (2010b), p.12.
Hybrid/ alternative energy sources	- Solar and biomass power reducing energy costs at RAF stations - Local renewable energy employed at Forward Operating Bases (FOBs) in Afghanistan - Alternative fuel and propulsion systems to improve engines technology	- Reduces cost and improves fuel efficiency/security - Helps meet increasing power demands of new weapons technologies - Strong potential to exploit civilian energy technologies	- Brown (2012) - Dixon (2012) - Dixon (2011) - Wall (2009), p.34
Unmanned systems	- <u>Air:</u> Unmanned aerial vehicles (UAVs) have been extensively used in Afghanistan and Iraq - <u>Air:</u> UK's Black Hornet unmanned air system is the 'world's first operational nanotechnology drone system' - <u>Air:</u> Rapid development of air combat UAVs (UCAVs) does not appear in the literature due to security classification - <u>Sea:</u> Growth of unmanned underwater vehicles (UUVs) and autonomous underwater vehicles (AUVs) in the maritime sector	- Attractive due to favourable costs, covert nature and lack of associated casualties - Smaller energy costs and logistical footprint - Move towards weaponisation - <u>Air:</u> Ever-smaller ('nano') systems, potentially using swarms in the air sector - <u>Sea</u>: Private sector leading developments here - Despite substantial potential, short-term technological maturity and reliability are uncertain	- IHS Jane's (2012) - Brown and Lee (2012) - Bull et al. (2012) - Dixon (2012), p.87 - Hennigan (2013), p.B2. - IHS Jane's (2013) - Keddie (2012) - Wall (2011), p.61.

Technology Area	Examples	Comments	References
Electronic surveillance	- Royal Navy recently announced state-of-the-art radar electronic support measures (ESM), enabling truly digital antenna, that had been under development for the past six years	- Highly sensitive area of technological development - Can facilitate use of commercial-off-the-shelf platforms - Current research addresses jammers, geolocation techniques, radar, and future challenges of urban warfare	- Scott (2012a) - Svitak (2012)
Geospatial intelligence (GEOINT)	- 3-D GEOINT is benefitting from advances in high-speed graphics processing cards that are improving imagining and disseminating intelligence more rapidly	- Sea: Driven by recent resurgence of piracy and shipping route needs - Land: Increasingly relevant given forecasted increase in urban warfare - Particularly well suited to benefit from commercial innovation, such as advances in the computing and games-playing industries	- Batey (2012)
Man–machine interface	- Air: New cockpit systems are relying on commercially-inspired electronic tablets and touchscreen capabilities to handle the modern complexity of mapping, tracking and target identification ability - Multifunction display (MFD) units emerging as a way to centralise maps, data, radar and sensor inputs - Air: Many unresolved issues with the human aspects of F35 cockpit	- Strong potential to benefit from off-the-shelf commercial advances in mobile and handheld computing - Trend towards improving accessibility and functionality - Evolution towards wearable technology that can make the soldier 'an individual C4ISR node on the modern battlefield'	- Ebbutt (2012a) - Jennings (2012)
Electro-optical systems and radar	- 3-D volume search radars (VSRs) have capitalised on advances in transmitting and processing, waveform generation, digital beamforming and electronic scanning and stabilisation - Electro-optical and infrared sensor technologies quickly approaching maturity, with application possible in non-lethal laser dissuasion devices, situational awareness systems, and other information-driven countermeasures	- Emphasis on these areas reflects an increased need for improved visual sensing capabilities and lighter, more sophisticated capabilities for unmanned vehicles - Benefits from related technological improvements in civil sector - Expected to expand as new detector materials reach maturity	- Anderson and Wilson (2012) - Barrie (2008) - Jennings (2012) - Scott (2013a) - Shumaker (2012)
Cyber warfare	- Particularly relevant to C4ISTAR concerns of informational sharing, intelligence and espionage, and 'cyber-situational awareness'	- Major area of increasing concern - Neither offensive nor defensive capabilities have reach full maturity, but they are predicted to play a larger role in future conflicts	- Keymer (2012) - Quintana (2012)

Technology Area	Examples	Comments	References
Weapons advances	- Integrating technological advances to increase range, lethality, speed, accuracy and stealth	- Electronics are becoming critical for weapons systems in every sector - Drive for weapons that can counter 'difficult air targets', like UAVs and air-to-surface weapons - Additional advances in precision and efficient power sources necessary for weapons to be effective offensively	- IHS Jane's (2012) - Barrie (2010) - Dowdall et al. (2004)
Kinetic	- Land: Guided small-arms munitions to reduce non-combatant casualties - Sea: Electromagnetic guns providing long-range, high-speed potential. - Air: Small, high-powered weapons with potential to be installed on UAVs	- Capacity for cross-sector application and adaptation	- Bradford (2012)
Directed-energy	- Laser systems - Radio-frequency weapons	- Identified area of immediate R&D investment	- Barrie (2010)
Precision-guided	- Land: Remotely operated stabilised small-calibre gun systems - Sea: Weapons that can be installed on naval platforms, or potentially on unmanned surface vessels (USVs)	- Response to capability need to adapt to new types of asymmetric littoral threats with proportionate and adaptable hard-kill effect	- Scott (2013b)
Engines technology	- Hybrid electric drive (HED) power reaching maturity - High-temperature combustion and turbine systems - Distortion-tolerant fans	- Capitalising on commercial developments to improve speed and efficiency - Opportunities to incorporate technologies from Formula One racing and motorsport contexts, such as suspension and braking and cooling systems	- IHS Jane's (2013) - IHS Jane's (2012) - Barrie (2009) - Brown (2012)
Simulation techniques	- High-level simulation full-motion video (FMV) technology used at the Joint Terminal Attack Controllers training centre	- UK Defence Training and Education Strategy has identified use of new simulation technologies as a training priority over the next decade - Simulation offers attractively lower training costs - Strong potential for commercial spin-in, particularly from entertainment gaming and 'serious games' developments	- Ebbutt (2012b) - Nash (2012) - Pengelley (2012) - Strachan (2011)

Source: RAND Europe analysis

Appendix F: Assessment of potential case studies

This appendix presents the project team's assessment of potential small-scale and in-depth case studies performed in Phases 2 and 3 of the project. The team followed a structured process to identify the final two case studies, using different sets of criteria.

The first assessment identified five small-scale case studies from sixteen technology areas of interest

In preparation for the third phase of the project, consisting of two case studies, we had done some preliminary thinking on which of the 16 technology areas identified through the REA would be most appropriate and enable the team to draw the highest level of conclusions. We performed this initial thinking during an internal workshop concluding the first study phase and considered each technology area along the following dimensions:

- Whether innovation could take place in **technologies, skills or processes**
- The **supply chain positioning** of innovations, including primes, SMEs and academia
- The potential for **sustainability**, for instance through future revenues, and whether there is a clear business case
- **Stakeholder appeal** within the MOD and the wider community
- **CADMID positioning** in relation with current equipment and programmes
- **Feasibility**, including, for instance, access to data.

The resulting assessment of the technology areas is shown in Table F-1.

Table F-1 Long list and assessment of potential case studies

Technology area	Pros	Cons	Military/ Civilian?
Cyber warfare	- Stakeholder appeal - Feasible - Breakthrough potential - High level of sustainability	- Congested area - Scope of the topic too big for the study	Both military and civilian
Additive manufacturing	- Stakeholder appeal - Across CADMID - Potential for process innovation and cross-sector application - Cost-saving abilities	- Limited MOD influence	Civilian
Man-machine interface	- Broad cross-sector use - Ability to add to existing platforms and to influence nature of combat - Opportunity to build upon civilian advances	- Lack of stakeholder appeal	Civilian
Underwater weapons	- Stakeholder appeal - Breakthrough potential - Tractable and specific	- Broad scope - Congested area	Military

Hybrid and alternative energy	- Direct link to specific requirements - Feasible	- Stakeholder appeal unclear	Civilian
Kinetic guided weapons	- Some sustainability - Some stakeholder appeal - Feasible	- Lack of civilian interest	Military
New materials	- Sustainable - Stakeholder appeal	- Low feasibility	Civilian
Directed-energy weapons	- Some stakeholder appeal	- Limited feasibility	Both military and civilian
Biotechnology	- Very likely to be disruptive - Supply chain dimension - Sustainable	- Low feasibility	Civilian
Swarms and Nano	- Varying levels of maturity	- Narrow scope - Limited cross-sector application	Both military and civilian
Engines	- Feasible	- Narrow scope - Limited cross-sector application	Both military and civilian

Source: RAND Europe analysis

Before discussion with the project sponsor, the shortlist of technology areas presented to the MOD at the end of Phase 1 consisted of:

- Additive manufacturing
- Cyber warfare, data security or synthetic environments
- Directed-energy weapons
- Hybrid energy and energy harvesting
- Advanced materials.

Following the discussion with the project sponsor, this list was modified to:

- Additive manufacturing
- Advanced materials
- Cyber warfare
- Data security / Big Data
- Hybrid energy and energy harvesting
- Synthetic environments.

However, following further discussion and initial research, cyber warfare was changed to cybersecurity and merged with data security, to accommodate data access issues and include developments in the civilian domain. Similarly, Big Data was removed as most technology development in this area takes place outside the UK. The US and China are currently the global leaders in the deep analytical talent required to capture value from Big Data, and forecasts suggest that this lead will further widen in the coming years.[178]

Two case studies were selected from the five scoped areas

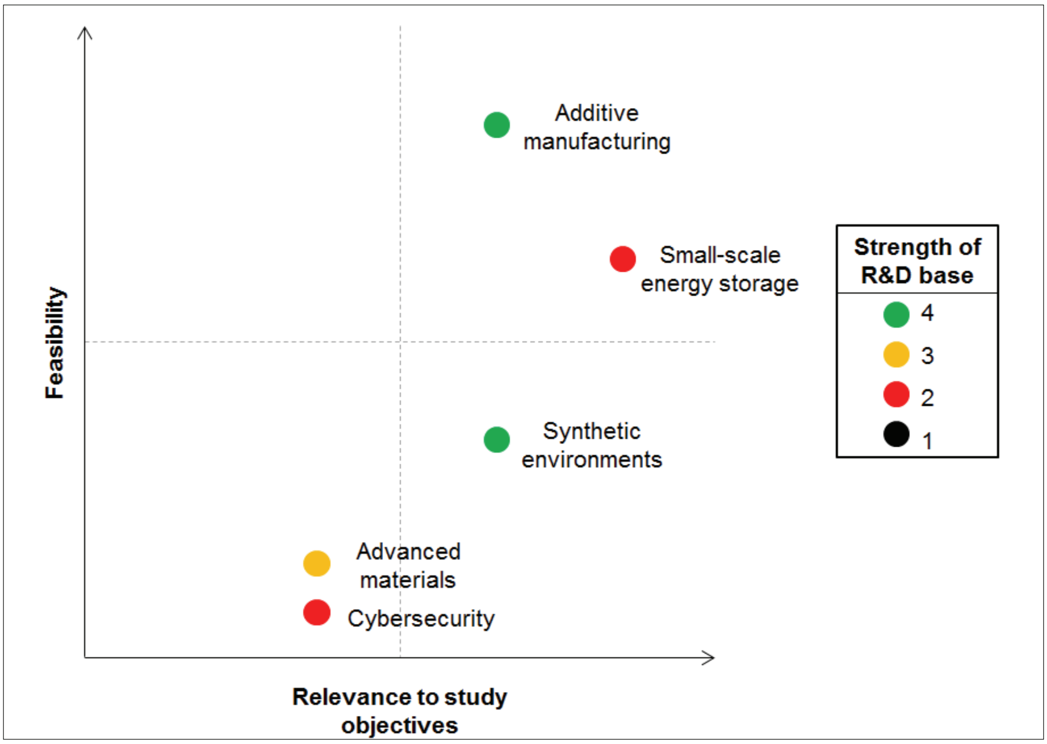
The second phase of the study consisted of five small-scale case studies – additive manufacturing, advanced materials, cybersecurity, small-scale energy storage, and synthetic environments – two of which were to be conducted in greater depth over the following phase of the study. Three dimensions were taken into account for the selection of the final two case studies:

[178] McKinsey Global Institute (2011), pp.103–6

1. The **scope and feasibility** of each case study. This touches on two aspects: firstly, that the technology area is defined with a manageable scope, and secondly, that the accessibility of data and the anticipated granularity would be reasonable to achieve within the constraints of Phase 3.
2. The **relevance to the study objective** – the five potential technology areas differ by profile, key actors, fragmentation level, role played by defence and proportion of public investment. As this will have an impact on the findings from each case study, it is important that this analysis is as aligned as possible with the study sponsor's expectations.
3. The **strength of the UK R&D base** – the extent to which the UK R&D base is developed will contribute to the depth of findings from the two case studies. The more mature the base is, the more we will be able to understand the factors that contributed to its development.

The selection of the final two case studies was made by the study sponsor. To assist in this decisionmaking, we performed a preliminary assessment along the three outlined criteria, the result of which is seen in Figure F-1. Based on this assessment, we suggested performing two case studies from a sub-selection of the following three: additive manufacturing, small-scale energy storage and synthetic environments. The MOD project sponsor chose additive manufacturing and synthetic environments.

Figure F-1 Assessment of the small-scale case studies



Source: RAND Europe analysis