A Wicked and Complex Problem-Based Analysis Framework

Applying Wicked Problem Thinking to the Supply Chain and Engineering Research Domain

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Declaration of Authenticity and Author’s Rights

This thesis is the result of the author’s original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed:

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Date: 19 April 2025

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Abstract

Climate change is perhaps the biggest challenge faced by humanity and one that affects all nations, organisations and individuals. Everyone is a stakeholder in climate change. It is therefore not surprising that there can seem to be as many views on what to do about it as there are stakeholders. The role of technological change and the means of enabling it through supply chains are secondary but essential elements of this difficulty. Problems like climate change can seem daunting due to their inherent complexity and the diversity of views that surround them, and while technological advances often seem to offer encouragement, they can often seem stages removed from the overarching systematic problem. Supply chains play a key role but add to this complexity of working towards net zero. As such, due to this severe complexity, net zero may be labelled as an impossible to solve task with little attempt made to approach it. This is one of the characteristics of wicked problems, under which climate change is classified. Understanding the key components necessary to approach in achieving net zero by breaking this down into smaller more achievable tasks, in other words decomposing it, appears to be a valid method for this. This is where this thesis is set, using established structured methodologies for assessing wicked problems.

In order to progress a chosen framework as a structured methodology, two case studies from the research environment are used, one focusing on an all-encompassing solution for net zero and another engineering focused on electrical machine requirements for 2050. The first case study is used to test the framework for its robustness. This is achieved by analysing the *Absolute Zero* report by the UK FIRES Research Group that lays out 13 actions to undertake to reach absolute zero emissions, as it is called in the report. When conducting the analysis, four positioning steps are used that have been summarised from the literature and a complexity classification card was developed to consolidate the analysis steps and visualise them for ease of understanding. The analysis led to iterations of the framework, and the development into a 16-box model to encompass the requirements from the research environment, which forms a key contribution from this thesis. The second case study, a roadmap from the Future Electrical Machines Manufacturing (FEMM) Hub on electrical machines, acts as a validation for the developed framework and offers insights into the effects of decomposition.

Based on this, the thesis provides some novel contributions to knowledge: 1. Applying the 9-Box Model in Engineering and Research Context, 2. Developing of a 16-box Model, 3. Advising mechanisms to approach wicked problems, 4. Applying the framework in the research domain, 5. Development of a Complexity Classification Card and 6. Terminology with regards to wicked and complex problems. These contributions combine to offer a novel approach for wicked problems like the climate crisis. The developed approach can be applied by research leaders in helping to shape research programmes, especially those which aim to progress far reaching and politically challenging issues like climate change by addressing specific technology needs and gaps. In this context it also has potential for future use for funders, strategist and policymakers in reviewing research propositions and helping assess the viability of impact against grand challenges.

Publications

Conference Proceedings:

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Chapter 1 – Introduction

1.1 Research Background

Sustainability is an increasingly prominent topic as the goal of net zero by 2050 comes closer. The importance, personal interest and passion for sustainability is what started the journey on this thesis. Considering sustainability, climate change is a key aspect, where supply chains and their move towards integrating sustainability are especially important. However, this is not as well researched as it could be. Dealing with supply chains from a sustainability perspective is challenging because as well as the technical and organisation considerations, political and stakeholder difficulties arise. Which results in a high complexity of integrating sustainability in supply chains. A concept that deals with complexity is that of wicked problems and in particular structured approaches to characterising them. One logical way of structuring is developing plans and timelines, such as roadmapping. This allows a time-based as well as thematic mean of subdividing the overall problem. This thesis therefore explores the value of wicked problem thinking and specifically the role of problem decomposition, especially on a time basis through technology roadmapping, in the context of supply chain sustainability.

1.1.1 Climate Change and Net Zero

Net zero by 2050 is a prominent global goal to limit the effects of climate change for future generations that cannot be ignored. The Paris Agreement was negotiated by 196 parties at the 2015 United Nations Climate Change Conference near Paris, France (United Nations, 2015). The Paris Agreement has a long-term temperature goal which is to keep the rise in global surface temperature to well below 2 °C (3.6 °F) above pre-industrial levels (United Nations, 2015). The treaty also states that preferably the limit of the increase should only be 1.5 °C (2.7 °F) (United Nations, 2015). A major concern for global warming is the emission of greenhouse gases, most prominently Carbon Dioxide (CO_2) emissions.

The Covid-19 Pandemic led to a significant drop in CO_2 emissions, with around 7% reduction from 2019 to 2020 (Friedlingstein et al., 2020). In the decade prior to this, CO_2 emissions were rising around 1% each year (Le Quéré et al., 2020). However, the drastic reduction in emissions due to the pandemic was based on involuntary changes in human activity, which is a key limiting factor for net zero. Every individual has a role to play for accomplishing the global net zero goal. These individuals include engineers who deal with part of the challenges associated with net zero, such as provision of energy and transportation. Engineers work at the level of specific solutions that have been decomposed from the challenge of net zero. Net zero and sustainability is the focus of many research fields. This research can, for example, be around developing new innovations and technologies for enabling net zero or processes that need to be optimised to meet net zero, such as supply chains. Like engineering, supply chains may profit from decomposing the approach of net zero down to manage the balance of supply and demand for achieving sustainability.

1.1.2 Supply Chains and Sustainability

Supply chains play a key role in the global economy, which becomes ever more noticeable in times of crisis. Whilst the positive side of globalisation is the facilitated trade of goods across the world, transport routes have become longer as a result which is critical for sustainability (Abbasi and Nilsson, 2012). In society, sustainability is an increasingly important factor for buying decisions, not only customers but also employees are more often demanding for sustainability issues to be addressed by companies (Carter and Easton, 2011). The World Economic Forum has published a report in collaboration with the Boston Consulting Group focusing on net zero and the supply chain opportunities in this (World Economic Forum, 2021). As part of this, it was found that the supply chains of eight industries around the world are responsible for over half of global greenhouse gas emissions, with the food industry accounting for around a quarter of global emissions (World Economic Forum, 2021). This highlights the importance of focusing on supply chain sustainability for advancing towards net zero.

However, sustainability in the supply chain can be a very complex research area, for example due to various stakeholders with differing requirements and expectations being involved. Therefore, it is a significant challenge to develop a supply chain to be more sustainable, as collaboration between different stakeholders is important. There is a whole category of situations where collaboration and stakeholder relationships are important. In terms of systems engineering, the relationship between supply chains and sustainability can be defined as a wicked problem on the basis that there is a clear interplay between stakeholder and technical decision making.

1.1.3 Wicked Problems

Wicked problems thinking originated in the 1970s with Rittel and Weber (1973) as a means of moving beyond the limitations of traditional problem-solving approaches. It is used extensively in social and policy planning, and has also become an important tool in framing management science problems. Its use in engineering and supply chain systems design has been less extensively researched.

Wicked Problems are often characterised as complex, interconnected and involving different stakeholders (Dentoni and Bitzer, 2015; Head and Alford, 2015). This somewhat overlaps with the two core elements that are important in wicked problems: the problem itself and those who are involved with it (Alford and Head, 2017). Super-wicked problems are similar to wicked problems, however there are four additional characteristics to super-wicked problems: 1) there is a time restriction, 2) the problems that are to be solved are caused by those that intend to solve them, 3) there is little to no central governance that addresses the issues, and 4) the problem solving is shifted to the future rather than taking responsibility and acting now (Levin et al., 2012). The approaches to solve both types of problems are similar and some approaches have been suggested in the literature. However, one overarching approach is the collaboration between different stakeholders, reflected also in supply chain sustainability. Therefore, a wicked problems approach to supply chain sustainability can be justified. Based on the importance of the wicked problems approach in moving sustainability in the supply chain forward, the focus of the research has moved away from supply chain sustainability towards wicked problems. Further developments in the field of wicked problems will in turn support the progress of supply chain sustainability. For approaching complex and wicked problems, there are some suggestions in the literature, with structured approaches being fundamental in this.

1.1.4 Structured Approaches to Wicked Problems

Alford and Head (2017) developed a framework, classifying problems from tame to very wicked. It is one of the first clearly structured approaches to characterise wicked problems. Another framework has been put forward by Schuelke-Leech (2020). However, this is simpler and solely focuses on problem aspects. Alford and Head (2017) add another element in their framework by also focusing on the stakeholders involved with the problems. Within this framework, some characteristics of each of the different problem types are explained which indicate a possible approach to overcome the wickedness of the problem. The problems in this may be subject to decomposition, which is the breaking down of complex problems into sub-problems as means of enabling resolution. This supports the move towards incorporating sustainability in supply chains. The framework by Alford and Head (2017), shown in Figure 1.1 below, forms the basis of the research in this thesis and will be built on.

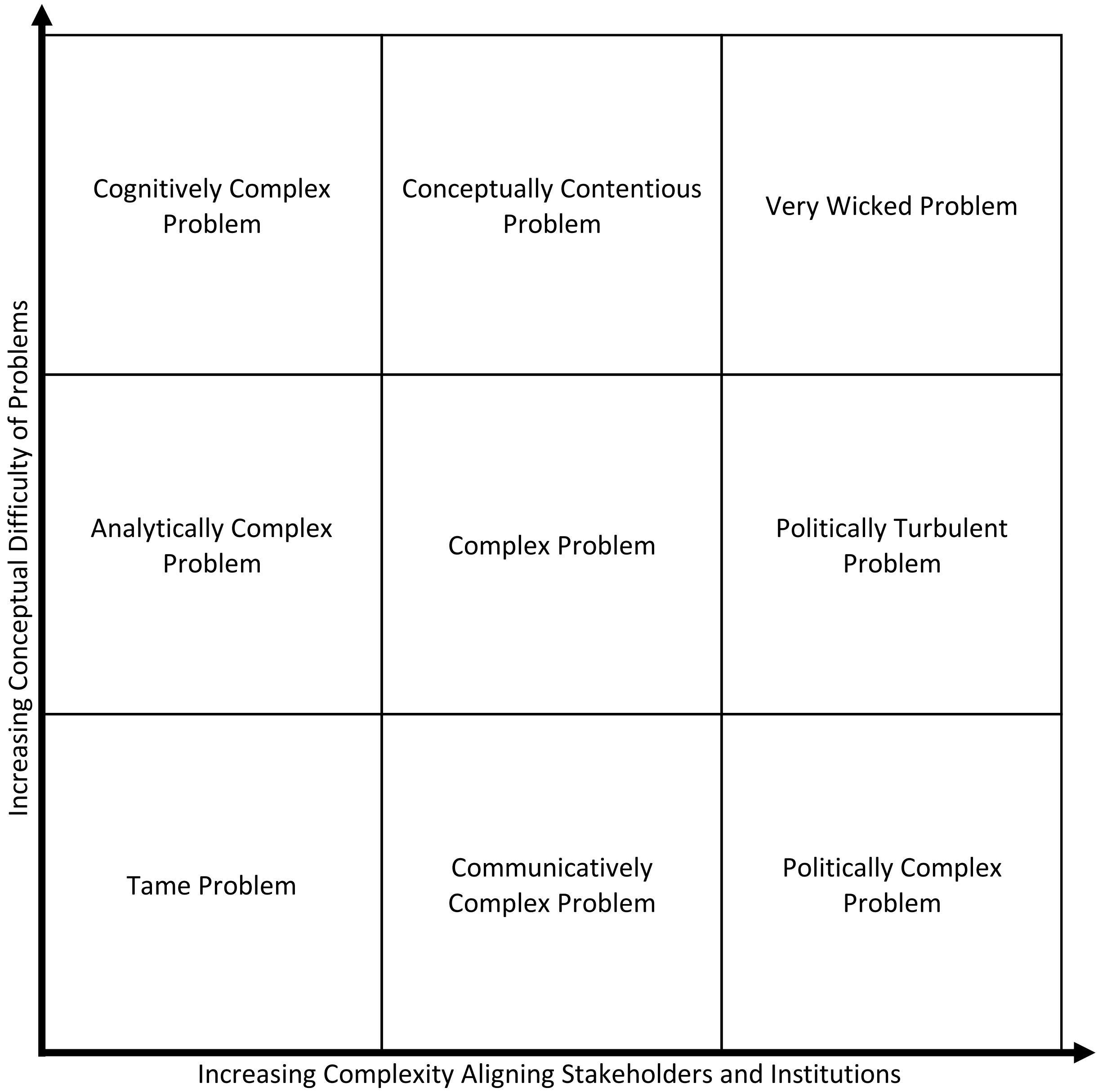


Figure 1.1 Wicked Problems Model (adapted from Alford and Head, 2017)

A set of four steps is developed to position situations onto the model of Alford and Head (2017), based on systematising the guidance provided in the research of Roth and Senge (1996) and Alford and Head (2017).

The first step focuses on the initial logic of where the project fits onto the typology. In the second step, the position of the problems is tested against a set of criteria, summarised from the previous work of Alford and Head (2017) and Roth and Senge (1996). The criteria are based on the two aspects of problems, the problem itself in the problem complexity and the stakeholders involved in the stakeholder difficulty factors. For the third step of positioning, different factors around the problem affecting the categorisation into the problem type are discussed by Alford and Head (2017), indicating that if more conditions apply to a problem, they increase in wickedness. Some factors are focused on the problem and others on the stakeholders involved. In the fourth and final step the position of the problems are checked again on their relative position to each other and the two axes. This approach is tested via case studies to determine its value in addressing the lack of a structured framework for classifying wicked and complex problems in the supply chain.

1.1.5 Roadmaps

Information sharing and communication are important for approaching wicked problems. Roadmaps are a communication tool that lays out how an organisation can align itself and its resources to develop solutions (Lee, Kim and Phaal, 2012). This can be classified as a structured method, decomposing a final goal along a timeline. Furthermore, collaboration is a key element in the roadmapping process, which is also important in the approaching of wicked problems.

1.2 Aims and Objectives, Research Questions

This thesis investigates how wicked problems are used in the engineering and supply chain space, especially in the context of sustainability and given some of the challenges introduced above. When applying structured approaches to wicked problems, it drives the user down the route of breaking them down, or *decomposition* as will be described in this thesis. A roadmap is a mechanism that allows you to decompose levels of a problem from drivers down to technology enablers, allowing decomposition in terms of subject area and critically time. Other forms of decomposition do not include this aspect of time. This forms the basis of the aim, objectives and research questions of the thesis.

1.2.1 Aim

To develop, test and apply a structured framework for classifying wicked and complex problems, in supply chain and engineering domains, which have been subject to degrees of decomposition.

This is essential in enabling an assessment of whether the process of decomposition, and decisions over the extent, or *degree of decomposition,* carries the risk of detracting from the original problem intent.

1.2.2 Objectives

1. To determine whether the decomposition of wicked problems, such as net zero, helps to approach the wicked problem.
2. To examine how the degree of decomposition affects how wicked and complex problems are approached.
3. To determine how a roadmap helps in the process of decomposing wicked problems.
4. To propose practical benefits from wicked problem thinking in relation to supply chain and engineering.

1.2.3 Research Questions

To achieve the aim with the objectives introduced above, a set of research questions around classification of problems, decomposition, roadmaps, engineering and the supply chain have been developed as a basis to guide the research.

Research Question 1: In what ways does problem categorisation and recognition of certain problems as complex or wicked help in driving tangible progress towards net zero supply chains and engineering solutions?

Research Question 2: Does the process of decomposing complex problems through approaches such as a roadmap change the nature of wicked problems?

Research Question 3: Is it appropriate to assume that engineering solutions in wicked problem domains are necessarily the subject of decomposition before being presented to the engineer?

Research Question 4: Is it appropriate to assume that supply and demand associated with wicked problem domains are necessarily the subject of decomposition before being presented to the supply chain?

Research Question 5: How does a technology roadmap impact the wickedness of the electrification problem?

Research Question 6: What is the degree of decomposition necessary for approaching problems?

1.3 Case Studies

1.3.1 Justification for Case Studies

Case studies are a valuable research method for investigating sustainability and research problems, which is difficult to do at an abstract level. For testing the framework and the positioning steps, two case studies from the research domain, which focus on sustainability and net zero, are analysed extensively. The chosen case studies represent different viewpoints from the engineering and research domain and are taken from two Engineering & Physical Sciences Research Council (EPSRC) research projects – UK FIRES (Allwood et al., 2019) and Future Electrical Machines Manufacturing (FEMM) Hub (Ward et al., 2023).

1.3.2 Absolute Zero Report– UK FIRES

To test and refine the framework, a case study in the form of a report by the UK FIRES research group is used. This is a consortium of universities made up of: University of Cambridge, University of Oxford, The University of Nottingham, Imperial College London, University of Bath, and University of Strathclyde. The report is called *Absolute Zero* and was written by a multidisciplinary research group of high-profile academics at the start of the programme and is still possibly the most publicly visible output from UK FIRES, having been debated in the House of Lords in 2020. It was published prior to the Covid-19 pandemic at the start of the programme as an outlook towards reaching absolute zero. It is a Report with the aim to provide a somewhat uniquely holistic agenda with 13 actions for achieving absolute zero emissions by 2050, as it is called in the report. To do this, it works on the basis of behavioural change.

Absolute Zero tackles climate change from top down, with the point of view of decomposition, doing so in a problematical way as this results in a set of 13 challenges that are not realistic. Furthermore, the problem of decomposition in the *Absolute Zero* Report is that the resulting points are not decomposed to the same level and due to this are not comparable. It deals with research and measures that have engineering and supply chain challenges. In terms of research, *Absolute Zero* argues to avoid techno-optimism, but supposes corrective actions that are problematical.

The analysis of the *Absolute Zero* Report in Chapter 4 showed that, when in a written narrative, the analysis is not easily understandable. As a result, a complexity classification card has been developed to visually display the steps and enable easier comprehension. Furthermore, the analysis revealed that the 9-box model put forward by Alford and Head (2017) does not suffice to meet the requirements for the characteristics of the 13 actions in the report. Based on the analysis of the *Absolute Zero* Report in this Thesis, I have developed the 9-box model to a new 16-box model that is more encompassing for these requirements. In order to validate this new 16-box model, another case study has been used which represents a different aspect of drive towards net zero, focussing more on engineering and technology change as opposed to behavioural change in the *Absolute Zero* Report.

1.3.3 Electrical Machines Roadmap – FEMM Hub

To validate the refined framework, a roadmap by the FEMM Hub is used. The FEMM Hub is a consortium of universities made up of: University of Sheffield, University of Strathclyde, Newcastle University, and University of Bristol. The Roadmap is specifically for electrical machines and was developed mid-way through the ongoing research of the FEMM Hub.

The roadmap tackles decomposition for engineering from the bottom up. It is about climate change and engineering with some similar characteristics to the *Absolute Zero* report. However, rather than focusing on behavioural change and avoiding techno-optimism, the roadmap focuses on technology development for electrical machines, arguing that these will play a major role in the move towards net zero.

The refined framework is used in Chapter 5 in the analysis of the roadmap for electrical machines, as electrification plays a key role on the path to Net Zero. To achieve the 2050 net zero target, a roadmap can be used as a form of decomposition and communication of the net zero problem. The analysis of the roadmap disclosed the necessity of the further boxes provided in the 16-box model.

1.4 Contribution to Knowledge

This research provides novel contributions to the field of wicked problems research.

1. *9-Box Model in Engineering and Research Context*

   Whilst there have been some approaches of wicked problems in an engineering context, the focus of this was on engineering education (Lönngren, 2017). In the work to date, the engineering focus has not been undertaken using a structured approach which makes deliberate stakeholder considerations, such as that of Alford and Head (2017). It is the first time the 9-box model by Alford and Head (2017) is applied to the climate change, engineering and supply chain context. Analysing *Absolute Zero* using the 9-box model and framework showed that there is a lack of categories in the model which led to the development of a 16-box model.

2. *Development of a 16-Box Model*

   A 16-box model has been developed for classifying situations onto it, based on a set of positioning criteria, to understand their characteristics. This provides an indication to the approaches necessary for moving forward with them. This will help in approaching wicked problems, such as in the integration of sustainability in the supply chain. The 16-box model addresses the gaps in the 9-box model: 1. situations where a solution is clear but no problem is outlined, 2. the situations are raised for stimulating debate without expecting to solve them. The application to the research space has opened up learning on the precise nature of problems presented in the academic context. The additional categories provided through the 16-box model enable the presentation of the nature of problems in the research context which the 9-box model was lacking.

3. *Mechanisms to approach wicked problems*

   Based on the classification of the situations on the model, some approaches have been suggested for moving forward with them. Furthermore, mechanisms to decrease the wickedness of situations have been introduced, for moving towards tame problems across the axes on the framework.

4. *Applications of the framework in the research domain*

   The model put forward has been used in two research case studies. It has been shown that the 9-box model did not have sufficient criteria for encompassing the requirements of the research domain case studies, including stronger engineering focus in the Roadmap analysis.

5. *Complexity Classification Card*

   A complexity classification card has been developed for a consolidated overview of the analysis criteria because a full text-based analysis of the four positioning steps was not easily comprehensible. The complexity classification card enables the analyst to spot patterns between different situations and facilitates the comparison between them.

6. *Terminology*

   Throughout the course of the research, some terminology has emerged as key when focusing on research in the field of wicked problems. Transition problems, secondary problems and interconnectedness are some key points to watch out for in future research.

   Transition Problems: This refers to problems where the implementation of a solution is subject to a transition period before being fully operationalised.

   Secondary Problems: This refers to problems that occur as a follow-up from primary problems.

   Interconnectedness: This refers to problems that are intertwined, advancing on one problem would have an effect on another problem.

1.5 Thesis Structure

Chapter 2: Literature Review

Chapter 2 provides the background information on several topics such as: supply chain sustainability and the importance of the wicked problems approach in this, systems thinking, design thinking and roadmaps. This approach has been taken because addressing the inherent questions of complexity that the thesis is investigating naturally results in questions about the interplay between approaches. The chapter concludes with the gaps in the literature to outline the aim, objectives and research questions for the thesis.

<u>Chapter 3:</u> Methodology

The methodology chapter picks up from the aim, objectives and research questions. How these research questions will be approached is discussed in the research methods. Case studies are identified as a suitable scope for the research. The chapter also includes the philosophical assumptions and provides details on the research approach with the four steps of analysis.

<u>Chapter 4:</u> Case Study 1 – *Absolute Zero* Report

This chapter uses a Report from the UK FIRES research group to test the 9-box model put forward by Alford and Head (2017). The framework has been adapted to a 16-box model as a result and a complexity classification card is developed.

<u>Chapter 5:</u> Case Study 2 – Electrical Machines Roadmap

The Electrical Machines Roadmap by the FEMM Hub is used in the analysis of the 16-box model for validating this. The sustainable lifecycle element of the roadmap has been chosen as the focus for the analysis, based on the emphasis of the thesis on sustainability.

<u>Chapter 6:</u> Findings and Discussion

In this chapter, the case studies are summarised and the main findings are discussed. Furthermore, a comparison between the two case studies is drawn. A main part of the chapter is also made up of reviewing the research questions to meet the aims and objectives of the thesis.

<u>Chapter 7:</u> Conclusion

The conclusion chapter presents the overall conclusions of the thesis and the importance of it for the research field. Limitations and further research to build on this thesis will conclude the chapter.

Chapter 2 – Literature Review

2.1 Introduction

The literature discussed in this chapter follows the process that took place to narrow down the scope of this thesis. Based on this, the literature reviewed has been selected to understand the interplay between the foundational themes along this process: Sustainability, Supply Chains, Systems Thinking, Design Thinking, Wicked Problems and Roadmapping. This led to the focus on the importance of the connection between technology roadmapping and wicked problems, such as the goal of net zero by 2050. The literature in this chapter will explore previous work across this broad landscape with a particular emphasis on exploring the connections between key concepts.

The search for literature started off focusing on supply chains and sustainability, which was the starting point for this thesis. Technical and organisational considerations, as well as political and stakeholder difficulties characterise the complexity of integrating sustainability in the supply chain. Another difficulty is that addressing sustainability in globalised supply chains is a problem which inherently operates at the system level, with interactions across various stakeholders in the supply chain, rather than being addressable at the level of a single organisation or nation. This increases the complexity of making supply chains more sustainable. The literature describes complex problems that are difficult to solve as Wicked Problems, where structuring methods to break down these problems across a timeline, such as roadmaps, are advantageous. The following sections will discuss the themes introduced here, leading up to the gap in the literature which informs the aim, objectives and research questions that conclude this chapter.

2.2 Supply Chains and Supply Chain Management

Supply chains play a vital role in the global economy. In times of crisis, their importance becomes increasingly noticeable. Globalisation has facilitated the trade of goods between different parts of the world, which also means that transport routes have been made longer, which is a critical factor regarding sustainability (Abbasi and Nilsson, 2012). Sustainability is a very present matter, customers and even employees are increasingly desiring companies to address issues regarding sustainability (Carter and Easton, 2011). However, the actions leading towards sustainability seem to be minimal. This is also the case for supply chain sustainability. This topic has sometimes been discarded from the research agenda, however interest in this field is growing.

Supply Chain Management was initially expressed as such by Oliver and Webber (1982), who are known as being the first to publish about Supply Chain Management in the literature (Corominas, 2013). In their publication, Oliver and Webber (1982) talk about supply chains, adding a new perspective to this in the form of supply chain management as the 'strategic balance of supply and demand'. This implies that supply chains are essentially systems. Hence, systems thinking would be an obvious approach for analysis of the literature which has considered this viewpoint. Section 2.4 explores literature on systems thinking and the connection of this to supply chains. No matter where we are in the world, supply chains are all around us. Over time, supply chains may change and evolve though, especially to continue to meet human needs (MacCarthy et al., 2016).

Corominas (2013) found that there is not one definition of supply chains or supply chain management that is used and accepted universally (Naslund and Williamson, 2010). Despite this, Corominas (2013) also summarised that supply chains can be seen as a network where collaboration plays a key role to obtain and deliver products, and that the relationship between suppliers and customers in a supply chain are valuable. Collaboration in the supply chain can also have a positive effect on environmental performance of a company (Vachon and Klassen, 2008). As a result, there will be a focus on sustainable supply chain management in the following sections.

2.3 Sustainable Supply Chain Management

Sustainability is a well discussed topic for several decades now. According to the United Nations Brundtland Commission, sustainability is when (United Nations, 1987: p.16):

> *"Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs."*

Research into sustainable supply chains is still in its early stages, however there has been a rise in the research focusing on this area (Winter and Knemeyer, 2013; Reefke and Sundaram, 2017). This increase has also meant that academics have developed different definitions of green and sustainable supply chain management. Sustainable supply chain management is sometimes argued to be an extension of green supply chain management (Ahi and Searcy, 2013). Incorporating environmental aspects into supply chain management is at the core of green supply chain management, whilst sustainable supply chain management moves beyond this and integrates broader aspects focusing on social and economic concerns (Ahi and Searcy, 2013). Economic, environmental and social factors are the three considerations incorporated in the triple bottom line of sustainability. The various definitions of sustainable supply chain management available could lead to some confusion when wanting to put sustainable supply chain management into practice though. Ahi and Searcy (2013) have analysed the different definitions circulating in the literature and have developed a set of 13 characteristics important for sustainability and supply chain management. Through the analysis it was clear that none of the definitions available in the literature incorporated all characteristics, therefore a new definition for sustainable supply chain management incorporating all characteristics has been proposed (Ahi and Searcy, 2013: p.339):

> *"The creation of coordinated supply chains through the voluntary integration of economic, environmental, and social considerations with key inter-organizational business systems designed to efficiently and effectively manage the material, information, and capital flows associated with the procurement, production, and distribution of products or services in order to meet stakeholder requirements and improve the profitability, competitiveness, and resilience of the organization over the short- and long-term."*

The definition introduces economic, environmental and social considerations, which are the three aspects that make up the concept of the triple bottom line of sustainability, arguing that economic, environmental and social aspects need to be considered to achieve sustainability holistically. From this definition it is clear that the triple bottom line plays a key role in sustainable supply chain management. The triple bottom line is a concept often used to characterise sustainability, also sustainable supply chain management (Carter and Easton, 2011). General research into sustainability is towards the top of the research agenda, as companies are looking to be sustainable in the long-term (Touboulic and Walker, 2015).

However, the economic perspective is prioritised in research, as it is most important to firms because it can determine the success and competitiveness of companies (Abbasi and Nilsson, 2012; Winter and Knemeyer, 2013). The underdeveloped social and environmental factors are just as important though to operationalise sustainable supply chain practices (Abbasi and Nilsson, 2012; Winter and Knemeyer, 2013; Sauter and Seuring, 2018). However, there are already some attempts to define practices for sustainable supply chain management and the focus in this area. This will be discussed further in section 2.3.1.

2.3.1 Sustainable Supply Chain Management Practices and Focus

Research on sustainable supply chain management has been greatly focused on consumer goods industries and transportation, as well as on large firms which are argued to be more likely to adopt sustainable supply chain practices (Carter and Easton, 2011; Esfahbodi et al., 2017). The reason for the focus on large firms could be a higher budget available to spend on sustainability and the reputational damage that might result from failure to adopt best practices. Assessing supply chains and their performance can help to direct where practices are most effective and where they could lead to significant improvements. Common approaches in this are the Supply Chain Operations Reference (SCOR) Model or the Balanced Scorecard. The Balanced Scorecard is a performance measurement tool that has gained in popularity since its initial adoption in the 1990s, where it was introduced by Kaplan and Norton (1992).

The idea for the balanced scorecard stems from the realisation that one measure alone cannot provide a clear overview for business performance and targets. For management it is important to have a balanced and comprehensive overview of financial and operational measures (Kaplan and Norton, 1992). The balanced scorecard is made up of measures around four perspectives: customer satisfaction, from the customer perspective, internal processes, from the internal perspective, innovation and improvement activities, from the innovation and learning perspective and financial measures, from the financial perspective (Kaplan and Norton, 1992). It is argued that often companies have too many measures to focus on, and the balanced scorecard is a tool that helps to keep the focus on the critical measures (Kaplan and Norton, 1992). At the heart of the balanced scorecard lies the strategy and vision of a company, with the aim of employees coming together and working towards these measures over imposing these changes onto them (Kaplan and Norton, 1992).

Hu, Leopold-Wildburger and Strohhecker (2017) argue that the balanced scorecard can help to put strategy into practice. With the rising importance of improving sustainability, the Balanced Scorecard has often been adapted to involve sustainability measures, changing its name to the Sustainability Balanced Scorecard (Tawse and Tabesh, 2023). For the development of a Balanced Scorecard, it has been argued that a strategy map should be created to facilitate this (Tawse and Tabesh, 2023). This can help to provide an overview of the company's strategy and highlight the measures for the balanced scorecard. In line with this is the idea that a scorecard can help decision makers to find solutions for sustainability by considering it holistically (Urbinati et al., 2022). This idea of considering holistically, indicates that the scorecard is important for supply chains in viewing them in their entirety. This supports the notion of supply chains as systems.

As discussed in the introduction to the balanced scorecard, as being a performance measurement tool, it can indicate areas where implementation of and improvements in practices can be effective. There are already some examples of practices for supply chains to improve their sustainability. Transportation is an area where the large carbon footprint is clear. Logistics overall has a negative impact on the environment, especially the expected growth of greenhouse gas emissions from freight transport is a concern (Abbasi and Nilsson, 2012; McKinnon, 2016). Different practices can be adopted to reduce the emissions from freight forwarding. It can already start at the supplier selection and go through to specifying transport routes as well as changing packaging (Carter and Easton, 2011). Furthermore, in the shipping industry, requiring vessels to slow down could make them operate at an optimised speed to reduce fuel consumption (McKinnon, 2016). Concerning the longer transport routes enabled through globalisation, it is also assumed that sourcing more locally, where possible, could reduce emissions drastically (McKinnon, 2016).

Furthermore, the relationships between business performance and sustainability are often in focus. The impact of this relationship still remains unclear though, it is unknown whether companies adopting sustainable supply chain practices result in a given economic performance, or whether it is mostly the well performing firms that decide to adopt those practices (Touboulic and Walker, 2015). Sustainable supply chain management development through multi-level frameworks is seen to incorporate the complexity and interconnectedness of supply chains (Rebs, Brandenburg and Seuring, 2019). As such, it can be argued that multi-level frameworks are important for sustainable supply chain management implementation and can be valuable when in focus in research areas.

In terms of innovation for sustainability, the academic sector holds a key responsibility for developing improvements. The translation of innovation themes against the supply chain perspective is examined in the research by Ward and Godsell (2019). Supply chains play a central role in enabling innovation. Ward and Godsell (2019) developed a 4-box model, showing the transition of the High Value Manufacturing Catapult to supply chain improvement areas, and a 9-box model, defined as a Systematised Model for Anchoring Innovation. See Figure 2.1 for the 4-box model and Figure 2.2 for the 9-box model. The High Value Manufacturing Catapult has been put forward by the UK Government and is a network of manufacturing innovation centres across the UK (Ward and Godsell, 2019).

Operational and Leadership	Business Improvement	Business Process Innovation (at the supply chain level)
Technology	Process Technology	Product Technology
	Performance	Strategic Growth

Figure 2.1 4-Box Model on transition of High Value Manufacturing Catapult into Supply Chain Improvement Space (adapted from Ward and Godsell, 2019)

Holistic Focus	Holistic Excellence Framework	Ecosystem	Cooperative Innovation
Operational and Leadership Focus	Business Improvement	Business Innovation on a company level	Sustainability Paradigm
Technology Focus	Process Technology Innovation	Product Technology	Integration and through life services
	Performance Improvement	Strategic Transformation	Systematic Cooperation

Figure 2.2 9-Box Systematised Model for Anchoring Innovation (adapted from Ward and Godsell, 2019)

Ward and Godsell (2019) have found that technology interventions to drive change cannot be addressed by individual companies in isolation and that collaboration is required for this. This explains the move from the 4-box model, showing the role of High Value Manufacturing Catapult to improve supply chain considerations, to the 9-box model, to provide a systematised model that includes why technological innovation and the market alone are not sufficient to address requirements for anchoring innovation. As part of this development to the 9-box model, Ward and Godsell (2019) have looked at nine challenges for innovation and provide interventions for each of these nine challenges to overcome them. The 9-box model enables to differentiate between situations and provide appropriate actions to them (Ward and Godsell, 2019). This was tested against strategic objectives of the High Value Manufacturing Catapult. This testing showed that having a structured approach to link supply chain and innovation is viable (Ward and Godsell, 2019). This could indicate that a structured approach will be a way forward for linking and integrating sustainability with the supply chain.

2.3.2 Sustainable Supply Chain Management Research Methods and Theories

Research into sustainable supply chains takes different forms. It is important for the research to be applicable to industry for implementation. Case studies are commonly used in this field which enable the insight into the way of doing business of certain industries or companies for example (Winter and Knemeyer, 2013). Furthermore, quantitative and qualitative methods are both used in the research on sustainable supply chain management. Qualitative research analyses relatively few cases that contain comprehensive data, for example from interviews or reports (Behnke, Baur and Behnke, 2010; Baur, 2019). Quantitative research analyses various cases, however, with little information within each case, for example from surveys (Baur, 2019). Verbal interpretations as opposed to probability and statistics further differentiated qualitative and quantitative research respectively (Goertz and Mahoney, 2012). Qualitative research methods are clearly in favour, as quantitative research has the risk that the data sets will not be large enough to extract generalisable and significant data (Carter and Easton, 2011). As well as the research methods, theories can help to structure research projects and put a specific theoretic lens onto them to explain whether particular approaches lead to desired outcomes.

Theories for sustainable supply chain management are important to make this area more explainable for industry and researchers. However, in the literature, the majority of papers do not examine theories and few articles focus primarily on theoretical aspects (Carter and Easton, 2011; Touboulic and Walker, 2015). Research that is not theory based is often descriptive rather than making significant contributions to theory (Hoejmose and Adrien-Kirby, 2012). When in focus, the theories that are mostly adopted are institutional theory, stakeholder theory, resource-based view, natural resource-based view, and transaction cost theory (Touboulic and Walker, 2015). Touboulic and Walker (2015) argue that it can be problematic to adopt these theories that have been developed in another research field to research in sustainable supply chain management, as sometimes these theories may not be so compatible with or relevant to the research focus. The theories discussed above are used more commonly in a business management context, as a result it has been chosen to not focus on the above listed theories as part of this research on sustainable supply chain management. Whilst there is little attempt to advance and develop sustainable supply chain management theories, there is a trend in research going towards theory development (Carter and Easton, 2011; Winter and Knemeyer, 2013). In their research focusing on the development of a theory for sustainable supply chain management, using a case study approach with ten examples, Pagell and Wu (2009) found that a mix of traditional supply chain management with more novel practices focusing on sustainability help to make supply chains more sustainable (Winter and Knemeyer, 2013). However, making supply chains more sustainable is restricted by the business model that needs to include environmental and social aspects, which indicates the importance of integrating all aspects of the triple bottom line for supply chains to be sustainable (Pagell and Wu, 2009; Touboulic and Walker, 2015). Research methods on sustainable supply chain management and the integration of theories exhibit key challenges, and challenges can also be exhibited in sustainable supply chain management itself.

2.3.3 Challenges for Sustainable Supply Chain Management

Disruptions in supply chains impede the progress for sustainability uptake, indicating the importance of supply chain resilience (Ghufran et al., 2022). Sustainability uptake in the supply chain may include the reduction of material waste and adhering to human rights and labour standards (Sarkis, 2003; Chen and Kitsis, 2017, Allenbacher and Berg, 2023). There are various challenges for sustainable supply chain management adoption due to its complexity based on the interconnectedness of the system (Elias et al., 2021). This points towards using a systems thinking approach for sustainable supply chain management. This will be further explored in section 2.4 on Systems Thinking, Complexity and Wicked Problems.

In terms of challenges, Abbasi and Nilsson (2012) have identified several supply chain organisational challenges reflected in sustainable supply chain management, for example: costs, complexity, operationalisation, mindset and cultural changes and uncertainties. Uncertainty is a factor that can prohibit change. The fear to change a system that has worked well in the past and the interpretation of sustainable supply chain operationalisation can hinder the implementation of sustainable supply chain practices due to the uncertainty of the outcome (Abbasi and Nilsson, 2012). As shown in the Covid-19 pandemic, when a change is imposed it is possible to adjust to this. However, this is based on an involuntary change. Sauter and Seuring (2018) suggest that implementing multi-tier sustainable supply chain practices could reduce this uncertainty. Additionally, developing policies can help companies to guide their focus in sustainable supply chain practices in order to somewhat reduce uncertainties, however, policies have been mainly focused on transport (Abbasi and Nilsson, 2012). An example of such policies is from the UK Government that has banned new diesel petrol cars from 2035, with only electric vehicles permitted from then on (Department for Transport, 2023a).

With regards to the social aspect, there are also challenges related to sustainable supply chain management. Organisational culture and mindset have a key impact on the implementation of sustainable supply chain practices (Abbasi and Nilsson, 2012). It is important that the views of employees are also incorporated in decisions (Touboulic and Walker, 2015). Carter and Easton (2011) suggest that a lack of transparency could prohibit the implementation of logistics social responsibility and management plays a role in this (Winter and Knemeyer, 2013). Abbasi and Nilsson (2012) argue that there is a challenge for managers to put sustainable and environmental management into the everyday decisions of businesses, a challenge that is based on the mindset and culture within organisations. To approach this, managers need to adapt and change their way of thinking (Abbasi and Nilsson, 2012). Top management engagement is important for employees to take on the responsibility to put into practice and live the sustainability measures developed (Abbasi and Nilsson, 2012; Esfahbodi et al., 2017). Furthermore, it has been found that the collaboration across the supply chain is key to achieve real impact in the change towards sustainable supply chain management, as there is a potential to reduce emissions through collaboration in closed loop supply chains (Abbasi and Nilsson, 2012).

2.3.4 Supply Chain Constraints and The Role of Collaboration

According to Vachon and Klassen (2008), collaboration with actors across the supply chain can positively affect environmental and manufacturing performance of a company. Esfahbodi et al. (2017) also suggest that the interaction between suppliers could impact sustainable supply chain management implementation. Managers are increasingly aware that the social and environmental responsibilities of a company involve various actors across the supply chain.

Therefore, it is important to look for ways to coordinate sustainability aims across supply chain partners as well as collaborating with the key supply chain actors (Winter and Knemeyer, 2013). Collaboration and coordination are especially important across the supply chain, as it may help different supply chain members to work towards a standard set of goals rather than having differing views and interpretations (Winter and Knemeyer, 2013).

Especially for the use of natural resources, collaboration and cooperation on an international basis is important due to the potential to contribute to the change of the natural resource system (IRP, 2019). Sometimes, resources are referred to as the physical currency of the economy (Desing, Braun and Hischier, 2020). This highlights the importance of resources. Since 1970, the use of natural resources has more than tripled, from around 27 billion tonnes in 1970 to 92 billion tonnes in 2017, with this growth being projected to continue to reach 190 billion tonnes by 2060, if the historical trends remain (IRP, 2019). It is expected that such a growth in use of resources would have a severe impact on the resource supply system, as well as increasing the impact on the environment (IRP, 2019). This indicates that the expected growth is difficult to be met with the current supply system, signifying that the resources could become scarce.

In line with this, it is known that some resources are finite, which could be seen as a concern for the economy, however with regards to the environment the concern is of the environmental impact of resources to potentially cause irreversible damages (Desing, Braun and Hischier, 2020). This is also partly due to the way these resources are used (IRP, 2019). The IRP (2019) argues that natural resources, based on their extraction and processing methods, are responsible for around half of the impacts of climate change.

To work against climate change, the backbone of many improvements necessary for the move towards net zero is electrification, where rare earth elements play a key role. Most rare earth elements are produced in China, which holds a key part of the rare earth element market imposing geopolitical risks as well as supply risks, that could hinder the progress for net zero (Serpell, Paren and Chu, 2021). Rare earth elements are used in magnets, for example in the production of electric vehicles (Serpell, Paren and Chu, 2021). Demand for rare earth elements is expected to double by 2035, from 200,000 tons in 2021, to 450,000 tons in 2035 (USGS, 2021; Serpell, Paren and Chu, 2021). To meet this demand, methods for reducing the demand of primary rare earth elements are necessary. An example of this would be to work with existing rare earth magnets by reusing and recycling them (Filho, 2016). This would require coordination and collaboration for setting up a supply chain for recovering existing magnets and repurposing them. This aspect of collaboration is key in the supply chain which can be enabled through information sharing, in order to create more transparency across the supply chain, and integrating processes (Reefke and Sundaram, 2017). Collaboration is an important element for systems thinking as well as the concept of wicked problems, where collaboration is important to solve complex issues.

2.4 Systems Thinking, Complexity and Wicked Problems

2.4.1 Systems and Systems Thinking

2.4.1.1 Systems

In systems thinking there is a general understanding that challenges dealt with daily can be considered as systems (Pidd, 2004). These systems are part of a wider environment of systems and include sub-systems (Pidd, 2004). Furthermore, systems are a combination of individual parts that provide a value greater than that of the individual parts in isolation (The Royal Academy of Engineering, 2007). These individual parts interact with each other and understanding the relationship across these parts to fully comprehend how a system operates is a challenge for engineers (The Royal Academy of Engineering, 2007). This challenge also involves having to holistically approach engineering systems to reflect the complexity of integrated systems design, bringing together all parts of the system to define its boundary in space, scope and time together with considering the implications this may have (The Royal Academy of Engineering, 2007). Considering the effects of decisions is the underlying principle for systems thinking and an essential part of engineering for sustainable development (The Royal Academy of Engineering, 2007).

2.4.1.2 Systems Thinking

Meadows and Wright (2008) developed an iceberg model of systems thinking to support approaching a challenge as part of the whole system that it exists in. The aim of the model is to help thinking more systematically on a certain challenge or event. Whilst the overall event is visible as the top the iceberg, various factors are not visible as they are below the sea level. These factors include: 1. the behaviour patterns and the trends in this over time, 2. the systems structure, how the parts are related and the ways the patterns are influenced and 3. the mental models behind the challenge or event, the beliefs, values and assumptions that make up the system (Meadows and Wright, 2008). In addition to this iceberg model for systems thinking by Meadows and Wright (2008), Cabrera and Cabrera (2018) have investigated different rules for it.

Cabrera and Cabrera (2018) have developed four rules of systems thinking: Distinction, System, Relationship and Perspective. In the distinction rule, individual parts can be distinguished from other parts they are with. For the systems rule, elements can be split into individual parts or put together to form a whole. In terms of the relationship rule, any part can relate to another part and impact this. In the perspectives rule, the individual parts can be looked at from different viewpoints and they can be a perspective for other parts. These rules are said to enable a universal approach to concepts (Cabrera and Cabrera, 2018). In addition to these rules, previous research has also distinguished systems thinking into different types.

Checkland (1985) has distinguished systems thinking into hard systems thinking and soft systems thinking. In hard systems thinking the focus is on more technical engineering challenges where there is a clear goal seeking orientation. In soft systems thinking the orientation is more towards learning and the focus is on more conceptual challenges to define actions to improve. Soft systems thinking, as in the soft system methodology, somewhat enables flexibility in the approach as the problem-solving progresses, whereas in hard systems thinking this is set from the beginning and the system of concern is seen as being obvious (Checkland and Tsouvalis, 1997).

Some literature on sustainable supply chain management focuses on systems thinking, arguing that it is important to consider it when working on sustainable supply chain management.

2.4.1.3 Systems Thinking and Supply Chains

Ghufran et al. (2022) describe systems thinking as a concept for problem solving which looks at issues in their totality. This is a key point because for supply chain sustainability, the whole of the supply chain must be considered to implement sustainability changes. Systems thinking can be interpreted through different lenses, for example as a theory, a paradigm or a belief system (Grewatsch, Kennedy and Bansal, 2023). In the case of approaching sustainability in supply chain management, systems thinking highlights that this should be done holistically and not independently (Ghufran et al., 2022).

Systems thinking can be a key approach for sustainable supply chain management and Rebs, Brandenburg and Seuring (2019) suggest a framework of systems thinking for this. It is argued that for decision making for sustainability in supply chains, systems thinking can be advantageous (Rebs, Brandenburg and Seuring, 2019). Systems thinking is also seen as playing a central role in integrating sustainability in the engineering domain, such as for sustainable manufacturing (Zhang, Calvo-Amodio and Haapala, 2013). This is explained by systems thinking enabling engineers to solve engineering problems holistically.

For the implementation of sustainability in supply chains, it is important that there is a strong exchange between actors across the supply chains. Due to the necessity of organising material and goods flow by communication and collaboration through sharing information in supply chains, they have an aspect of complex systems dynamics to them involving living feedback loops (Rebs, Brandenburg and Seuring, 2019). This is a factor reflected in wicked problems, that could also be considered in the approach for integrating sustainability in supply chains.

2.4.2 Wicked Problems

Rittel and Webber (1973) set the research basis for wicked problems through defining a set of primary characteristics, based on the idea of wicked problems stemming from social policy. Rittel and Webber (1973) argue that problems from scientists and engineers, such as in the natural sciences area, can be defined and solutions for them can be found, whereas for problems of planning in the social or policy area it is not possible to define them and solve them completely. These are, what they call, the wicked problems. Wicked problems are argued to outline the gap between problems in social sciences and the natural sciences (Zellner and Campbell, 2015). The ten characteristics of wicked problems outlined by Rittel and Webber (1973) are the following:

1. “There is no definitive formulation of a wicked problem
2. Wicked problems have no stopping rule
3. Solutions to wicked problems are not true-or-false, but good-or-bad
4. There is no immediate and no ultimate test of a solution to a wicked problem
5. Every solution to a wicked problem is a “one-shot operation”; because there is no opportunity to learn by trial-and-error, every attempt counts significantly
6. Wicked problems do not have enumerable (or exhaustively describable) set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan
7. Every wicked problem is essentially unique
8. Every problem can be considered to be a symptom of another problem
9. The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem’s resolution
10. The planner has no right to be wrong”

Over the years, more research into wicked problems has been conducted (Weber and Khademian, 2008; Levin et al., 2012; Dentoni and Bitzer, 2015; Head and Alford, 2015; Peters, 2017). Wicked problems are often characterised as complex problems that are interconnected and involve different stakeholders (Dentoni and Bitzer, 2015; Head and Alford, 2015). This complexity, with the fact that the definitions of these problems are not clear, makes it increasingly difficult for engineers to solve them (Schuelke-Leech, 2020). This stems from the fact that engineers are problem solvers, however more in terms of rigid and defined problems with clearly outlined solution methods (Schuelke-Leech, 2020). Wicked problems are inherently not rigid and are therefore not amendable to clearly defined solution methods though. Therefore, the classical approach of engineers to solve problems cannot be directly extrapolated and used within wicked problems. Lönngren (2017) has investigated the role of wicked problems in engineering education, which is lacking due to the reason confirmed by Schuelke-Leech (2020) that engineers are educated on clearly structured problems. Furthermore, Lönngren (2017) found that engineers need clear and structured guidance to integratively approach wicked problems.

This clear structure is not given in wicked problems though. They involve stakeholders whose values are different and often in contradiction to each other, increasing the difficulty of agreement (Kennedy et al., 2017). For decreasing the complexity of a wicked problem, having an agreed definition is the first step, which proves complex in itself due to the stakeholders involved where agreement is often lacking (Kennedy et al., 2017). Grewatsch, Kennedy and Bansal (2023) see a rise in wicked problems, through digital technologies increasing complexity and interconnectedness. However, it is also argued that problems which are seemingly difficult to solve are simply labelled as wicked problems to justify not attempting to solve them (Peters, 2017). Examples of wicked problems are ones related to sustainability, as well as poverty and inequality (Dentoni and Bitzer, 2015; Peters, 2017). Another concept similar to that of wicked problems is super-wicked problems, under which Levin et al. (2012) classify global environmental issues, such as climate change. There are four additional characteristics which are unique to super-wicked problems: 1) there is a time restriction, 2) the problems that are to be solved are in fact caused by those that intend to solve them, 3) there is little to no central governance that addresses the issues, and 4) the problem solving is shifted to the future, rather than taking responsibility and acting now (Levin et al., 2012). In the following the concept of wicked problems will be focused on, however the ideas are also applicable to super-wicked problems, such as sustainable supply chain management.

2.4.3 Approaching Wicked Problems

There has been no analysis of wicked problems in their entirety (Kennedy et al., 2017). When approaching wicked problems, Zellner and Campbell (2015) found that often further problems are uncovered during the process. Furthermore, the approach in wicked problems needs clarity, which is often lacking (Zellner and Campbell, 2015). The existing literature suggests several ways for attempting to solve wicked problems. For example, rather than individuals approaching wicked problems, collaboration between different stakeholders should be facilitated and form the basis of any approach to a wicked problem (Weber and Khademian, 2008). Stakeholders are especially important in the approach for wicked problems and their engagement is key (Zellner and Campbell, 2015). Wicked supply chain problems can only be addressed on a collaborative basis, not through individual organisations. This could be explained by stakeholders having experiences personal to them as well has having access to different pools of resources which will inevitably result in diverse ways of approaching a problem (Dentoni and Bitzer, 2015). Hence, networks have been claimed to be better at solving wicked problems as they attempt to resolve issues in a less centralised way, which somewhat enables flexibility (Peters, 2017). The characteristics of wicked problems suggest that one solution to them cannot be found, but that the way in which the problems are defined indicate a possible approach (Head and Alford, 2015). Therefore, this aspect of flexibility is especially important to adjust the way of action when unexpected incidents come up during the process (Weber and Khademian, 2008). Furthermore, one of the difficulties that stakeholders may be confronted with when attempting to solve problems collaboratively is the flow and exchange of information across different stakeholders, indicating that stakeholder engagement is vital throughout the process (Weber and Khademian, 2008). This problem of information sharing is reflected in supply chain sustainability, as suggested by Reefke and Sundaram (2017).

In the literature, some typologies and frameworks for problems, including wicked problems, have been developed with the aim of helping to understand and classify them. For example, Alford and Head (2017) have worked on the development of a typology for wicked problems, highlighting that they have two core elements: the problem itself and those involved with it. Along this line of thought they have come up with a model using nine boxes to classify problems according to their wickedness. An adaptation of this is shown in Figure 2.3 below.

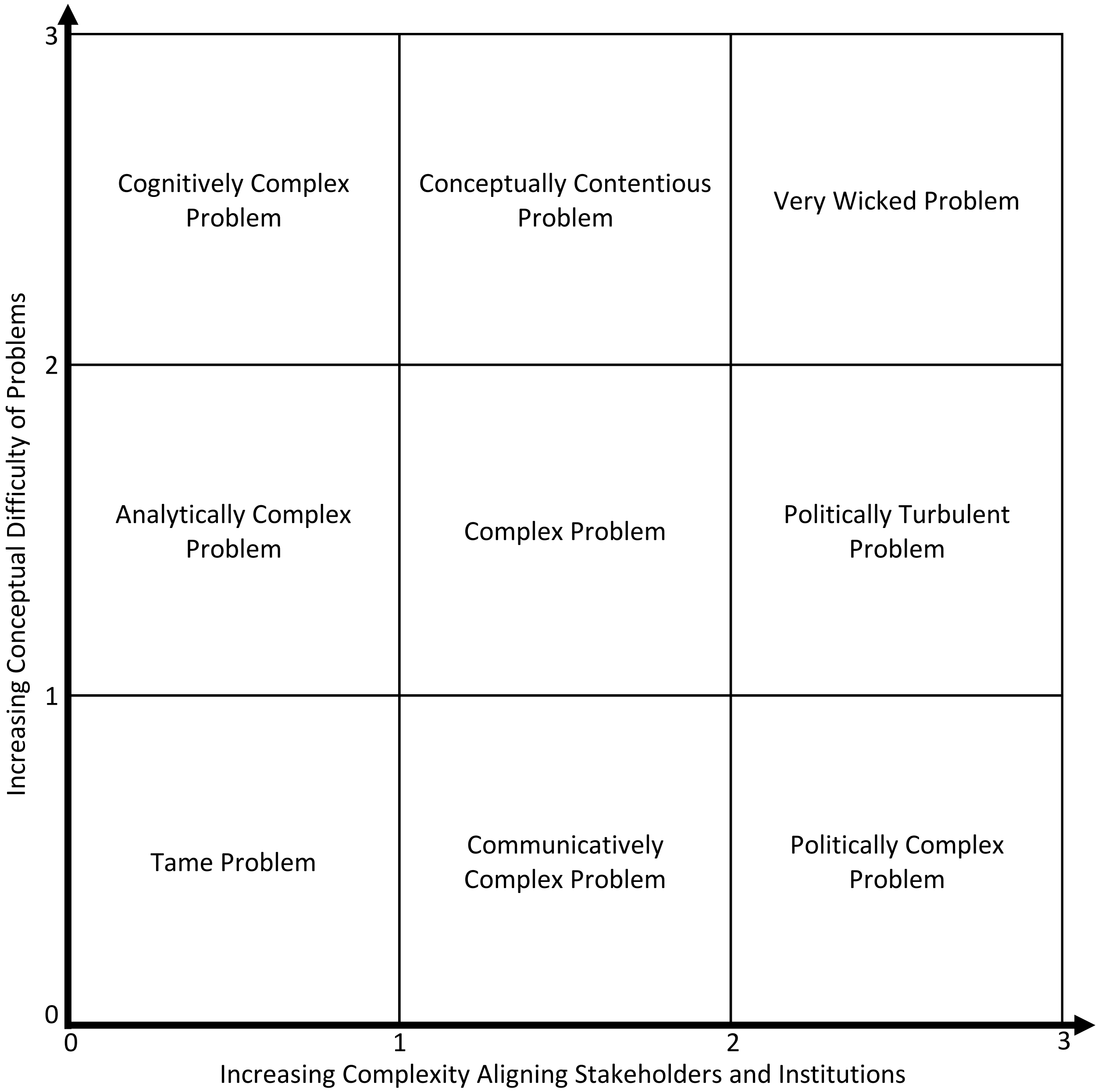


Figure 2.3 Wicked Problems Model (adapted from Alford and Head, 2017)

The two axes of this model are divided into three dimensions. For the problem itself, shown on the y-axis, the first dimension is when the problem is clear and the solution is clear. The second dimension is when the problem is known, however the solution is unknown. The final dimension is when neither the problem nor the solution is known. For the stakeholders, shown on the x-axis, the three dimensions are: 1) Knowledge and interest are shared between stakeholders, 2) knowledge is fragmented across stakeholders making it difficult to have a holistic overview, however stakeholders agree on the problem and possible solutions, 3) knowledge and interests are fragmented across stakeholders. When putting these dimensions together on a diagram, there are nine outcomes, categorising problems by a degree of wickedness. For both aspects, the first dimension points towards a tamer problem and as it increases to the third dimension, the problem becomes more complex and wicked.

In addition to providing this typology of problems, Alford and Head (2017) argue, in line with the nine categories of problems, that problem wickedness increases when problems have certain features, such as little knowledge on the problem, knowledge spread between stakeholders, conflict amongst stakeholders involved. This is a key point for the overall research that follows.

Overall, Alford and Head (2017) argue that their typology is more detailed than others. Typologies from research following this have also been less detailed. Schuelke-Leech (2020) has looked at wicked problems in engineering problem solving and developed a typology focused on well-structured and ill-structured problems. Their research has not included a review of the developments by Alford and Head (2017). Figure 2.4 below shows an adaptation of the typology proposed by Schuelke-Leech (2020).

Complex, undefined solutions	Originative Problems	Wicked Problems
Solid, defined solutions	Routine Problems	Process-Oriented Problems
	Well Structured Problems	**Ill-structured Problems**

Figure 2.4 Problems Model (adapted from Schuelke-Leech, 2020)

The model from Schuelke-Leech (2020) is unarguably simpler than the one proposed by Alford and Head (2017) in terms of providing less differentiation between problem types. Along with this, the Alford and Head (2017) model provides an overview of the two problems aspects, the problem itself and those involved with it. The Schuelke-Leech (2020) model does not consider the stakeholder aspect and focuses purely on problem characteristics, around the structure of the problem and whether there are possible solutions for this. This is part of the Alford and Head (2017) model on the problem side, where the problem definition and the solution make up the three dimensions. When comparing these two models, it can be summarised that the Alford and Head (2017) model provides a deeper understanding of different problem types based on the interplay of the problem and stakeholders. In addition to these frameworks for characterising problems that can help to point towards an approach to them, there are further ideas for approaching wicked problems.

Another method for approaching wicked problems is using Problem Structuring Methods, as suggested by Yearworth (2016). It is argued that when using Problem Structuring Methods with stakeholders it can help to make sense of problem contexts (Yearworth, 2016). Nine key elements for Problem Structuring Methods are defined: 1. Improvement Activity, 2. Systemic Approach, 3. Adaptation/Creativity, 4. Methodological Lessons, 5. Worldviews, 6. Messiness, 7. Interactive/Iterative/Therapeutic, 8. Subjectivity and 9. Limits. It is argued that having a clear definition of the problem structuring methods with these nine aspects would be interesting for engineers as an audience that is pragmatic in the nature of their doing (Yearworth, 2016). For approaching a wicked problem, stakeholder groups must define and take ownership of the desired solution and at the start the who and what of the solution must be defined before going into the how, when and why (Yearworth, 2016). Furthermore, Yearworth (2016) suggests that shared interest and agreement between stakeholders on a specific way forward can help work towards a certain goal together, which can be supported by enforcement, for example through government regulations regarding the environment. This work somewhat reflects the idea of the later published research by Alford and Head (2017) where stakeholder agreement is important for having a tamer problem.

It is also suggested that Engineers are to use Problem Structuring Methods on sustainability problems by; having a clear objective along with stakeholder engagement, develop current methods to approach problems in a more inclusive way, and deploying methods quickly due to the time constraint regarding climate change (Yearworth, 2016).

As well as Problem Structuring Methods, Seager, Selinger and Wiek (2012) see systems engineering as a modern approach to wicked problems which involves improvement through systems level integration. They argue that there are two perspectives to this: 1. engineering within the limitations of sustainability by working with conventional settings such as cost minimisation and return maximisation, 2. Expanding towards the integration of the triple bottom line of sustainability within the approach. Furthermore, Seager, Selinger and Wiek (2012) argue that systems engineering focuses on efficiency and indicate that it is not the best approach for wicked problems and rather focuses on the improvement of business as usual.

Seager, Selinger and Wiek (2012) have developed a taxonomy for sustainable engineering science, dividing approaches to sustainability into: business-as-usual, systems engineering and sustainable engineering science. They identify that only sustainable engineering science has some understanding of wicked problems. Seager, Selinger and Wiek (2012) argue that compared to business-as-usual and systems engineering, sustainable engineering science enables more collaborative inclusion across disciplines and flexibility to holistically solve the complexity and interconnectedness that characterise wicked problems. This would question the idea of using systems engineering as an approach to wicked problems. Further details to justify why sustainable engineering science is a favourable approach are discussed in the following paragraphs that expand on the approaches business-as-usual, systems engineering and sustainable engineering science.

An overview of the approaches to sustainability is given under five key aspects: Attitude towards technology, focus, expert and ethical culture, approach to complexity, approach to conflicting views. As part of this, the systems engineering approach is divided into engineering within ecological constraints and sustainable engineering.

For business as usual the orientation towards sustainability is divided into: 1. optimistic outlook on technology, 2. the focus is on creating new things, and resources while overlooking scale and efficiency, 3. The expert and ethical culture is based on depth in single sub-discipline with professional ethics, 4. complexity is approached through simplification and reduction, 5. The approach to conflicting views is the defense of the techno-industrial spirit and rejection of contrasting perspectives (Seager, Selinger and Wiek, 2012).

For systems engineering in the engineering within ecological constraints the orientation towards sustainability is divided into: 1. pragmatic outlook on technology, 2. the focus is on cost optimisation of maturing technology while ignoring scales, 3. The expert and ethical culture is classified with multidisciplinary teams, taking a social ethics approach, 4. The approach to complexity is on cost-benefit optimisation and efficiency and 5. conflicting views are handled through litigation and regulation (Seager, Selinger and Wiek, 2012).

The systems engineering approach to orientation towards sustainability for sustainable engineering is similar to that of engineering with ecological constraints, however it differs in three of the five aspect: the focus is on optimisation for the triple bottom line, whilst the scale is also disregarded, the approach to complexity is minimising risk and the approach to conflicting views is having participation in a structured format (Seager, Selinger and Wiek, 2012).

For sustainable engineering science the orientation towards sustainability is divided into: 1. The attitude towards technology is sceptic, 2. The focus is on sustainability as a wicked problem, 3. The expert and ethical culture is interactive with macro ethics, 4. The approach to complexity involves flexibility, anticipation and resilience, 5. The approach to conflicting views is collaboration and deliberation (Seager, Selinger and Wiek, 2012). This highlights the idea of collaboration for approaching wicked problems.

Whilst systems thinking can be seen as a concept for sustainable supply chain management, it can also be applied to solve wicked problems, where complexity and interconnectedness lies at the heart of this. Zellner and Campbell (2015) see an overlap between wicked problems characteristics and complex systems. There is an overlap between the elements making up wicked problems and complex systems analysis. According to Zellner and Campbell (2015), the elements that make up wicked problems, such as complexity and uncertainty, are used in the complex systems analysis approach. This will be the focus of the following section, as well as the more human-centred approach of design thinking.

2.5 Systems Thinking, Design Thinking and Wicked Problems

Grewatsch, Kennedy and Bansal (2023) argue that systems thinking can help to examine dynamics and change of wicked problems. This is supported by Kennedy et al. (2017) who use systems thinking and theory to make a framework for developing strategy to approach wicked problems. They propose a tool for social marketers to understand the structure of and analyse wicked problems.

Zellner and Campbell (2015) have used complex systems to examine the characteristics of wicked problems as proposed by Rittel and Webber in 1973, which are seen to be reflected in a systems thinking perspective. Complex systems are sometimes argued to be an adaptation of wicked problems (Zellner and Campbell, 2015). Within complex systems, exchange of information, energy and matter between stakeholders is selective and decentralised (Zellner and Campbell, 2015). This decentralised aspect is important in the approach to wicked problems. Therefore, complex systems could be seen as an adequate method for wicked problems. Complex systems have the ability of re-evaluating regularly (Zellner and Campbell, 2015). This is a key factor for flexibility important in approaching wicked problems. However, this flexibility is sometimes argued as being negative through not having a defined approach lined out (Zellner and Campbell, 2015).

Despite the potential of systems thinking, Cabrera, Colosi and Lobdell (2008) argue that systems thinking alone is not the answer to problems, whether they are on a local scale, such as traffic management, or global scale, such as global warming. Although, systems thinking is said to be a part of the problem-solving efforts for such problems (Cabrera, Colosi and Lobdell, 2008). Though systems thinking can be seen as an attempt for approaching wicked problems, there is compelling research in the literature that states that systems thinking is not the right approach to wicked problems (Zellner and Campbell, 2015; Grewatsch, Kennedy and Bansal, 2023; Rittel and Webber, 1973). Already back in 1973, when Rittel and Webber developed the idea of wicked problems, systems thinking was discussed. However, it has been found that systems thinking does not work in the approach for wicked problems (Rittel and Webber, 1973). This is reflected in more current literature, with Zellner and Campbell (2015) arguing that complex systems are not appropriate for solving wicked problems, but rather help to decrease their wickedness in some degree, which could be defined as decomposing a wicked problem into smaller parts. This is extended by Grewatsch, Kennedy and Bansal (2023) that found systems thinking to be quite a novel approach for wicked problems, but not one that provides the solution for them. Another method discussed in the literature on wicked problems is design thinking, which is somewhat more human-centred compared to systems thinking.

Design thinking is shifting the focus from product design to problem solving (Baker and Moukhliss, 2020). It is argued that design thinking can support in developing solutions for complex problems (Overmyer and Carlson, 2019), which could mean that it is a suitable method for approaching wicked problems. For problem solving in line with design thinking, there are five characteristics that designers should incorporate (Carlgren, Rauth and Elmquist, 2016):

1. User Focus: the understanding of user needs under user focus
2. Problem-Framing: defining and clarifying the problem leading to possible solutions
3. Visualisation: reviewing numerous solutions to the problems and displaying them visually
4. Experimentation: repeatedly testing the possible solutions
5. Diversity: building diverse teams with a wide range of perspectives, fostering collaboration

Whilst Carlgren, Rauth and Elmquist (2016) see collaboration as an element of design thinking, Baker and Moukhliss (2020) highlight that design thinking may be collaborative at times, but it is handled more independently at other times. To successfully approach wicked problems, collaboration across stakeholders is a key element and must increase (Baker and Moukhliss, 2020). Furthermore, stakeholders attempting to approach wicked problems should consider the problem context (Overmyer and Carlson, 2019). When the problem context is constant, existing problem-solving methods are suitable (Dorst, 2015). In a wicked problem context, this stability is not given though, indicating that routine problem-solving is not the answer and a new method is required. This is a drawback for using design thinking in the approach of wicked problems. This drawback is further emphasised by Dorst (2015) who points out that design thinking cannot be easily used across domains other than design. Wicked problems are diverse though, so a method that can incorporate this diversity in its approach, as well as facilitating communication, is key for wicked problems.

Communication and information sharing is an important aspect of implementing sustainability into processes, such as supply chains. This is somewhat reflected in systems thinking and design thinking, however based on the literature arguing that they may not provide the optimal approach to wicked problems, another concept where collaboration, communication and information sharing is important has been found. Roadmaps can act as a form of communication to inform about future actions (Willyard and McClees, 1987), due to this they have the potential to be used for approaching wicked problems. As a result, roadmaps will be explored in the following section.

2.6 Roadmaps

Roadmaps come in different forms, with many plans and outlooks labelled as roadmaps as they provide a somewhat structured view to the future. Roadmapping can be used as a planning tool, for example for showing the necessary development of required skills (Ghazinoory et al., 2017). It can help to integrate innovation in industrial processes to strengthen social, environmental and economic performance, which are important components of sustainable development (Ding and Ferràs Hernández, 2023). Roadmaps have the purpose to show the path towards a certain goal in time. This is of key importance regarding net zero where a specific time goal has been set of 2050 across many parts of the world. Some key questions raised that roadmaps can provide answers to are: Where are we going? Where are we now? How can we get there? (Phaal, Farrukh and Probert, 2004; Phaal and Muller, 2007; Phaal, Farrukh and Probert, 2007; Phaal and Muller, 2009). These are important questions to answer also for sustainable supply chains and net zero.

Different types of roadmaps are used for different purposes. Two known examples for roadmaps are strategic roadmapping, S-Plan, and technology roadmapping, T-Plan (Institute for Manufacturing, 2024). These types of roadmaps will be explored in the following section 2.6.1 on roadmap types and examples.

2.6.1 Roadmap Types and Examples

When it comes to the types of roadmaps and their format, there is not one defined style that is adopted across the literature. The Institute for Manufacturing provides an overview of roadmapping focusing on two types: strategic roadmapping under the S-Plan, and technology roadmapping under the T-Plan. The S-Plan is used for policy, sector, business unit and corporate roadmaps, whilst the T-Plan focuses on technology, product and service roadmaps (Institute for Manufacturing, 2024). The International Energy Agency (2020) argues that transformation of technology is required to meet international sustainability goals. This highlights the importance of technology for sustainable development. Based on this, the roadmapping literature discussed in the following sections will be heavily focused on the technology roadmapping, and less focused on the strategic roadmapping.

Technology Roadmapping was introduced in industry (Phaal et al., 2011). In the 1970s, Motorola initially created technology roadmaps to bring product development and supporting technologies together, aligning technology investments and development of capabilities (Bernal et al., 2009). Motorola differentiated technology roadmaps into two types, Emerging and Product Technology Roadmaps (Willyard and McClees, 1987). Whilst the emerging technology roadmap is focused on a specific technology and the progress of this over time, the product technology roadmap focuses on providing a full overview of the products from the past, through the present to the future (Willyard and McClees, 1987). Another difference between emerging and product technology roadmaps is the time frame of three to eight years (Willyard and McClees, 1987).

Technology roadmaps are argued to be most commonly used for the strategic planning and management of technology in manufacturing (Lee and Park, 2005). However, the roadmapping approach can be used in different contexts and adapted according to this, which indicates that the approach is flexible (Cho and Lee, 2014). This is an important factor when regarding the application of roadmaps for wicked problems where flexibility is important. Some of the literature points towards different types of roadmaps within technology roadmaps, such as industry technology roadmaps, science and technology roadmaps, product technology roadmaps and product roadmaps (Kostoff and Schaller, 2001). However, for this classification there is no clear line that is common across the literature, and the classification varies across the literature (Phaal, Farrukh and Probert, 2004; Garcia and Bray, 1997). The type of roadmap is also linked with the process of roadmapping that takes place.

As introduced above, roadmaps come in different types and find application in a variety of fields with a focus on different levels (Amer and Daim, 2010). Regarding net zero as a wicked problem, which is difficult to approach with a traditional engineering method, there are roadmaps available from the engineering side with a view towards net zero.

Examples of this come from the Aerospace and the Automotive Sector. The Aerospace Technology Institute has published a document on Technology Pathways to Enable Zero-Carbon Emission Flight under the title of Technology Roadmaps (Hadnum, Pacey and Milne, 2022). The Pathway anticipated is dependent on the size of the aircraft in question: sub-regional could use a battery electric propulsion system, regional aircraft could use a hydrogen fuel cell, regional, narrowbody and midsize aircraft could use a hydrogen gas turbine, whilst sustainable aviation fuel can be used across all aircraft sizes, from sub-regional to widebody.

Another example is that of the Advanced Propulsion Centre, which is focused on the automotive industry, with a drive towards a net-zero future. As part of this, technology roadmaps and product roadmaps have been published (Advanced Propulsion Centre UK, 2023). The technology roadmaps are focused on Fuel Cell, Lightweight Vehicle and Powertrain Structure, Thermal Propulsion Systems, Power Electronics, Electric Machines and Electric Energy Storage. For the product roadmaps the focus is on Bus and Coach, Light Duty Vehicle <3.5t and Heavy Goods >3.5t and off-highway vehicle. The difference between the technology and product roadmap can be seen as the product roadmap focusing on specific vehicle types and the technology roadmaps focusing on specific technologies that could be applied in different vehicle types.

There are also more general outlooks for net zero that could resemble a roadmap approach in terms of providing specific time goals up until 2050. An example of this is a part in the *Absolute Zero* Report published by the EPSRC UK FIRES research group, which is a consortium of universities across the UK that looks at integrating resource efficiency in the UK industrial strategy. Within the *Absolute Zero* report, 13 actions are suggested to be the key for reaching absolute zero, which is referred to as such based on the reasoning that the zero emissions target is absolute and there is no negative emission or carbon offsetting option (Allwood et al., 2019). The areas the 13 actions are based on are the following: 1. Road Vehicles, 2. Rails, 3. Flying, 4. Shipping, 5. Heating, 6. Appliances, 7. Food, 8. Mining Material Sourcing, 9. Materials Production, 10. Construction, 11. Manufacturing, 12. Electricity, 13. Fossil Fuels. The report is based on using the technologies that are available today to work towards absolute zero, as future technological developments cannot be relied on (Allwood et al., 2019). The 13 actions within the *Absolute Zero* Report are divided into four specific time goals: 2020-2029, 2030-2049, 2050, and beyond 2050. Electrification plays a key role in the 13 actions, where it is argued that most of the energy uses have the potential to be electrified apart from shipping and flying (Allwood et al., 2019).

Electrical Machines are the enablers of the electrification necessary in the move towards a net zero world. With the increased demand for electrification and the associated increase in demand for electrical machines the importance of planning for this has augmented. A roadmap from the FEMM Hub focuses on electrical machines and the road to electrical machines to 2050 (Ward et al., 2023). Within the roadmap, four areas of need have been identified, four supply chain responses have been formulated, technical opportunities have been highlighted, the features of future electrical machines have been listed and factors for the manufacturing factory of electrical machines have been determined (Ward et al., 2023). These five factors come together in the development of the roadmap of electrical machines. In the roadmap, the overall needs and the supply chain responses are two overarching elements present throughout each of the time steps displayed.

No matter the type or application of roadmaps, the aspect of communication plays a central role. In times of growth in science and technology, clear direction and collaboration across academia and industry is necessary which can be supported by roadmaps as a means of communication (Kajikawa et al., 2008). Whilst there is no single method for the development of roadmaps, their aim in giving an orientation to stakeholders for planning activities accordingly through this element of communication is understood (Daim and Oliver, 2008). This is supported by the development of roadmapping involving stakeholders working in collaboration to define the elements of the roadmap (Martin and Daim, 2012). In extension to this, the literature on technology roadmapping highlights a main benefit of roadmapping as being the improved planning and decision-making capabilities of organisations (Lee, Kim and Phaal, 2012). In terms of wicked problems, such as supply chain sustainability and net zero, roadmaps could be argued to be a suitable method for approaching wicked problems as they provide a timeline of solutions to be reached. This is supported and justified with the collaborative process of creating a roadmap, together with the characteristic of roadmaps as a structured means of communication and the overall use and values of roadmaps that will be expanded on in the following sections.

2.6.2 Roadmapping Process

Roadmaps are made up of two axes, with one axis focusing on the time and the other on the themes of innovation which could be structured over several layers (Phaal et al., 2011). There are some challenges associated with developing roadmaps though, especially focused on how to approach it for the first time and how to keep the process ongoing to reflect changes (Phaal, Farrukh and Probert, 2001). When developing a roadmap for the first time, the focus should be on an area that is not too complex (Phaal, Farrukh and Probert, 2001). For example, technologies and products are the core layers for developing a technology roadmap and can provide a starting point, but further layers can be added in order to customise it (Phaal, Farrukh and Probert, 2001). Once participants are familiar with the process, further layers can be added to the roadmap (Phaal, Farrukh and Probert, 2001). The set-up of roadmaps is as such that there is a degree of interconnectedness among roadmap layers (Daim, Amer and Brenden, 2012). As discussed above, there is no one specifically formulated methodology for roadmapping though, in other words the development of roadmaps does not follow a specific process that is applicable universally (Lee, Kim and Phaal, 2012; Milshina and Vishnevskiy, 2019). However, Amer and Daim (2010) argue that the process of technology roadmapping has become increasingly robust and systematic. This somewhat stands in contradiction to the other works mentioned previously, where it is argued that roadmapping does not have a specific method.

With the introduction of roadmapping by Motorola, the product technology roadmap has been described in eight sections (Willyard and McClees, 1987):

1. Business Description
2. Forecasting Technology
3. Technology Roadmap Matrix
4. Quality
5. Resource Allocation
6. Patent Portfolio
7. Descriptions of Products, Status Reports & Summary Charts

8. Minority Reports

These eight sections could indicate that there is a degree of structure provided in the roadmap method. The Institute for Manufacturing (2024) also introduced an approach to roadmapping that has often been used: strategic roadmapping S-Plan and technology roadmapping T-Plan. This indicates that elements of a structured method for roadmapping are available. The development of both roadmap types is dependent on group effort, whilst the time frame differs: the S-Plan can be carried out in a one-day workshop and the T-plan requires four workshops to be completed (Institute for Manufacturing, 2024). The T-Plan approach for roadmapping was developed as part of a three-year EPSRC research programme to facilitate the implementation of roadmapping in companies (Phaal, Farrukh and Probert, 2001). The four workshops in the process for roadmap development involve multidisciplinary participation from both the commercial and technical teams in a company (Phaal, Farrukh and Probert, 2001).

The roadmapping process has some key positives that are not solely focused on the roadmap as the final outcome, but the collaboration between stakeholders that plays a key role in the process (Martin and Daim, 2012). As part of this, identifying stakeholders is a starting point in the development of technology roadmaps, coming together in workshops to reach agreements across stakeholders (Amer and Daim, 2010).

A challenge for roadmapping lies in the fact that developing a roadmap relies on past information to predict future developments (Willyard and McClees, 1987). It is clear that over the years, circumstances may change which can affect the roadmap plans. This is why roadmaps should be reviewed and updated frequently as changes over time in technologies could have an impact, they should be a living document to enable flexibility, interactivity and automation (Amer and Daim, 2010; Yuskevich et al., 2021). The aspect of flexibility is also reflected as a key factor for the approaches to wicked problems and benefits from communication.

2.6.3 Roadmapping for Communication

The process of roadmapping can be used as a means of communication due to the interactions between actors involved for the development of the roadmap, boosting the credibility of a technology roadmap, which can be seen as a communication in itself for visualising corporate goals (Lee, Kim and Phaal, 2012). It also supports the communication within companies to have a shared understanding within companies (Phaal et al., 2003), such as shared understanding on technologies that need to be developed for products to come (Willyard and McClees, 1987). Establishing and communicating linkages between technology resources and company objectives presents a challenge for many organisations and this is where technology roadmapping can support (Phaal, Farrukh and Probert, 2001). It can be used as a form of communication to support planning and strategy for technology development (Phaal, Farrukh and Probert, 2001). Furthermore, roadmaps can act as a tool for communication by giving an orientation to stakeholders for planning activities accordingly (Daim and Oliver, 2008). With regards to supply chains and especially for the importance of improving sustainability in supply chains, roadmaps can help improve the communication within organisations and across supply chains (Lee, Kim and Phaal, 2012). This highlights the use and value of roadmapping.

2.6.4 Use and Value of Technology Roadmaps

Roadmapping is a collaborative process that enables the sharing of resources and can be positive for learning and networking, also for learning on an ongoing basis where regular review and development are required (Battistella, De Toni and Pillon, 2015; Ho and O'Sullivan, 2017). Furthermore, it can act as a tool of coordination of stakeholders (Vishnevskiy, Karasev and Meissner, 2016). This can help to create a common vision and provide a high-level, concise view (Daim, Amer and Brenden, 2012).

Daim and Oliver (2008) have identified that the literature on technology roadmapping highlights that the values of it for organisations lies in five key areas: Improved communication, setting priorities and focused planning, long-term planning, integrating strategy, product and technology plans, and the opportunity of technology plans in different levels, such as corporate or national-level. These benefits stem from both the process of roadmap development and the final output of a roadmap. In roadmapping, collaboration across different stakeholders is a key element, which supports on the key values introduced above.

Systems thinking and roadmapping are discussed as an approach to wicked problems. In the development of wicked problems, Rittel and Webber (1973) argue that systems thinking is not a suitable method for wicked problems, such as sustainable supply chains and net zero. Technology roadmapping provides an alternative method for this, in entailing collaboration and communication which are key factors for approaching wicked problems. Roadmapping looks at a specific timeframe, which is reflected in net zero goals across the world. As such, it can be argued that roadmapping can be suitable for mapping out the steps leading to net zero. Furthermore, roadmaps are made up of different levels that are interconnected and wicked problems are characterised through their interconnectedness.

2.7 Conclusion

Literature around the fields of supply chain management, with a focus on sustainability, wicked problems, systems thinking, design thinking and roadmapping has been explored. Due to the importance of and reliance on supply chains in the world, their sustainable development plays a key role in the move towards net zero goals. The implementation of sustainability in supply chains poses various challenges though, especially regarding the interconnectedness of actors across the chain. This indicates that systems thinking could be a valuable approach for sustainable supply chain management, looking at the problem holistically and not independently (Ghufran et al., 2022). However, due to the complexity of implementing sustainability in the supply chain and the importance of collaboration in doing so, it can indicate that this points towards it as being classified as a wicked problem. These types of problems originate from social policy with the argument that natural science problems have clear definition and approaches (Rittel and Webber 1973). From this background, engineers are argued to be educated on issues which are clear and have a defined method for solving them. With the path towards sustainability, it is important for engineers to move away from the strictly rigid approaches and think more creatively around possible solutions.

In the approach to wicked problems through collaboration, the aspect of communication plays a central role. This is reflected in the roadmap area, where a roadmap can be used as a form of structured communication, for example for strategy. In terms of sustainability and net zero by 2050, roadmaps can help to visualise the pathway to this by highlighting areas of work through decomposing. This shows that there is value in roadmaps for net zero. The following sections highlight the gap in the literature that provides the basis for this research and leads into the aim, objectives and research questions to fill this gap.

2.7.1 Gap in Literature

Multi-level frameworks are argued to be a good approach to sustainable supply chain management. They could provide a basis for capturing the complexity and interconnectedness of the technical and organisational considerations that make integrating sustainability into supply chains difficult. This is described as a wicked problem. Frameworks could help to categorise these problems, make their structure clearer and decrease their wickedness by some degree through decomposing the problem into smaller parts. Structure and guidance are key for engineers approaching problems. However, the literature is lacking frameworks that enable engineers to categorise problems and understand their structure.

Various factors need to be considered for approaching the wicked problem of net zero. Electrification is a key part for moving towards net zero, however the development of this to meet the requirements for net zero are not clear. There is a clear time constraint for this though which should be considered for the development of electrification to enable net zero. Roadmaps enable to capture this aspect of time, but discussion in the literature on their importance for wicked problems is lacking and shows a gap in the literature.

2.8 Aim and Objectives

2.8.1 Aim

To apply, test and further develop a structured framework for wicked and complex problems, in supply chain and engineering domains, which have been subject to degrees of decomposition.

2.8.2 Objectives

1. To determine whether the decomposition of wicked problems helps to approach the wicked problem.
2. To examine how the degree of decomposition affects how wicked and complex problems are approached.
3. To determine how a roadmap helps in the process of decomposing wicked problems.
4. To propose practical benefits from wicked problem thinking in relation to supply chain and engineering.

2.9 Research Questions

1. In what ways does problem categorisation and recognition of certain problems as complex or wicked help in driving tangible progress toward net zero supply chains and engineering solutions?
2. Does the process of decomposing complex problems through approaches such as a roadmap change the nature of wicked problems?
3. Is it appropriate to assume that engineering solutions in wicked problem domains are necessarily the subject of decomposition before being presented to the engineer?
4. Is it appropriate to assume that supply and demand associated with wicked problem domains are necessarily the subject of decomposition before being presented to the supply chain?
5. How does a technology roadmap impact the wickedness of the electrification problem?
6. What is the degree of decomposition necessary for approaching problems?

Chapter 3 – Methodology

3.1 Introduction

As introduced in the conclusion of the literature review above, net zero as a wicked problem potentially benefits from a structured approach decomposing it, such as in a roadmap. The aim and objectives of the thesis are laid out to examine this, along with the supporting research questions. This chapter will focus on the methodology for answering the research questions raised.

3.2 Introduction to Research Methodology

To work on the research questions introduced above, a suitable research methodology needs to be adopted. In the literature there are various works focusing on methodology approaches in different research fields. Elements to be discussed as part of the research methodology are the research philosophy, methodology and methods. The wicked problems approach itself is philosophical, highlighting the importance of discussing the research philosophy underlining this. Therefore, fitting frameworks to support this are important. Before delving into the explanation of these elements, two models of research methodology will be introduced highlighting their interplay. Following this the philosophy underpinning the research will be discussed, before explaining the methods of research chosen to gather data and the subsequent analysis of the data.

3.3 Research Methodology Models

Two models providing an overview of the key aspects to consider when formulating the overall research methodology are the *research onion* developed by Saunders, Lewis and Thornhill (2019) as shown in Figure 3.1, and the *trunk of the tree* by Easterby-Smith et al. (2021) shown in Figure 3.2.

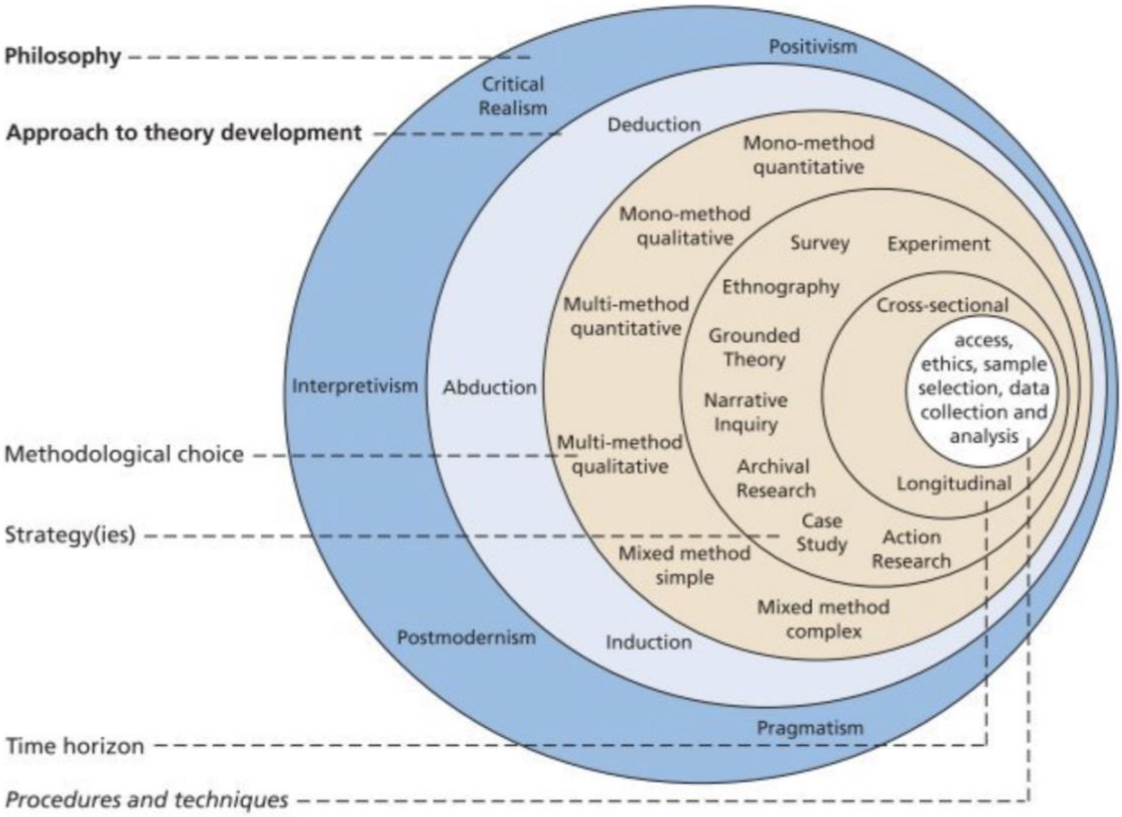


Figure 3.1 The research onion (Saunders, Lewis and Thornhill, 2019)

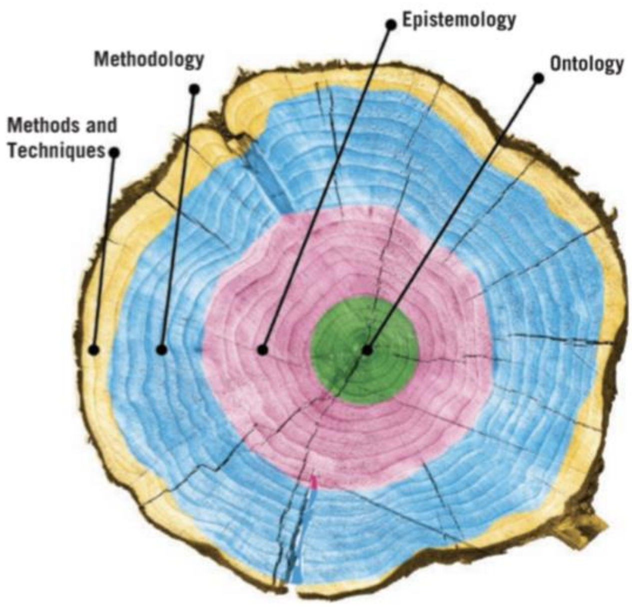


Figure 3.2 The trunk of the tree (Easterby-Smith et al., 2021)

Comparing the two models, it can be noted that they incorporate similar categories, however these categories are inverted in their position. Whilst the research onion works from the outside to the inside and with each layer taken away you process with the research methodology, the tree trunk model works the exact other way around; from the inside to the outside. It could be argued that the research onion is an extension to the tree trunk due to providing more detail to the four categories from the tree trunk and further categories, like the approach to theory development. The ontology and epistemology of the tree trunk are elements of research philosophy which is reflected in the research onion. Methodology in the tree trunk is like the methodological choices in the research onion, methods and techniques of the tree trunk are reflected in the strategies, time horizon and procedures and techniques.

Both models work with the basis that the research will be founded on assumptions (Easterby-Smith et al., 2021). These models are used as a basis to structure the methodology development for this research. First the focus of section 3.4 will be on the philosophical assumptions, including the ontology and epistemology. Then the methodology for conducting the research will be discussed in section 3.5. This is followed by outlining the research approach in section 3.6.

3.4 Philosophical Assumptions

An important part of the research approach is the research philosophy which is concerned with the assumptions and beliefs in the process of developing new knowledge (Saunders, Lewis and Thornhill, 2019). The research philosophy helps to create the research design appropriate to specific research projects (Easterby-Smith, Thorpe and Jackson, 2012). Often researchers may follow previous research methods without diving deeper into the research philosophy and to reflect on the process of the research. This potentially limits the research quality as well as prohibiting researchers to unfold their creativity (Easterby-Smith, Thorpe and Jackson, 2015). This highlights the importance of the research philosophy in creating new knowledge. The models in Figures 3.1 and 3.2 show that the research philosophy is the first area to focus on when developing the research methodology. The research philosophy entails different factors, such as the ontology and epistemology.

3.4.1 Ontology

As shown in Figure 3.2, the ontology forms the central part of research design and it is often the first to be discussed under research philosophy (Easterby-Smith, Thorpe and Jackson, 2015). Saunders, Lewis and Thornhill (2023) introduce ontology as the assumptions on how researchers see and study their data, referred to as the assumptions on reality nature.

According to Easterby-Smith, Thorpe and Jackson (2015), there are different types of ontology, all of which include their own aspects of truth and facts; Realism, Internal Realism, Relativism, Nominalism. These ontological positions can be placed on a continuum from Realism to Nominalism.

In Realism, there is only one truth in which facts exist that can be uncovered (Easterby-Smith, Thorpe and Jackson, 2015). In addition, in internal realism truth exists that cannot be easily understood and is rather a hidden truth, however, there are distinctive facts that are not enabling direct access (Easterby-Smith, Thorpe and Jackson, 2015). In contrast, in relativism there are various truths and the facts are dependent on an individual's viewpoints. Lastly, in nominalism there is no truth, and the facts are based on how individuals shape them.

Reviewing the types of ontologies discussed above, it can be concluded that the ontology applicable to this research is relativism. With regards to the continuum of ontology, this research is more towards the internal realism side of relativism.

Why Relativist Ontology is suitable for this research?

The aim of the research is to apply, test and further develop a structured framework for wicked and complex problems in different domains. Testing a structured framework is dependent on the cases of analysis chosen and the viewpoints at a given moment in time, which explains the use of a relativist ontology. Furthermore, Rittel and Webber (1973) highlight the lack of a clear formulation of wicked problems, which adds to the relativist ontology being most suitable due to definition of the problem being dependent on those defining it. The viewpoints in the analysis will be built based on information available at this moment that must be uncovered, which is where internal realism comes in. The relativist ontology will be reflected in the discussion of section 3.5, the methodology and section 3.6, the research approach.

3.4.2 Epistemology

Epistemology is about understanding how we think about knowledge (Saunders, Lewis, and Thornhill, 2019). It looks at how we interact with the world and explains how we know what we know (Easterby-Smith, Thorpe, and Jackson, 2015). There are two main types of epistemology: positivism and social constructionism (Easterby-Smith, Thorpe, and Jackson, 2015). Since 1980, there's been a shift from positivism to constructionism, though some studies mix both approaches (Easterby-Smith, Thorpe, and Jackson, 2015). Positivism focuses on explaining things objectively, aiming to measure specific factors without letting personal opinions affect the results (Easterby-Smith, Thorpe, and Jackson, 2015; O'Gorman and MacIntosh, 2015). On the other hand, social constructionism emphasises how people, through sharing experiences, work together to build a shared understanding of reality (Easterby-Smith, Thorpe, and Jackson, 2015). Social constructionism is sometimes also called interpretivism or interpretive methods (O'Gorman and MacIntosh, 2015).

There are more factors that distinguish the positivism epistemology from the social constructionism epistemology. Easterby-Smith et al. (2021) have developed a table to outline these differences, shown below in Table 3.1:

Table 3.1 Research Epistemology

	Positivism	**Social Constructionism**
Researchers	Must be independent	Are part of what is being observed
Human Interests	Should be irrelevant	Are the main drivers of science
Explanation	Must demonstrate causality	Aim to increase general understanding of the situation
Research Progress through	Hypothesis and deductions	Gathering rich data from which ideas are induced
Concepts	Need to be defined so that they can be measured	Should incorporate stakeholder perspectives
Units of Analysis	Should be reduced to the simplest terms	May include the complexity of 'whole' situations
Generalisation through	Statistical probability	Theoretical abstraction

Sampling requires	Large numbers selected randomly	Small numbers of cases chosen for specific reasons

In the context of wicked problems, the factors identified above are reflected within them. The complexity of whole situations in the units of analysis is reflected in wicked problems in their consideration to be symptoms of further problems (Rittel and Webber, 1973). In addition to this, human interests are foundational for wicked problems, they are not irrelevant due to the rigid guidelines for approaching them.

Based on the evaluation of these differences between positivism and social constructionism, the epistemology that fits for this research is social constructionism. This will be further discussed in the section below.

Why Social Constructionist Epistemology is suitable for this research?

Several of the points in the outline of positivism and social constructionism make it clear that social constructionism is applicable to this research. The units of analysis are pointed out as including the complexity of whole situations. This links directly with the idea of wicked and complex problems, acting as complex whole situations. Sampling also fits with social constructionism, as for this research a dedicated number of case studies are chosen due to the specific characteristics that they have enabling the gathering of rich data. The social constructionist epistemology will be reflected in the discussion in section 3.5, on the methodology, and section 3.6, the research approach.

3.5 Methodology

Understanding the philosophical background for this research, the relativist ontology and the social constructionist epistemology, helps in the justification of the appropriate methodology design. The aim of the research is: To apply, test and further develop a structured framework for wicked and complex problems, in supply chain and engineering domains, which have been subject to degrees of decomposition. To approach this aim and to answer the research questions developed as a result of the literature gap found through the literature review in the previous chapter, the appropriate framework needs to be discussed. This will be the focus of the following sections.

3.5.1 Introducing the Framework

A framework from the literature has been adapted to help the classification and solving of complex problems, also known as wicked problems, through four steps. The research of Alford and Head (2017) and Roth and Senge (1996) have formed the basis for the development of the four analysis steps.

Alford and Head (2017) developed a typology for differentiating between types of wicked problems. In their research, they have reviewed previous developments in the field of wicked problems and identified weaknesses. The Alford and Head (2017) typology focuses on two aspects that are to be considered with problems, which is the problem itself and the stakeholders involved with the problem. As shown in the Figure 2.2, which pictures the 9-box model by Alford and Head (2017), these two aspects are divided into three dimensions. For the problem itself, shown on the y-axis, the first dimension is when the **problem is clear** and the **solution is clear**. The second dimension is when the **problem is known**, however the **solution is unknown**. The final dimension is when neither the **problem nor the solution are known**. For the stakeholders, shown on the x-axis, the three dimensions are: 1) Knowledge and interest are shared between stakeholders, 2) knowledge is fragmented across stakeholders making it difficult to have a holistic overview, however stakeholders agree on the problem and possible solutions, 3) knowledge and interests are fragmented across stakeholders.

Putting these dimensions together on a diagram, there are nine outcomes, categorising each problem by a degree of wickedness. For both aspects, the first dimension points towards a tamer problem and as it increases to the third dimension, the problem becomes more complex and wicked.

3.5.2 Framework Positioning Steps

Based on systematising the narrative guidance provided in the research by Alford and Head (2017) and Roth and Senge (1996), four steps are suggested to position problems on the typology of Alford and Head (2017). The first step focuses on the initial logic of where the project fits onto the typology. In the second step, the position of the problems is tested against a set of criteria, summarised from the previous work of Alford and Head (2017) and Roth and Senge (1996). The criteria are based on the two aspects of problems, the problem itself in the problem complexity and the stakeholders involved in the stakeholder difficulty factors. The overall concepts behind these criteria come from the literature by Alford and Head (2017) and Roth and Senge (1996), but the consolidation and written out questions found below have been developed as part of the methodology process for this research. Table 3.2. below shows the set of criteria for the second analysis step.

Table 3.2 Step 2 Problem Complexity and Stakeholder Difficulty Factors	
Problem Complexity Factors	1. Is there a clear and unambiguous definition of the problem?
	2. Is the nature of the problem agreed and accepted by all stakeholders?
	3. Is the problem accepted as a technological one?
	4. Is the problem accepted as one of organisational and leadership setup?
	5. Does the problem extend beyond technology, organisation and leadership?
	6. Is the viable solution available?
	7. Has a clear and accepted solution or approach been agreed?
	8. Is there a known / defined relationship between actions and outcomes?
	9. Is there a clear and demonstrable relationship between assumed cause of the problem and resulting effects?
Stakeholder Difficulty Factors	1. Are the stakeholders involved with developing the solution acting in cooperation?
	2. Are the stakeholders who will need to accept and implement the solution known?
	3. Are the stakeholders who will need to accept and implement the solution acting in cooperation?
	4. Does the sum of knowledge needed to resolve the problem reside within a single party? (i.e. can the problem be addressed within a single organisational unit (team, plant, company, etc.)?)
	5. Are multiple parties, with potential or actual conflicts of interest, needed to address the problem? (where multiple parties are required is there inherent difficulty in co-operation?)
	6. Are there diverse values, mental models, aspirations among decision makers?
	7. Does deep conflict exist in assumptions and beliefs?
	8. Do people share underlying values which can drive common perspectives and alignment in their actions?

For the third step of positioning, different factors around the problem affecting the categorisation into the problem type are discussed by Alford and Head (2017), indicating that if more conditions apply to a problem, they increase in wickedness. Some factors are focused on the problem and others on the stakeholders involved. The criteria proposed by Alford and Head (2017) used in the third step for positioning problems are shown in Table 3.3 below.

Table 3.3 Step 3 Problem Focused and Stakeholder Focused Criteria

Problem Focused Criteria	
Structural complexity	Is there inherent intractability of the technical (ie non-stakeholder-related) aspects of the problem?
Knowability	Is there little knowledge about the issue? Is relevant information hidden, disguised or intangible? Does it comprise multiple complex variables? Do its workings require action to discover causal links and outcome?.
Knowledge-framing	Does some of the knowledge receive either too much or too little attention because of the way it is framed, thereby distorting our understanding?
Stakeholder Focused Criteria	
Knowledge fragmentation	Is the available knowledge fragmented among multiple stakeholders, each holding some but not all of what is required to address the problem?
Interest-differentiation	Do the various stakeholders have interests (or values) which are substantially in conflict with those of others?
Power-distribution	Is there a dysfunctional distribution of power among stakeholders?

By contrast, a problem is more likely to be tame if it is knowable, the knowledge is publicly shared or accessible, there are no deep conflicts of interest among stakeholders, and power is well distributed.

In the fourth and final step the position of the problems are checked again on their relative position to each other and the two axes. The research from Roth and Senge (1996) has been used as a basis for this. The overall concept on these problem comparison questions comes from the work by Roth and Senge (1996). This work has been reviewed as part of the methodology development for this research and the questions formulated below are the result of this. Table 3.4 below shows the criteria for the fourth analysis step.

Table 3.4 Step 4 Problem Comparison Questions
Step 4 Roth and Senge (1996) Problem Comparison Questions
1. Are the issues generic (rather than specific to one company or industry) and what is the potential impact?
2. Are critical stakeholders engaged in the problem and / or its solution?
3. Do people involved foresee difficult change issues (seem impossible to surmount)?
4. Can the impacts be leveraged and diffused widely beyond the primary application?
5. Can leaders in organisations engaged in the project take action, or form teams to take action regarding the issues addressed?
6. Does past research provide a foundation of prior theory, acting as a starting point?

The position of the problem on the typology framework following these positioning steps indicates some actions that can be taken in order to approach the problem.

The four steps introduced above provide a comprehensive positioning process for wicked and complex problems. Going through a written-out format of this with the four steps and the detail included under these four steps is difficult to follow. As a result, it has been decided to consolidate this into a complexity classification card format, following the idea of a scorecard. This will provide a structure to the positioning and the reasons behind this through providing a clearer overview. Further discussion of this can be found in Chapter 4 under section 4.2.

3.6 Research Approach

3.6.1 Case Study Research

The aim of this research is to apply, test and further develop a structured framework for wicked and complex problems, in supply chain and engineering domains, which have been subject to degrees of decomposition. The suitable research approach for this aim is a case study, which is concerned with answering questions on the "how" and "why" (Benbasat, Goldstein and Mead, 1987; Yin, 2003). They enable intensive and in-depth analysis of specific real-life cases to further develop theory, test theory or build theory (Yin, 1994; Yin, 2018). This is further supported by Dooley (2002) who argues that case study research is often seen as a method for applying or implementing theory. This emphasises the applicability of a case study approach to the development of the structured framework for wicked and complex problems.

Case studies can be structured in different ways, such as a single case, multiple cases, a holistic case and an embedded case as suggested by Yin (2018). A single case may be chosen because of the significance of a specific case and going deeper into this, multiple cases may be chosen to enable replication of findings between cases or to examine findings in cases that are purposely different. (Yin, 2018). The choice between a single case and multiple cases can be based on choosing between the depth of the research, focusing on a single case, and breadth of the research, focusing on multiple cases (Easton, 1995). The unit of analysis may be determined with choosing holistic cases or embedded cases (Saunders, Lewis and Thornhill, 2023). In holistic cases, the focus is on exploring the entirety of a specific case, such as a whole organisation, whereas in embedded cases specific sub-themes are chosen for analysis (Yin, 2018).

Data collection for case studies is relatively open and can include both qualitative and quantitative data (Saunders, Lewis and Thornhill, 2023). Examples of the data used in case studies are surveys, questionnaires, interviews and document analysis (Dooley, 2002). There is a focus on the analysis of documents and reports for this research. This is supported by the framework introduced above which provides a clear structure to classifying problems through a set of four steps. Case studies with associated theory profit from having a dedicated structure (Weick, 1979).

3.6.2 Case Studies Chosen

To understand whether the framework introduced above will help the approach of complex problems, two cases with different characteristics to them will be analysed as lined out using the four steps. This analysis is conducted by each of the research group members and the supervisors of this thesis. Subsequently the individual analyses are reviewed. This has been done to minimise bias in the positioning of problems onto the framework. The cases are chosen due to their clear link to wicked and complex problems such as climate change. In addition to this, the cases are related to research, providing an insight into supply chains for climate change and engineering developments. Another reason for choosing these cases over live cases are the lockdown restrictions in the Covid-19 pandemic in which this research has started. Furthermore, the cases engaged a wide range of stakeholders, which is a difficult to achieve in the restrictions of a lockdown. The first case study, introduced in section 3.6.2.1

below, is a report published through the EPSRC funded research programme UK FIRES (Allwood et al., 2019), focusing on resource efficiency in the future industrial strategy of the UK. This case study is used to test the framework and further develop it. The second case study, introduced in section 3.6.2.2 below, is a roadmap on electrical machines for 2050 published by the Future Electrical Machines Manufacturing (FEMM) Hub (Ward et al., 2023). This case study is used to validate the developed framework.

3.6.2.1 Absolute Zero by UK FIRES

In the analysis of the first case, the focus is on testing the framework and its applicability. To do this, the report by the UK FIRES research group called *Absolute Zero* (Allwood et al., 2019) is used where the focus is on the actions that are necessary to reach absolute zero emissions by 2050 using the technologies that are already available. UK FIRES is a consortium of universities across the UK made up of: University of Cambridge, University of Oxford, The University of Nottingham, Imperial College London, University of Bath, and University of Strathclyde. The *Absolute Zero* report was written by a multidisciplinary research group of high-profile academics at the start of the programme, prior to the Covid-19 pandemic, and is still possibly the most publicly visible output from UK FIRES, having been debated in the House of Lords in 2020. With the point of view of decomposition, *Absolute Zero* approaches climate change from top down. It starts from net zero and proposes a single level of decomposition which makes it quite unusual in the net zero research context. The report argues to provide a holistic agenda for achieving absolute zero emissions by 2050 through 13 actions that work on the basis of behavioural change and avoiding techno-optimism. Through a critical analysis, the different actions suggested in the *Absolute Zero* report will be mapped onto the framework using the four steps as discussed. As *Absolute Zero* focuses on the path of the UK for reaching absolute zero, the analysis will also take a main UK focus. The analysis will help to uncover whether breaking the complex problem of achieving Absolute Zero into 13 smaller sub-problems will help to overcome the overall problem. The 13 sub-problems in *Absolute Zero* provide a good number of sub-cases for analysis and hence a rich data set. In the literature, climate change is often discussed as a wicked problem or even a super-wicked problem. Due to being labelled as a wicked problem, taking action against it is often seen as too difficult as there is no clear direction on where to start. Breaking down this problem into 13 actions as proposed in the *Absolute Zero* report starts to put different directions out as to where actions can be taken to approach the problem. However, the actions in the *Absolute Zero* report are provocative, as will be clear when going into detail on the actions proposed.

3.6.2.2 Electrical Machines Roadmap for 2050 by FEMM Hub

Following the testing of the framework by applying it to the *Absolute Zero* Report, a subsequent analysis is carried out using the roadmap on electrical machines published by the FEMM Hub. The reason for the application of the adapted framework from the first case study is to confirm this. The FEMM Hub is a consortium of universities made up of: University of Sheffield, University of Strathclyde, Newcastle University and University of Bristol. The electrical machines roadmap was developed mid-way through the ongoing research of the FEMM Hub. In contrary to the *Absolute Zero* Report, the roadmap tackles decomposition for engineering from the bottom up. The roadmap is more engineering and technology focused and is based on several pillars for electrical machines for 2050, such as defining high level needs, supply chain responses and technical improvement factors. Rather than focusing on behavioural change and avoiding techno-optimism like in *Absolute Zero*, the roadmap looks at technology development necessary for electrical machines and argues that electrical machines will play a major role for moving towards net zero. Part of the roadmap also focuses on sustainability and the circular economy. With the motivation of the research project stemming from net zero and going into wicked and complex problems, the section of the roadmap on sustainability and the circular economy is the one most applicable to this research.

The reason for the testing of the framework with further application for confirmation is confirmed by the literature. Dubois and Gadde (2002) argue that a framework is expected to develop throughout a study due to analysis and research providing deeper viewpoints. The analysis of the second case studies acts as a vehicle to evaluate the revision of the framework proposed as a result of the first case study. Regarding the holistic or embedded categorisation of case studies outlined in the previous section, it could be argued that the first case is more a holistic case and the second one embedded. In the first case, one whole report is undergoing analysis, whereas in the second case a specific theme of the report, sustainability and circular economy, is used in the analysis.

The cases provide a comprehensive overview and outlook relevant to the research aim and objectives. Based on this, the analysis of these two reports is sufficient for gathering rich data for the testing and further development of the framework, through the process of the four steps.

3.7 Summary

In this chapter the methodology for approaching the research aim and objective as well as the research questions has been outlined. The first step for this was to determine the philosophical assumptions, clearly linked to the philosophical concept of wicked problems. The ontology underpinning this research is relativism due to testing the structured complex and wicked problems analysis framework being dependent on the cases of analysis chosen with the viewpoints at this moment in time based on the information available currently. The lack of a clear outline of wicked problems reinforce this. The epistemology applicable is social constructionism, for example due to the focused choice of the two case studies and theoretical elements. This is further supported by the wicked problem characteristics outlined by Rittel and Webber (1973), where human interests are important and the interconnectedness of wicked problems. With the philosophical assumptions clearly defined, the research methodology has been outlined with the introduction of the structured framework, that is suggested to aid approaching wicked problems, and its four steps to classify problems according to their wickedness or complexity. Following this the research approach has been discussed with case studies forming the basis. The justification for a case study approach has been given, as well as for the case studies chosen due to their different characteristics and providing a clear link to the research on wicked and complex problems.

Chapter 4 – Case Study: UK FIRES *Absolute Zero* Report

4.1 Introduction

The research methodology for working towards the aims and objectives has been outlined in the previous chapter. The purpose of this chapter is the testing of the framework brought forward by applying it to the UK FIRES *Absolute Zero* Report. This will highlight areas of development of the framework for improvement which will be the result of this chapter.

4.2 Introduction to testing the framework

To understand whether the framework introduced in the previous chapter helps the approach of complex problems a report published through the EPSRC funded research programme UK FIRES, focusing on resource efficiency in the future industrial strategy of the UK, is analysed and used as a case study in this chapter to test the framework. In the report called *Absolute Zero* (Allwood et al., 2019), the focus is on the actions that are necessary to reach absolute zero emissions by 2050. The premise the *Absolute Zero* Report is built on is that of a period of constraint and the economic impact of this that is required to enable absolute zero by 2050. This gives time for further developing technologies that can be deployed for 2050 without causing a further CO_2 impact. The *Absolute Zero* Report is relevant for the research of this thesis for various reasons:

- It deals with the wicked problem of decarbonisation and addresses this via a process of decomposition.
- The decomposed solutions still have some of the characteristics of wicked problems and would be political challenging.
- Most of the proposed measures have supply chain implications which links back to the origin of the research on supply chains.
- *Absolute Zero* also results from a research study which fits the scope of this analysis.

Through a critical analysis, absolute zero and the different actions suggested in the UK FIRES report are mapped onto the framework as discussed. As the report focuses on the path of the UK for reaching absolute zero, the analysis mainly takes a UK focus. The analysis uncovers whether breaking a complex problem into smaller sub-problems helps to overcome the overall problem. This process of breaking down problems into sub-problems is being brought forward as a definition of decomposition from this thesis. In the literature, climate change is often discussed as a wicked problem or even a super-wicked problem. Due to being labelled as a wicked problem, approaching it is often seen as too difficult as there is no clear direction on where to start. Decomposing this problem into 13 actions, as proposed in *Absolute Zero*, starts to put different directions out as to where actions can be taken to approach the problem. *Absolute Zero* suggests that if all 13 actions are addressed, net zero, as required under UK Legislation, will be achieved.

The actions proposed in the *Absolute Zero* report to approach the complex problem of absolute zero by 2050 are outlined in Table 4.1 below (Allwood et al., 2019).

Table 4.1 Absolute Zero Actions	
1. Road Vehicles	Transition of traditional petrol and diesel engines to electric, lighter vehicles.
2. Rail	Rail to grow as substitute for domestic and international flight, electric trains and dominant method for freight.
3. Flying	Closing of airports until 2050. After 2050 new sustainable ways of flying.
4. Shipping	There are currently no freight ships operating without emissions, so shipping must contract and stop until 2050.
5. Heating	Gas boilers replaced by electric heat pumps and buildings retrofitted, heating reduced to 60% of today's use, can be increased as supply of non-emitting electricity expands.
6. Appliances	Home appliances become smaller and electrified to reduce power requirement to use 60% of today's energy. Can be changed with increasing supply of non-emitting electricity.
7. Food	Consumption of beef and lamb phased out as well as imports not transported by trains. Energy required to cook or transport food reduced to 60% and when zero-emission electricity availability increases, the energy required for this can also increase.
8. Mining and material sourcing	Iron ore and limestone phased out, metal scrap supply chain expands, demand for scrap steel and ores for electrification rises.
9. Materials Production	Increasing steel recycling, cement and emitting plastics phased out, as well as new steel.
10. Construction	Focus on retrofit and adaption of existing buildings. Conventional mortar and concrete phased out. Buildings optimised for material saving.
11. Manufacturing	Material supply contracts, goods made with 50% of material, new design and manufacturing practices.
12. Electricity	Wind and solar grow as quick as possible, non-electrical motors and heaters phased out, all energy supply by 2050 will be non-emitting.
13. Fossil fuels	Fossil fuels phased out, development of carbon capture and storage may allow resumption of use of gas and coal for electricity.

Absolute Zero has decomposed the acknowledged problem of climate change with absolute zero emissions into 13 actions to help overcome the seemingly impossible to solve challenge. The analysis of the report with the introduced framework is aimed at examining whether the wicked problem of absolute zero remains wicked when decomposed into these 13 actions or whether it becomes more approachable.

Absolute Zero provides a system level analysis and works on the assumption that through the implementation of all these 13 actions proposed, absolute zero emissions will be achieved. The 13 actions become problems when looking into the ways of adopting them, based on the *Absolute Zero* line of thought that there will be no changes in technology, but rather people are required to change their behaviour. This is when the 13 actions become problems of acceptance and adoption, and there are problems around getting compliance with the 13 actions. As a result of this, the 13 propositions are used as problems of adoption to position onto the framework introduced in the previous section, according to the four positioning steps. For enabling a meaningful analysis of the framework, the *Absolute Zero* Report is used with a contextual assessment of the 13 problems. The aim of this is to test the methodology of the framework rather than providing an exhaustive analysis of *Absolute Zero.*

Appendix 1 shows an example of the fully documented analysis of problem 1 on Road Vehicles from the *Absolute Zero* Report. The analysis was conducted according to the positioning steps developed in Chapter 3 and spans across nine pages. This example shows that when the analysis is conducted in a written format, it is difficult to compare positions of problems against each other, for example based on the length of analysis. This led to adapting the research method to try to find a more consolidated and visual overview of the analysis steps. Furthermore, it was found that step 1 of the analysis of *Absolute Zero* can also be used as a summary step. This is because step 2 is an extension of step 1, whereby further detail is used in step 2. Therefore, step 2 is used as the main step for finding the positioning of problems onto the framework. Reviewing the methods discussed in the literature review, the balanced scorecard came to mind as an example for creating a visual overview of the steps for analysis here. This led to the idea of the *complexity classification card*, as a more consolidated approach which still includes the points from the four steps. The complexity classification card is a key improvement to the previous written out method, as it enables to follow the analysis more clearly through providing a more concise display of the analysis. Each problem is analysed individually and displayed in a consolidated format with the *complexity classification card*. Since step 4 is concerned with a comparison of problems against each other it can only be used at the end of the analysis of all 13 problems.

4.2.1 New Analysis Procedure

To have a clear overview of the analysis following its modification, a summary of the new analysis procedure is provided here. The first step is a summary step, introducing the problem and providing an overview of the key considerations for the problem in question. This step is applicable throughout the analysis of the individual problems. This is also the case for Step 2 which remains unchanged from the original steps. It offers a detailed analysis of the problem with the two aspects important to consider: the problem itself and the stakeholders involved with it. Step 3 is concerned with factors of categorising the problem into the different problem types on the framework. Again, they are focused on the problem and stakeholders involved with it. Step 3 is also used throughout the analysis of the individual problems. Step 4 is used once all the problems have been analysed with the three previous steps. It compares the position of problems relative to each other and therefore can only be used for analysis following the introduction of all problems up until this point. Step 2 and Step 3 are displayed on the complexity classification card. An example explaining the set-up of this is shown in Table 4.2 below.

Table 4.2 Example Complexity Classification Card

Problem Title

Outline: Brief outline of problem

Step 1: Summary Evaluation

Summary of key factors of problem

Table to examine position of problems on 9-Box framework using Problem Complexity and Stakeholder Difficulty Criteria. Criteria divided into level of importance for problem positioning.

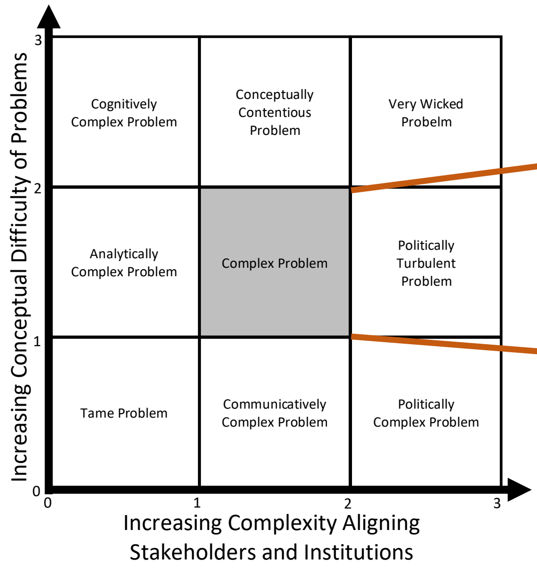
9-Box Model where box in which the problem for classification sits shown by colouring in the box grey.

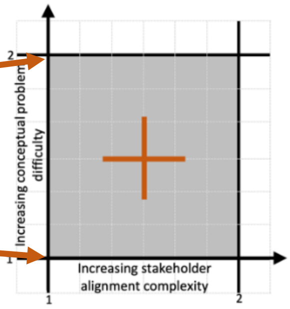
Problem Complexity Overview

Written analysis to provide foundation for problem complexity criteria classification.

Stakeholder Difficulty Overview

Written analysis to provide foundation for stakeholder difficulty criteria classification.





Zoomed in view of box in which problem sits to show exact position and extent of problem with length of lines based on factors from table of step 3. below.

Table examining problem and stakeholder factors for determining extent of problem. Classified into low, high, and medium used for length of lines.

Step 2: How Complex is the Problem?

Problem complexity criteria	Problem complexity slider (Low / High)	Stakeholder difficulty criteria	Stakeholder difficulty slider (Low / High)
Clear and unambiguous definition	X	Stakeholders developing solution cooperating	X
Stakeholder agreement and acceptance	X	Stakeholders to accept and implement solution known	X
Technological problem	X	Stakeholders to accept and implement solution cooperating	X
Organisational and Leadership problem	X	Knowledge for resolving problem in one party	X
Beyond technology organisation and leadership	X	Multiple parties needed to address problem	X
Viable solution	X	Diverse values in decision makers	X
Solution agreed	X	Conflict in assumptions and beliefs	X
Defined relationship between actions & outcomes	X	Shared values	X
Relationship between cause and effects	X		

Step 3: Problem Extent – How big is the problem?

Problem Factors	Impact on problem extent	Stakeholder Factors	Impact on stakeholder extent
Structural Complexity	Low	Knowledge Fragmentation	Low
Knowability	Medium	Interest differentiation	Medium
Knowledge Framing	High	Power distribution	High

Overview: Written analysis to provide basis for problem extent.

Overview: Written analysis to provide basis for stakeholder extent.

4.2.2 Description of Complexity Classification Card Set-Up

The criteria of step two are visualised in a table to the bottom left of the complexity classification card, titled '*Step 2: How Complex is the Problem?*' and displayed with a slider to show the problem complexity. This provides the basis of individual complexity indices $IC_{1..N}$, where N is the number of individual complexity criteria and stakeholder difficulty indices, $ID_{1..M}$, where M is the number of individual stakeholder criteria. Furthermore, they are assessed based on level of importance (shown in the card by colours: green criteria are of critical importance, amber criteria are of moderate importance and red shows neutral criteria) which can be used to attach individual weight factors for complexity $WC_{1..N}$, and difficulty $WD_{1..M}$,. The level of importance of each criterion has been determined by the key factors that impact the problem under analysis and the criteria that these key factors fit into. The decision on the level of importance displayed in the analysis has been a collective decision from the research group with the supervisory team of this thesis. The green criteria take the most weight for the position of the problem, with the amber taking less weight in this. The red criteria are neutral for positioning. The classification of the criteria in the table is used to position the problem into one of the nine boxes on the framework which is then coloured in grey. This table also determines the exact position of the problem within the box, shown by where the two lines on the zoomed in box meet. A written overview of the problem complexity and stakeholder difficulty criteria is provided following this table in two boxes to the top right of the complexity classification card.

The slider positions and colour alignments map directly to the aggregate scores for the specific criteria for the problem under analysis. Some of the criteria when clearly present indicate a high complexity, whilst others indicate a low problem complexity. The problem complexity can be classified as lower if:

- the problem is clear and has an unambiguous definition,
- stakeholders are in agreement and acceptance of the problem,
- there is a viable solution,
- the solution is agreed,
- there is a defined relationship between actions and outcomes and
- there is a relationship between cause and effect

The problem complexity is higher if:

- the problem is technological,
- it is an organisational and leadership problem, and
- the problem goes beyond technology, organisation and leadership

For the stakeholder criteria there is a similar split between ones indicating a lower stakeholder difficulty and ones indicating a higher stakeholder difficulty when characteristics of problems. Stakeholder difficulty is lower when:

- stakeholders developing the solution are cooperating,
- stakeholders to accept and implement the solution are known and cooperating,
- knowledge for resolving the problem is within one party, and
- stakeholders have shared values

Stakeholder difficulty is higher when:

- multiple stakeholders are needed for addressing the problem,
- there are diverse values and conflicting assumptions in beliefs

These criteria for high stakeholder difficulty and high problem complexity are inverted in their positioning to enable the aggregation of the scores together with the low impact scores.

Based on aggregate weighted problem complexity scores as follows

$$Aggregate\ Problem\ Complexity = \frac{\sum_{i=n}^{N} IC_i WC_i}{N}$$

and aggregate weighted stakeholder difficulty scores

$$Aggregate\ Stakeholder\ Difficulty = \frac{\sum_{j=m}^{M} ID_j WD_j}{M}$$

Another table to the bottom right of the complexity classification card, titled '*Step 3: How Problem Extent – How big is the Problem?*' is used to show the criteria of step 3 for determining the extent of the problem. The impact of the criteria is divided into low, medium and high. To emphasise the problem extent of the points under analysis, this impact is attributed to impact ranks 0, 1, 3 and 9, often used by six sigma practitioners (Praxie, 2024). These impact ranks are matched with the impact classification to magnify the effect, low is 1, medium is 3 and high is 9. These individual impact ranks are attributed a specific line length which is then added up and used for visualising the extent of the problem. This is shown in the zoomed in version of the box in the framework. The longer the line, the higher the impact on the problem aspect in question. A written overview below this provides a foundation for analysis with the problem and stakeholder factors to determine their extent on the problem under analysis.

Similar to the step 2 criteria, there is a split in the step 3 criteria for ones indicating a negative impact on the problem and stakeholder extent, and others having a positive impact. When structural complexity, knowledge framing, knowledge fragmentation, interest differentiation and power distribution are present, they have a negative impact on the stakeholder and problem criteria. Only the Knowability criteria indicates that when there is knowledge on a given topic, the impact on the problem extent will be lower. The Problem Factors Impact are represented by PI_k, Stakeholder factors impact is represented by SI_l. The weighted impact is shown by WI_k and WI_l, with U representing the problem impact criteria and V the Stakeholder Impact criteria.

$$Aggregate\ Problem\ Impact = \sum_{k=1}^{U} PI_k WI_k$$

$$Aggregate\ Stakeholder\ Impact = \sum_{l=1}^{V} SI_l WI_l$$

The modified analysis procedure and the complexity card are used in the following pages for the analysis of positioning absolute zero and the 13 problems from *Absolute Zero*. The analysis on the following pages is the result of a collective exercise with the analysis that was conducted by the individual research group members with the supervisory team for this thesis.

4.3 Testing the Framework

Table 4.3 Complexity Classification Card Absolute Zero

4.3.1 Absolute Zero

Outline: To cut greenhouse gas emissions to zero.

Step 1: Summary Evaluation

Greenhouse gas emissions are to be cut to zero by 2050, which has been anchored in the UK law (Allwood et al., 2019). In the *Absolute Zero* mindset, technologies of today are used as a basis for approaches to cut emissions based on the assumption that new technologies are not going to have been fully deployed by 2050. Cutting greenhouse gas emissions to zero is a challenge that must encompass the approach from various angles to be achieved. Furthermore, it is based on the cooperation of the UK population to change habits. Electrification is deemed as the solution for absolute zero, listing 13 problems for moving towards this. This points towards the 13 problems being secondary problems of absolute zero. In other words, absolute zero has been decomposed into 13 problems. However, not all the problems listed are able to work with electrification, such as shipping and flying.

Problem Complexity Overview

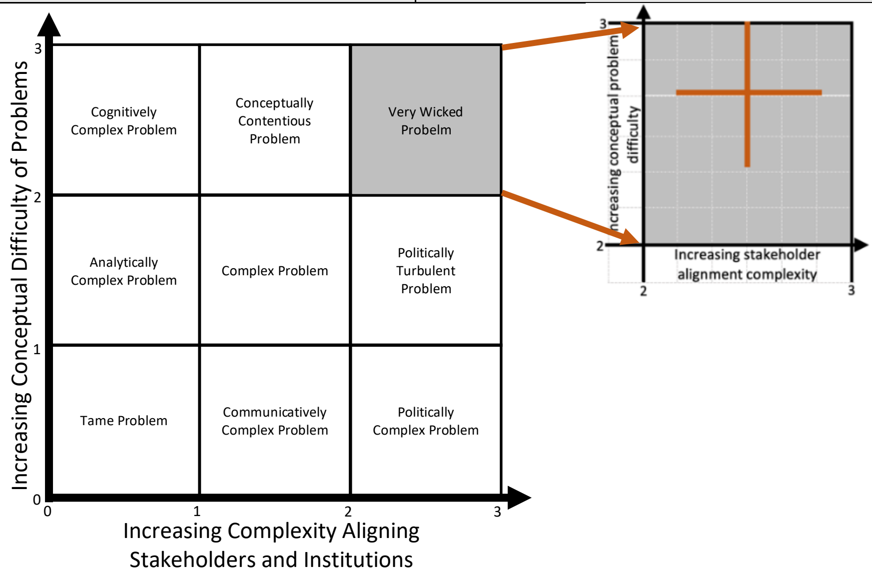
Formulated more like a solution and not a problem. No clear path for achieving this can be directly identified. Element of stakeholder agreement and acceptance with UK law of cutting greenhouse gas emissions to zero, however not with *Absolute Zero* thought which diminishes agreement and viability of solution. Argued that technologies of today are used for absolute zero, indicating limited technological aspect. Organisational and leadership aspects of the problem are given for coordination of activities for secondary problems.

Stakeholder Difficulty Overview

Solution for *Absolute Zero* encompasses various approaches, where overall cooperation of developing solution is limited. Stakeholders for accepting and implementing solution partly known. High reliance of cooperation with population to change habits, diminishing overall cooperation of stakeholders for accepting and implementing solution also based on variety of activities for achieving this. Various parties needed for addressing the problem, indicating diversity of values.

Step 2: How Complex is the Problem?

Problem complexity criteria	Problem complexity slider (Low – High)	Stakeholder difficulty criteria	Stakeholder difficulty slider (Low – High)
Clear and unambiguous definition	X	Stakeholders developing solution cooperating	X
Stakeholder agreement and acceptance	X	Stakeholders to accept and implement solution known	X
Technological problem	X	Stakeholders to accept and implement solution cooperating	X
Organisational and Leadership problem	X	Knowledge for resolving problem in one party	X
Beyond technology organisation and leadership	X	Multiple parties needed to address problem	X
Viable solution	X	Diverse values in decision makers	X
Solution agreed	X	Conflict in assumptions and beliefs	X
Defined relationship between actions & outcomes	X	Shared values	X
Relationship between cause and effects	X		



Step 3: Problem Extent – How big is the problem?

Problem Factors	Impact on problem extent	Stakeholder Factors	Impact on stakeholder extent
Structural Complexity	High	Knowledge Fragmentation	High
Knowability	Medium	Interest differentiation	Medium
Knowledge Framing	High	Power distribution	High

Overview: Complexity of the primary problem is high. Some knowledge on activities required for achieving absolute zero. However, basing approaches solely on electrification as way forward.

Overview: Knowledge fragmented largely across stakeholders due to encompassing various activities for successful implementation. This indicates likelihood of interest differentiation. Each stakeholder holds power for accomplishment of absolute zero.

Table 4.4 Complexity Classification Card Problem 1: Road Vehicles

4.3.2 Problem 1: Road Vehicles

Outline: Transition of traditional petrol and diesel engines to electric, lighter vehicles.
Associated CO_2 Emissions: 99 Mt CO_2 in UK in 2021 (Department for Transport, 2023b).

Step 1: Summary Evaluation

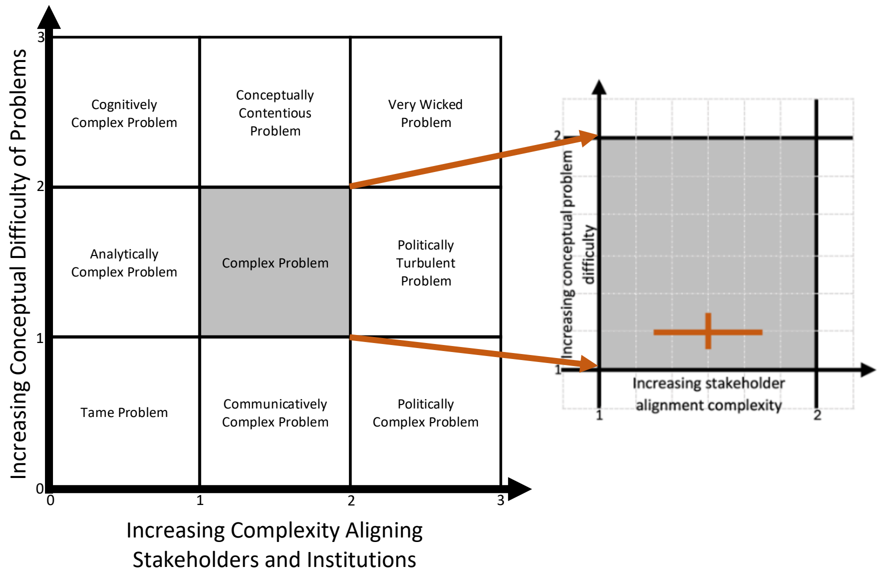
The problem around road vehicles involves stopping the development of petrol and diesel engines with new vehicles to be electric, compatible with absolute zero and reduced in size (Allwood et al., 2019). From this, a problem cannot be clearly defined but rather a set of solutions are displayed. These solutions are: 1. stopping the development of petrol and diesel engines, 2. new electric vehicles, 3. vehicles that are compatible with absolute zero and 4. new vehicles must be reduced in size. In the automotive industry there is a move towards electric vehicles, however there is limited collaboration for this amongst manufacturers. There is a secondary problem around road vehicles, whereby an infrastructure to enable the use of electric vehicles must be ensured. There are various prerequisites for a charging infrastructure, including material availability and availability of electricity. The development of an infrastructure for charging of electric vehicles is prone to a transition period, which would impact the time for implementing the solutions and elongate the process. These types of problems are somewhat different from the secondary problems identified previously, but can be classified as a sub-level of these and are hereby introduced as transition problems.

Problem Complexity Overview

The problem is two-fold; 1. stopping petrol and diesel engine development and 2. new vehicles to be compatible with absolute zero only. Stopping the development of petrol and diesel engines can be done immediately. This would lead to follow-up problems, known as secondary problems. Secondary problems are also associated with absolute zero compatible vehicles, like material availability for manufacturing and the infrastructure for charging.

Stakeholder Difficulty Overview

Amongst stakeholders it is known that cooperation is the core of overcoming this problem. Acceptance of these vehicles by consumers is a central part to this. The knowledge for stopping the development resides in one place, Original Equipment Manufacturers. This is different for developing vehicles compatible with absolute zero, where knowledge is spread amongst stakeholders.



Step 2: How Complex is the Problem?

Problem complexity criteria	Problem complexity slider (Low – High)	Stakeholder difficulty criteria	Stakeholder difficulty slider (Low – High)
Clear and unambiguous definition	X	Stakeholders developing solution cooperating	X
Stakeholder agreement and acceptance	X	Stakeholders to accept and implement solution known	X
Technological problem	X	Stakeholders to accept and implement solution cooperating	X
Organisational and Leadership problem	X	Knowledge for resolving problem in one party	X
Beyond technology organisation and leadership	X	Multiple parties needed to address problem	X
Viable solution	X	Diverse values in decision makers	X
Solution agreed	X	Conflict in assumptions and beliefs	X
Defined relationship between actions & outcomes	X	Shared values	X
Relationship between cause and effects	X		

Step 3: Problem Extent – How big is the problem?

Problem Factors	Impact on problem extent	Stakeholder Factors	Impact on stakeholder extent
Structural Complexity	Low	Knowledge Fragmentation	Medium
Knowability	Low	Interest differentiation	Medium
Knowledge Framing	Medium	Power distribution	High

Overview: Complexity of the primary problem is low. There is a lot of knowledge on absolute zero compatible vehicles already, with some barriers to the solution implementation stemming from secondary problems.

Overview: The knowledge is spread amongst stakeholders. With various stakeholders involved interest differentiation is inevitable. Power distribution is a major factor in this, for example with consumers dependent on developments of car manufacturers.

Table 4.5 Complexity Classification Card Problem 2: Rail

4.3.3 Problem 2: Rail

Outline: Rail to grow as substitute for domestic and international flight, electric trains and dominant method for freight.

Associated CO_2 Emissions: 2.2 Mt CO_2 in UK in April 2022 to March 2023 (Office of Rail and Road, 2023).

Step 1: Summary Evaluation

The problem with rail is focused on growing domestic and international rail to substitute flying and low-occupancy car travel, expanding the railway network and having electric trains as dominant freight while shipping declines. Rather than having a clear definition of the problem, this is a mixture of problems and solutions. The problem seems to be around flying, low-occupancy car travel and freight by shipping, where rail is seen as an alternative. The solution provided is growing domestic and international rail through expanding the railway network and replace freight by shipping with electric trains. This expansion of the railway network would be prone to a transition period though. Furthermore, rail cannot provide a comprehensive alternative to flying though based on various factors, especially on an international level regarding island nations such as the UK. It is recognised that an expansion of the railway network is necessary to enable improvements in railway, however there are some prerequisites that need to be considered for this around material availability and land availability. These can be classified as secondary problems.

Step 2: How Complex is the Problem?

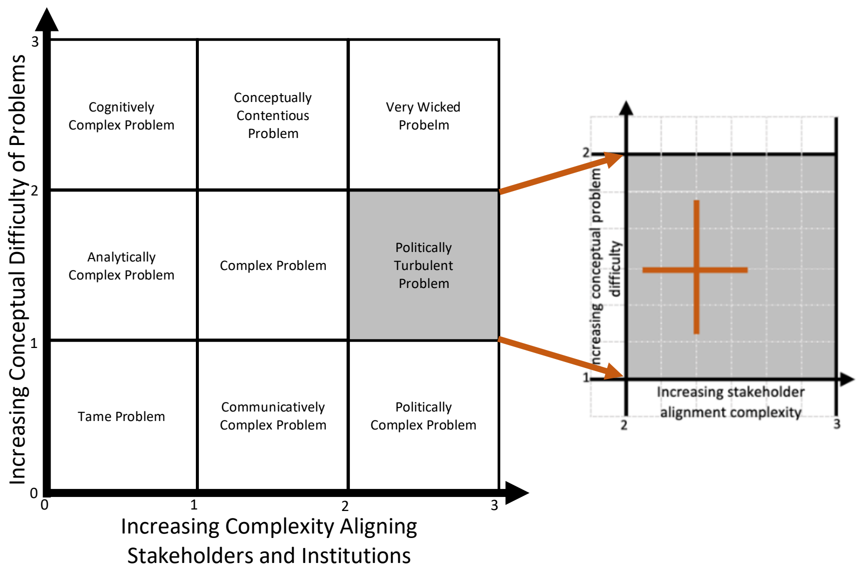
Problem complexity criteria	Problem complexity slider (Low – High)	Stakeholder difficulty criteria	Stakeholder difficulty slider (Low – High)
Clear and unambiguous definition	X (far left, green)	Stakeholders developing solution cooperating	X (far right, green)
Stakeholder agreement and acceptance	X (amber)	Stakeholders to accept and implement solution known	X (far left, green)
Technological problem	X (green)	Stakeholders to accept and implement solution cooperating	X (amber)
Organisational and Leadership problem	X (amber)	Knowledge for resolving problem in one party	X (far right, green)
Beyond technology organisation and leadership	X (far left, amber)	Multiple parties needed to address problem	X (far right, green)
Viable solution	X (green)	Diverse values in decision makers	X (amber)
Solution agreed	X (amber)	Conflict in assumptions and beliefs	X (red)
Defined relationship between actions & outcomes	X (amber)	Shared values	X (amber)
Relationship between cause and effects	X (red)		

Problem Complexity Overview

The problem has several parts to it: rail as a subsitute for low-occupancy car travel, domestic and international flight. Electric trains as substitute for shipping. Key technological challenges. Clear barrier for UK to implement approaches, high reliance on shipping due to geographical reasons. Not planned to implement this outside of *Absolute Zero*, rather thought provoking suggestion. Decrease in CO_2 emissions when replacing short haul flights with rail (Reiter, Voltes-Dorta and Suau-Sanchez, 2022).

Stakeholder Difficulty Overview

Policymakers and providers of alternative transport methods, such as rail, would need to cooperate on this. No plans to completely phase out flying and shipping for rail, so cooperation for enabling this is limited. Knowledge for solving this problem would be split amongst stakeholders, so multiple parties necessary to address problem.



Step 3: Problem Extent – How big is the problem?

Problem Factors	Impact on problem extent	Stakeholder Factors	Impact on stakeholder extent
Structural Complexity	High	Knowledge Fragmentation	Medium
Knowability	High	Interest differentiation	Medium
Knowledge Framing	Low	Power distribution	High

Overview: From a technical perspective it is not possible to replace flight by rail, this has a high complexity. Secondary problems associated with this, such as displacement of populations due to land required for expanding rail infrastructure. This is also a secondary problem, providing an infrastructure for rails relies on external factors such as material availability and has a high problem complexity. Minimal knowledge on implementing solutions for this, which could be explained by abstractness of solution that is not planned to be commercialised.

Overview: There is a controversy around rail wanting to increase business but flight not wanting to decrease. Potentially rather an expansion of rail and flight in the future to provide opportunity for all consumers. Contentiousness weighing out costs with benefits which are deemed to be marginal. Interest differentiation regarding displacement of populations, with populations opposing this expected. Knowledge is split amongst stakeholders, each having the power to stop the implementation.

Table 4.6 Complexity Classification Card Problem 3: Flying

4.3.4 Problem 3: Flying

Outline: Closing of airports until 2050. After 2050 new sustainable ways of flying

Associated CO_2 Emissions: 32 Mt CO_2 for flights departing UK in 2023 (Transport and Environment, 2024).

Step 1: Summary Evaluation

This action point on flying includes closing all airports in the UK by 2050, with no flying at all to take place in 2050. Only after this year there will be a slow uptake of flying with electric planes only. Rather than providing an overview of what the problem is with flying, a solution of closing all airports is proposed as the only way to achieve absolute zero by 2050. When looking at the industry however, there is no sign of stopping flying completely, which suggests that the *Absolute Zero* Report is making a thought-provoking suggestion in a research environment to get readers thinking, rather than making a serious suggestion. When looking at the developments in the area of flying, there are efforts to develop methods of more sustainable flying, rather than aiming to stop completely.

Problem Complexity Overview

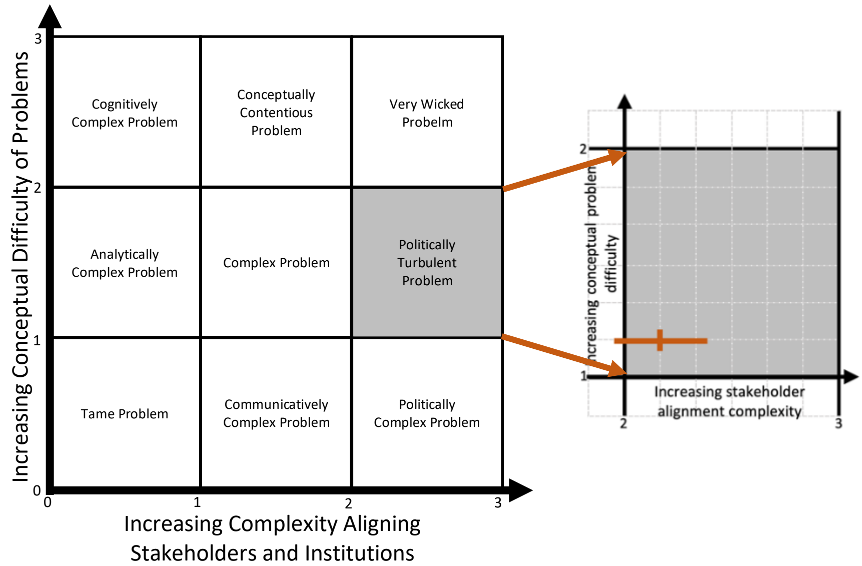
Clear statement of closing all airports and stopping flying. Viable solution that is not discussed outside of *Absolute Zero* and demonstrates the abstraction of this suggestion. No agreement between stakeholders for implementing this. There is also a problem of adoption when thinking about putting this problem into practice. No technological issue of closing all airports. Organisation difficulties for enforcing implementation. Covid-19 showed that with grounding flights, there is a large decrease in CO_2 emissions.

Stakeholder Difficulty Overview

Cooperation expected to be difficult because of opposing stakeholder groups. Enforcement, as in Covid-19, shows possibility of stopping flying. Many stakeholders to accept solution, mainly consumers, which does not affect implementation. Sum of knowledge to close airports rests with airports, so multiple parties for this are not required. Multiple stakeholders affected with secondary problem of alternatives.

Step 2: How Complex is the Problem?

Problem complexity criteria	Problem complexity slider: Low		High	Stakeholder difficulty criteria	Stakeholder difficulty slider: Low		High
Clear and unambiguous definition	X			Stakeholders developing solution cooperating			X
Stakeholder agreement and acceptance			X	Stakeholders to accept and implement solution known			X
Technological problem	X			Stakeholders to accept and implement solution cooperating			X
Organisational and Leadership problem		X		Knowledge for resolving problem in one party	X		
Beyond technology organisation and leadership	X			Multiple parties needed to address problem	X		
Viable solution	X			Diverse values in decision makers		X	
Solution agreed			X	Conflict in assumptions and beliefs		X	
Defined relationship between actions & outcomes	X			Shared values	X		
Relationship between cause and effects		X					



Step 3: Problem Extent – How big is the problem?

Problem Factors	Impact on problem extent	Stakeholder Factors	Impact on stakeholder extent
Structural Complexity	Low	Knowledge Fragmentation	Low
Knowability	Low	Interest differentiation	Medium
Knowledge Framing	Low	Power distribution	High

Overview: There is low structural complexity of closing airports, with a high complexity of the secondary problem for maintaining business and lifestyle freedoms. There is ample knowledge about the issue due to the high impact of it.

Overview: The interests between stakeholders vary, especially from airline operators and governments which have opposing interests. Covid-19 has shown that when governments enforce measures, there is a clear power distribution element that can be exerted.

Table 4.7 Complexity Classification Card Problem 4: Shipping

4.3.5 Problem 4: Shipping

Outline: There are currently no freight ships operating without emissions, so shipping must contract and stop until 2050.

Associated CO_2 Emissions: 5 Mt CO_2 in UK in 2021 (Department for Transport, 2023b).

Step 1: Summary Evaluation

The problem with shipping is outlined that: as there are no ships operating without emissions, shipping must contract at first and then stop completely by 2050. This highlights that there is a problem around the emissions of ships and straight away suggests a solution to stop this completely. Similar to stopping flying completely, this solution for shipping is a thought-provoking suggestion which is not considered seriously outside of the *Absolute Zero* Report. There is a high reliance on shipping by the global economy, which would lead to severe secondary problems if it were stopped entirely. It would not be possible to balance out a stop in shipping without a change in lifestyles and population distribution. The distribution of populations to overcome the consequences of a stop in shipping can be classified as an extreme secondary problem. Especially for island nations, such as the UK, a stop in shipping could impede an adequate supply of populations.

Step 2: How Complex is the Problem?

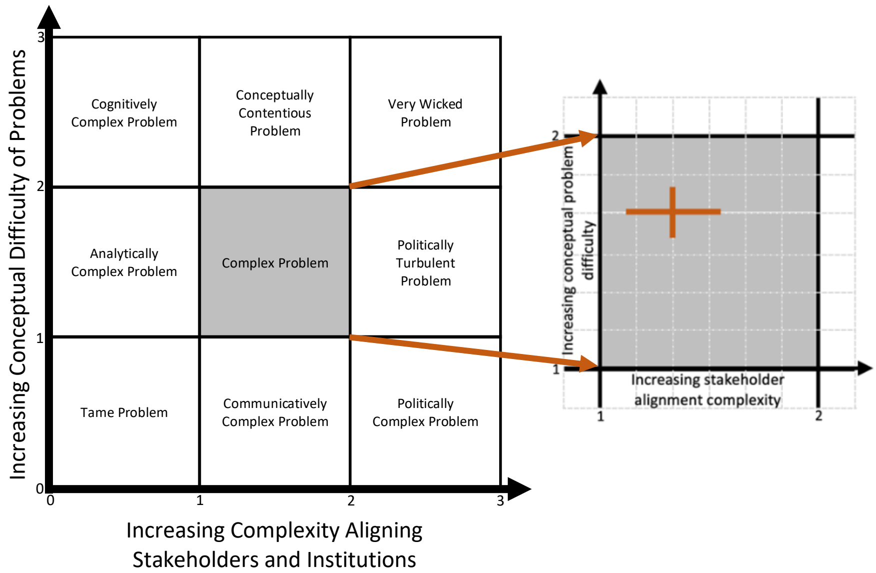
Problem complexity criteria	Problem complexity slider: Low	Problem complexity slider: High	Stakeholder difficulty criteria	Stakeholder difficulty slider: Low	Stakeholder difficulty slider: High
Clear and unambiguous definition	X		Stakeholders developing solution cooperating		X
Stakeholder agreement and acceptance		X	Stakeholders to accept and implement solution known	X	
Technological problem	X		Stakeholders to accept and implement solution cooperating	X	
Organisational and Leadership problem		X	Knowledge for resolving problem in one party	X	
Beyond technology organisation and leadership	X		Multiple parties needed to address problem	X	
Viable solution		X	Diverse values in decision makers	X	
Solution agreed		X	Conflict in assumptions and beliefs	X	
Defined relationship between actions & outcomes		X	Shared values	X	
Relationship between cause and effects		X			

Problem Complexity Overview

Problem is clear. Stopping shipping not planned outside of *Absolute Zero*, rather to seek more sustainable alternatives for shipping, hence no agreement on this. Highlights abstraction of suggestion. Not a technological problem to stop shipping, would lead to secondary problems though around ensuring supply of goods around the world, especially for island nations such as the UK.

Stakeholder Difficulty Overview

No stakeholder collaboration. Stakeholders implementing solution are shipping companies, acceptance spread across different stakeholders, also consumers. Knowledge rests within shipping companies, so not many parties required to implement this. Lack of discussion of zero shipping outside of *Absolute Zero* makes discussion of values and beliefs about this point extremely difficult.



Step 3: Problem Extent – How big is the problem?

Problem Factors	Impact on problem extent	Stakeholder Factors	Impact on stakeholder extent
Structural Complexity	Low	Knowledge Fragmentation	Low
Knowability	Medium	Interest differentiation	Medium
Knowledge Framing	Medium	Power distribution	High

Overview: From a technical perspective there is no barrier for stopping shipping. Primary problem complexity is low. A secondary problem resulting from this, such as continuing to meet the needs of populations across the world would be highly impacted. Due to this secondary problem complexity is high. Knowledge around impacts of shipping on the environment, knowledge gap in providing solution to this.

Overview: Logistics around implementation are complex, involving different stakeholders to ensure movement of goods. Interest differentiation between origin of countries, island nations highly impacted by this and could be cut off from being supplied with goods to meet needs, therefore less interested to stop shipping. Power to stop implementation rests with shipping companies.

Table 4.8 Complexity Classification Card Problem 5: Heating

4.3.6 Problem 5: Heating

Outline: Gas boilers replaced by electric heat pumps and buildings retrofitted, heating reduced to 60% of today's use, can be increased as supply of non-emitting electricity expands.

Associated CO_2 Emissions: 76 Mt CO_2 in UK from housing in 2021 (Department for Environment, Food & Rural Affairs, 2024).

Step 1: Summary Evaluation

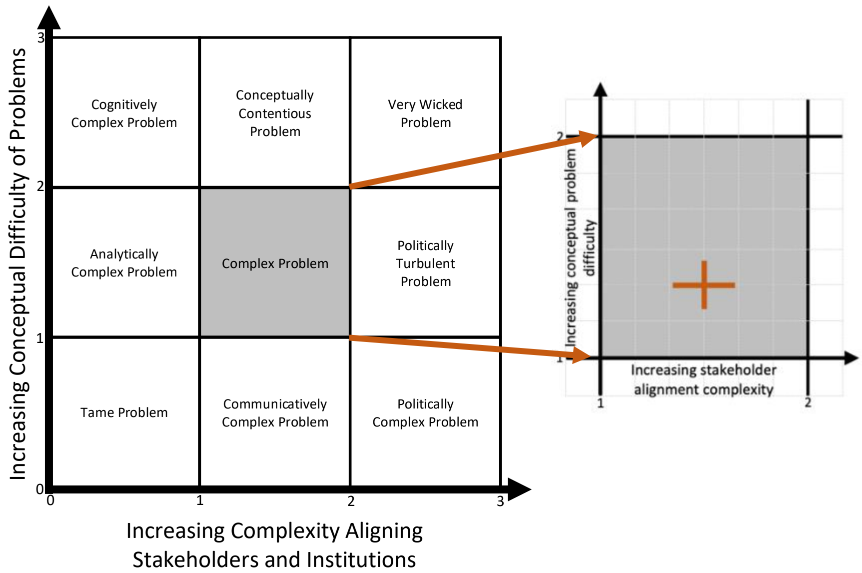
The problem of heating is outlined through electric pumps replacing gas boilers, with heat pumps providing all heating, retrofitting buildings, and in 2050 using only 60% of heating used nowadays. There are various parts to this, most of which are describing solutions. The problem seems to be around gas boilers and the way of construction of existing buildings. There are directly some solutions provided for this, with replacing gas boilers by electric pumps and retrofitting buildings. Another solution is to reduce the use of heating by 40% and have all heating provided by heat pumps. Implementing these changes pose difficulties as secondary problems. This includes ensuring the availability of electric pumps for the replacing of gas boilers, material availability and human resource plays a key role of this, as well as having the qualified workforce for installing these pumps. This is similar for the retrofitting of buildings, where there could be restrictions with resources and building infrastructures; staff needs to be qualified for retrofitting and material availability needs to be ensured as well. This raises a question of how to manage transition, whether it is better to immediately replace all gas infrastructure or wait for current installations to reach the end-of-life. This is another transition problem.

Problem Complexity Overview

Several aspects to this problem; replacing gas boilers with electric heat pumps, retrofitting housing and reducing use of heating altogether. Net zero heating planned in the UK by 2050. Technological problem for implementation and secondary problems of availability of electric heat pumps. Also organisational aspects to the problem of coordination. Solution viability dependent on overcoming secondary problems. Solution not viable as decrease in use of heating highly dependent on consumers.

Stakeholder Difficulty Overview

Requirement of stakeholder coordination acknowledged. Stakeholders for accepting and implementing solution are known. Difficult to determine cooperation between stakeholders for implementation. Secondary problems of skilled workforce for installation. Sum of knowledge not within one stakeholder group, but multiple stakeholders required for solving this problem. Difficult to determine values and beliefs on this point.



Step 2: How Complex is the Problem?

Problem complexity criteria	Problem complexity slider (Low – High)	Stakeholder difficulty criteria	Stakeholder difficulty slider (Low – High)
Clear and unambiguous definition	X (middle, green)	Stakeholders developing solution cooperating	X (green)
Stakeholder agreement and acceptance	X (low, yellow)	Stakeholders to accept and implement solution known	X (low, green)
Technological problem	X (middle, green)	Stakeholders to accept and implement solution cooperating	X (middle, yellow)
Organisational and Leadership problem	X (middle, green)	Knowledge for resolving problem in one party	X (high, green)
Beyond technology organisation and leadership	X (low, yellow)	Multiple parties needed to address problem	X (green)
Viable solution	X (middle, green)	Diverse values in decision makers	X (middle, red)
Solution agreed	X (low, yellow)	Conflict in assumptions and beliefs	X (middle, red)
Defined relationship between actions & outcomes	X (middle, red)	Shared values	X (middle, red)
Relationship between cause and effects	X (middle, red)		

Step 3: Problem Extent – How big is the problem?

Problem Factors	Impact on problem extent	Stakeholder Factors	Impact on stakeholder extent
Structural Complexity	Low	Knowledge Fragmentation	Low
Knowability	Medium	Interest differentiation	Medium
Knowledge Framing	Medium	Power distribution	High

Overview: Technical difficulty of replacing gas boilers with electric heat pumps at once, based on secondary problem of availability of resources. Moderate primary problem complexity, high secondary problem complexity. High knowability on problem, for example Future Homes Standard in the UK (HM Government, 2021).

Overview: Knowledge fragmented between stakeholders. Interest differentiation present, consumers held back to replace existing heating system when this is working well, whilst the government in the UK has a planned path for this. This is where the power distribution comes in and the government can set specific standards.

Table 4.9 Complexity Classification Card problem 6: Appliances

4.3.7 Problem 6: Appliances

Outline: Home appliances become smaller and electrified to reduce power requirement to use 60% of today's energy. Can be changed with increasing supply of non-emitting electricity.

Associated CO_2 Emissions: 2,872.3 Mt CO_2 globally in 2022 (International Energy Agency, 2023).

Step 1: Summary Evaluation

Concerning appliances, *Absolute Zero* states that they should become electrified and smaller to reduce power use, gas cookers should be phased out for electric hobs and ovens. Overall appliances in 2050 should use 60% of the energy they use today and meet efficiency standards. The problem with appliances is not clearly stated, but from the way it is written in the *Absolute Zero* Report, it can be concluded that the problem is around the energy use. Several solutions to this are proposed:

1. Electrifying appliances,
2. Making appliances smaller,
3. Developing appliances meeting efficiency standards.

The problem with gas cookers is also to do with energy use, but more focused on the issue of using gas, where the solution of replacing them with electric hobs and ovens is given. Working on these solutions requires several prerequisites. Smaller and electrified appliances need to be developed by workforce skilled with this, the manufacturing of these appliances would be impacted as well as ensuring the material availability. This is also the case for electric hobs, where the availability of them would have to be ensured as well as workforce to install them. These prerequisites can be named as secondary problems of improving appliances for absolute zero.

Step 2: How Complex is the Problem?

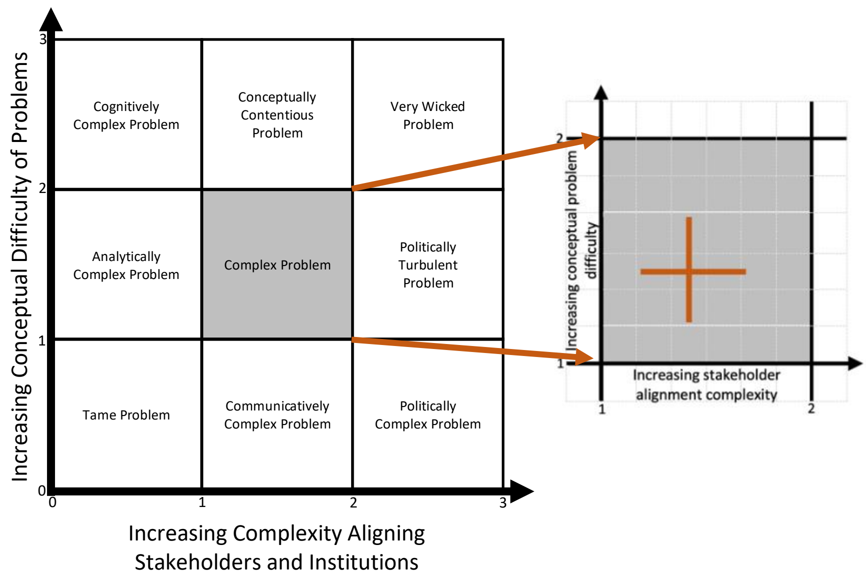
Problem complexity criteria	Problem complexity slider (Low – High)	Stakeholder difficulty criteria	Stakeholder difficulty slider (Low – High)
Clear and unambiguous definition	X (green, low end)	Stakeholders developing solution cooperating	X (red, middle)
Stakeholder agreement and acceptance	X (yellow, middle)	Stakeholders to accept and implement solution known	X (green, low end)
Technological problem	X (green, towards high)	Stakeholders to accept and implement solution cooperating	X (red, middle)
Organisational and Leadership problem	X (yellow, middle)	Knowledge for resolving problem in one party	X (green, high end)
Beyond technology organisation and leadership	X (yellow, low end)	Multiple parties needed to address problem	X (green, high end)
Viable solution	X (green, towards high)	Diverse values in decision makers	X (yellow, middle)
Solution agreed	X (yellow, middle)	Conflict in assumptions and beliefs	X (red, middle)
Defined relationship between actions & outcomes	X (red, middle)	Shared values	X (red, middle)
Relationship between cause and effects	X (red, middle)		

Problem Complexity Overview

Problem around use of energy by appliances. Efficiency standards not defined. Stakeholders involved may be reluctant to try out new appliances because of being used to existing ones. Introduction of energy efficiency labels can support with this. Technological problem due to necessary development of appliances with new requirements, which needs organisation. Secondary problem around availability of resources. Solution viability dependent on availability of such appliances following their development.

Stakeholder Difficulty Overview

Cooperation on this not so clear. Stakeholders for implementation and acceptance known, difficult to determine cooperation amongst these. Not one stakeholder holds all information, multiple stakeholders required for approaching problem. Values and beliefs difficult to determine.



Step 3: Problem Extent – How big is the problem?

Problem Factors	Impact on problem extent	Stakeholder Factors	Impact on stakeholder extent
Structural Complexity	High	Knowledge Fragmentation	Medium
Knowability	Medium	Interest differentiation	Medium
Knowledge Framing	Medium	Power distribution	High

Overview: From a technical perspective it is not possible to replace all existing home appliances at once, indicating a high structural complexity. The secondary problem around availability of resources for alternative appliances also has a high structural complexity. There is some knowledge available on this topic, with energy ratings providing an insight for consumers.

Overview: Knowledge for a solution spread amongst multiple stakeholders, also based on range of appliances in question. Governments have a high power through introducing standards for the use of appliances and their energy efficiencies. Individuals also have a role to play in this by changing lifestyles to use appliances more considerately.

Table 4.10 Complexity Classification Card Problem 7: Food

4.3.8 Problem 7: Food

Outline: Consumption of beef and lamb phased out as well as imports not transported by trains. Energy required to cook or transport food reduced to 60%

Associated CO_2 Emissions: 158 Mt CO_2 in UK in 2019 (Forbes, Fisher and Parry, 2021).

Step 1: Summary Evaluation

The problem is focused on consumption of beef and lamb that should be stopped completely. Imports other than by train are to be stopped, as well as frozen ready meals and fertiliser use. Energy used for cooking and transporting food in 2050 should be reduced to 60% of today's levels. There are various parts to this problem, many of which provide solutions. The problem that can be clearly read out of this is the energy used for cooking and transporting food. The solution to this is reducing of energy by 40% and transporting by train rather than other methods. The problem with frozen meals stems from the fact that they require energy for manufacturing, which would be reduced when producing less frozen ready meals (Allwood et al., 2019). Fertiliser is not used efficiently, therefore reducing the use, and using more efficiently is expected to have a positive effect for moving towards absolute zero. Beef and lamb are specifically picked out for consumption to be completely stopped based on the emissions for producing these which are higher than for other common foods (Allwood et al., 2019). These switches in diet are difficult due to various reasons, such as eating habits deeply anchored in cultures and routines. A switch in diets would also need to be sustained through ensuring availability of alternative resources, such as land for growing crops, highlighting secondary problems.

Step 2: How Complex is the Problem?

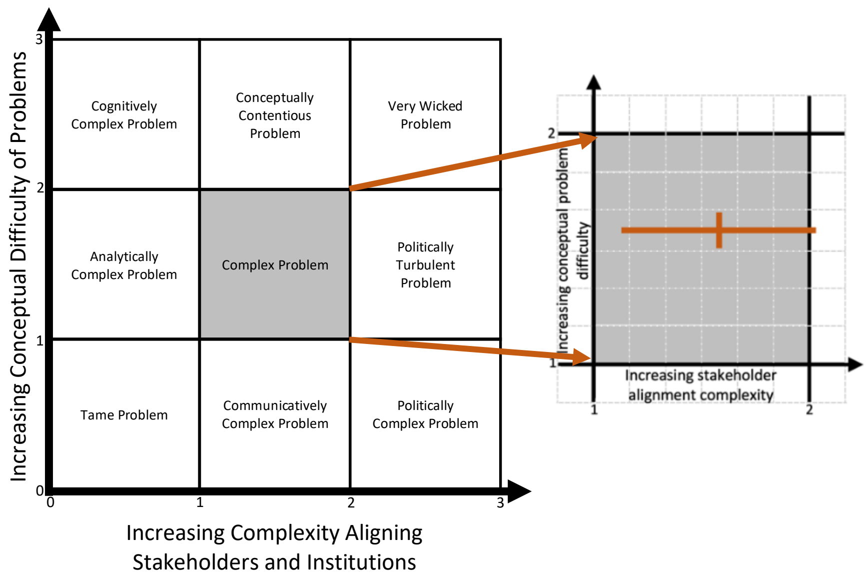
Problem complexity criteria	Problem complexity slider: Low	Problem complexity slider: High	Stakeholder difficulty criteria	Stakeholder difficulty slider: Low	Stakeholder difficulty slider: High
Clear and unambiguous definition		X	Stakeholders developing solution cooperating		X
Stakeholder agreement and acceptance		X	Stakeholders to accept and implement solution known	X	
Technological problem	X		Stakeholders to accept and implement solution cooperating	X	
Organisational and Leadership problem	X		Knowledge for resolving problem in one party	X	
Beyond technology organisation and leadership	X		Multiple parties needed to address problem		X
Viable solution		X	Diverse values in decision makers	X	
Solution agreed		X	Conflict in assumptions and beliefs	X	
Defined relationship between actions & outcomes	X		Shared values	X	
Relationship between cause and effects	X				

Problem Complexity Overview

Various sub-problems come together in this one around food, with energy used by appliances and for transportation for example. No clear definition and acceptance difficult. There are technological and organisational elements to the problem. Somewhat extends this due to consumer behaviour playing a major role in success of approaching this problem. Not planned to stop beef and lamb consumption – provoking suggestion of *Absolute Zero* for readers to question their diets and get them thinking.

Stakeholder Difficulty Overview

Acknowledged that stakeholder cooperation on this would be necessary, not clearly shown publicly though. Various stakeholders involved for implementing this. Knowledge spread across stakeholders, therefore multiple stakeholders necessary for approaching problem. Values and beliefs more dominant in this problem. Diets may be based on cultural backgrounds. High controversy in the public on the consumption of meat, based on different reasons.



Step 3: Problem Extent – How big is the problem?

Problem Factors	Impact on problem extent	Stakeholder Factors	Impact on stakeholder extent
Structural Complexity	Low	Knowledge Fragmentation	High
Knowability	Medium	Interest differentiation	High
Knowledge Framing	Low	Power distribution	High

Overview: Technical complexity of stopping consumption of beef and lamb is low, as well as stopping use of frozen ready meals, imports not coming by train, use of fertilisers and reduce electricity for cooking. High complexity around secondary problem of jobs in meat industry for example. Knowledge available on impacts of meat consumption on emissions.

Overview: Knowledge for approaching problem fragmented across stakeholders. Justification of meat consumption framing standpoint on this problem based on previous habits. Interest differentiation based on high controversy of production and consumption of meat and animal-based products. Food producers hold a high power in the transformation of the food industry.

Table 4.11 Complexity Classification Card Problem 8: Mining Material Sourcing

4.3.9 Problem 8: Mining Material Sourcing

Outline: Iron ore and limestone phased out, metal scrap supply chain expands, demand for scrap steel and ores for electrification rises.

Associated CO_2 Emissions: 17.18 Mt CO_2 in UK in 2021 for Mining and Quarrying (UK Government Climate Change, 2023).

Step 1: Summary Evaluation

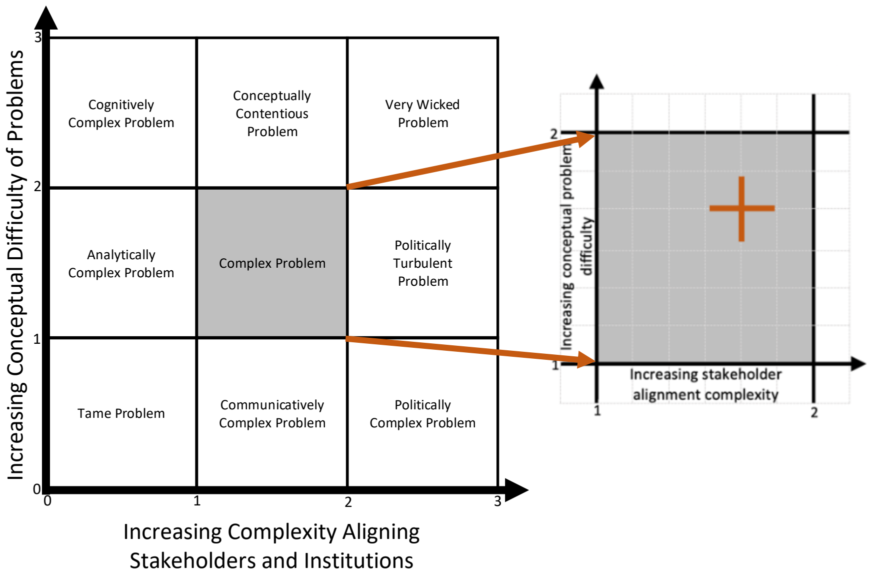
For Mining and Material Sourcing there are three key points: 1. Phasing out iron ore and limestone, 2. Increasing demand of materials for electrification and 3. Expand metal scrap supply chain. There are significant secondary problems associated with this, especially regarding the expansion of the metal scrap supply chain which requires a supporting infrastructure. The increasing demand of materials for electrification is dependent on the availability of these materials. For example, the transition from combustion-based propulsion to electrical propulsion implies changes in materials utilisation, especially around critical materials for electrification to produce magnets, such as rare earth elements. This is another transition problem. The re-use of materials is based on a very low level of current global utilisation, there is not a stable circulation of these materials, which would make the impacts of transition to electrification much more severe than at face value. Iron ore and limestone are key resources in the construction industry, where alternatives must be sought to sustain the industry and the population with housing.

Problem Complexity Overview

Several elements make up this problem from *Absolute Zero*. There is no clear definition of problem, rather solutions provided. There are significant secondary problems on this, notably providing infrastructure for metal scrap supply chains and alternatives of iron ore and limestone. Some technological difficulties of this problem, especially around the expansion of metal scrap supply chain which would also require organisational coordination. Not planned to phase out iron ore and limestone.

Stakeholder Difficulty Overview

Cooperation amongst stakeholders difficult to determine based on diversity of problem elements. Due to this the knowledge for resolving this problem resides within several stakeholders and common values and beliefs are not expected. Some knowledge on the stakeholders that would be involved.



Step 2: How Complex is the Problem?

Problem complexity criteria	Problem complexity slider (Low – High)	Stakeholder difficulty criteria	Stakeholder difficulty slider (Low – High)
Clear and unambiguous definition	X	Stakeholders developing solution cooperating	X
Stakeholder agreement and acceptance	X	Stakeholders to accept and implement solution known	X
Technological problem	X	Stakeholders to accept and implement solution cooperating	X
Organisational and Leadership problem	X	Knowledge for resolving problem in one party	X
Beyond technology organisation and leadership	X	Multiple parties needed to address problem	X
Viable solution	X	Diverse values in decision makers	X
Solution agreed	X	Conflict in assumptions and beliefs	X
Defined relationship between actions & outcomes	X	Shared values	X
Relationship between cause and effects	X		

Step 3: Problem Extent – How big is the problem?

Problem Factors	Impact on problem extent	Stakeholder Factors	Impact on stakeholder extent
Structural Complexity	Medium	Knowledge Fragmentation	Medium
Knowability	Medium	Interest differentiation	Medium
Knowledge Framing	Medium	Power distribution	Medium

Overview: From a technical perspective, stopping mining of iron ore and limestone is possible, this has a low complexity. Expanding the metal scrap supply chain is dependent on support in the form of an infrastructure for this, which is a secondary problem. Complexity of the secondary problem is high. Phasing out of iron ore and limestone not discussed outside of *Absolute Zero*, so the knowledge on this is limited. Steel scrap supply chain expanding in the UK, with waste management being a key factor in this (Bonaplata, 2023).

Overview: Knowledge is fragmented across stakeholders for this problem, especially regarding a developing of the metal scrap supply chain. Some elements of interest differentiation and power can be mostly exerted by governments.

Table 4.12 Complexity Classification Card Problem 9: Materials Production

4.3.10 Problem 9: Materials Production

Outline: Increasing steel recycling, cement and emitting plastics phased out, as well as new steel.
Associated CO_2 Emissions: 6,380 Mt CO_2 globally in 2016 (Hertwich, 2021).

Step 1: Summary Evaluation

As part of materials production steel recycling should grow, cement, new steel and emitting plastics are to be phased out and production of materials is electric. This somewhat overlaps with Problem 8, where metal scrap supply chain also plays a central role. The secondary problem of having an infrastructure for metal scrap supply chain also plays a role for this problem on steel recycling. The implementation of this is subject to a period of transition. Overall, materials production focuses more on solutions, rather than defining a problem. A problem can be picked out regarding emitting plastics and production of materials that should be made electric, indicating that current production methods are not in line with absolute zero. Cement, new steel and emitting plastics can be phased out without having to rely on further stakeholders. However, there is a high reliance on cement in the construction industry which makes a sooner phasing out of it unlikely. For example, expanding the rail network implies resource use from construction. Another secondary problem arises regarding the electric production of materials that is dependent on resources, regarding both material and human.

Problem Complexity Overview

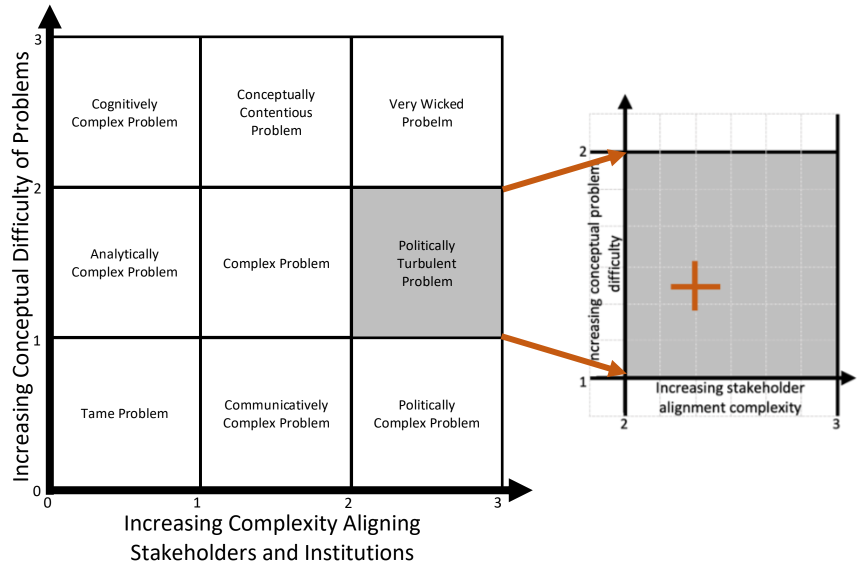
Problem outline is clear, involving several elements. Due to not having one direct focus, stakeholders involved with each different material mentioned vary, no overarching agreement. Technological aspect of problem present. Due to the diverse aspects of the problem, elements of leadership and organisation are required. Limited viability of solution, due to dependence on change in production methods to be electric. Some ideas around relationships between cause and effects and actions and outcomes.

Stakeholder Difficulty Overview

No overarching cooperation across stakeholders. No need for cooperation when wanting to phase out materials. For electrifying production of materials, the producers of this have the highest responsibility, however there is a dependence on other stakeholders to change the previous production processes. Knowledge for this is therefore also spread amongst stakeholders. Diversity of beliefs and values around this difficult to determine. General negative connotation of use of plastics.

Step 2: How Complex is the Problem?

Problem complexity criteria	Problem complexity slider: Low	Problem complexity slider: High	Stakeholder difficulty criteria	Stakeholder difficulty slider: Low	Stakeholder difficulty slider: High
Clear and unambiguous definition	X		Stakeholders developing solution cooperating		X
Stakeholder agreement and acceptance		X	Stakeholders to accept and implement solution known	X	
Technological problem		X	Stakeholders to accept and implement solution cooperating	X	
Organisational and Leadership problem		X	Knowledge for resolving problem in one party		X
Beyond technology organisation and leadership	X		Multiple parties needed to address problem		X
Viable solution		X	Diverse values in decision makers	X	
Solution agreed		X	Conflict in assumptions and beliefs	X	
Defined relationship between actions & outcomes		X	Shared values	X	
Relationship between cause and effects		X			



Step 3: Problem Extent – How big is the problem?

Problem Factors	Impact on problem extent	Stakeholder Factors	Impact on stakeholder extent
Structural Complexity	Low	Knowledge Fragmentation	Medium
Knowability	Medium	Interest differentiation	Low
Knowledge Framing	Medium	Power distribution	Medium

Overview: Technically it is possible to stop production of cement, new steel and emitting plastics. Structural complexity of this is low. Secondary problems would arise from this though with providing alternatives for these materials, indicating a high structural complexity. Knowledge on electrification of production processes is developing.

Overview: Each material has its own set of stakeholders. For the development of steel recycling, several stakeholders have a key importance. Acquisition of infrastructure, development of supply chain arrangements and ways of making money in this are key factors that have a high complexity themselves. Interest differentiation dependent on material in question. Interest of businesses active in steel, plastics and cement not seeking to stop their business activity. Power distribution for stopping cement, new steel and emitting plastics production is limited. This has a higher significance for steel recycling and electrical production methods.

Table 4.13 Complexity Classification Card Problem 10: Construction

4.3.11 Problem 10: Construction

Outline: Focus on retrofit and adaption of existing buildings. Conventional mortar and concrete phased out. Buildings optimised for material saving.

Associated CO_2 Emissions: 81.59 Mt CO_2 in UK in 2021 (UK Government Climate Change, 2023**).**

Step 1: Summary Evaluation

This problem on construction speaks about a reduced cement supply that must be compensated by material efficiency before conventional mortar and concrete are phased out completely. Steel recycling also plays a key part in the problem on construction, like the previous two problems, 8 and 9. Furthermore, there is a focus on retrofitting and adapting buildings. The construction points are formulated as solutions, without providing an explanation why the solutions are necessary or what the problems behind them are. This point on construction shows the interconnectedness with other problems. Retrofitting of buildings also plays a central role for heating, where retrofitting is seen as a solution. To implement the solutions, there are prerequisites that can be named secondary problems involving various stakeholders. A way for improving material efficiency for cement must be found as well as having an infrastructure in place for steel recycling. For retrofitting and adaptation of buildings it is also necessary to find ways of doing this. There are problems associated with retrofitting, as this may be limited for legacy buildings. Changing this to enable a retrofit of buildings to match absolute zero requirements will take time and impedes a smooth transition to absolute zero.

Step 2: How Complex is the Problem?

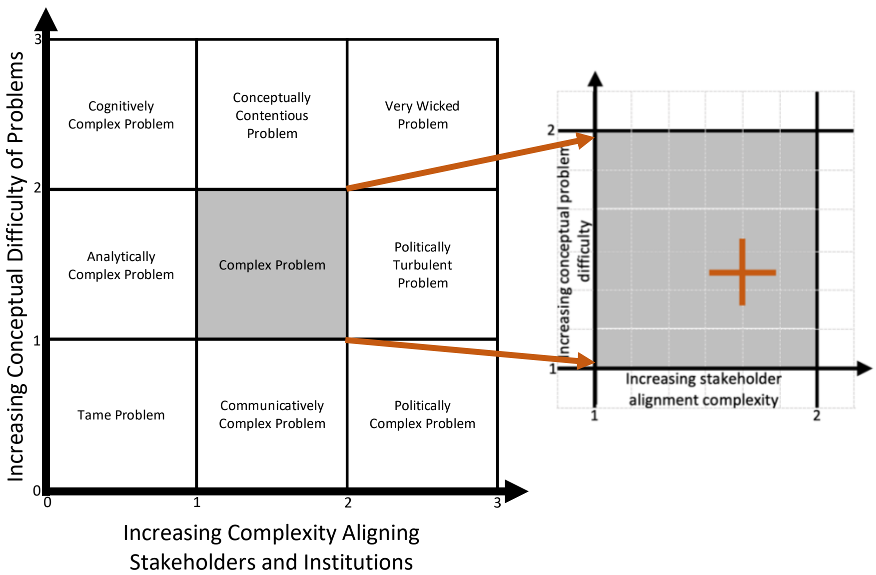
Problem complexity criteria	Problem complexity slider (Low – High)	Stakeholder difficulty criteria	Stakeholder difficulty slider (Low – High)
Clear and unambiguous definition	X	Stakeholders developing solution cooperating	X
Stakeholder agreement and acceptance	X	Stakeholders to accept and implement solution known	X
Technological problem	X	Stakeholders to accept and implement solution cooperating	X
Organisational and Leadership problem	X	Knowledge for resolving problem in one party	X
Beyond technology organisation and leadership	X	Multiple parties needed to address problem	X
Viable solution	X	Diverse values in decision makers	X
Solution agreed	X	Conflict in assumptions and beliefs	X
Defined relationship between actions & outcomes	X	Shared values	X
Relationship between cause and effects	X		

Problem Complexity Overview

Four parts to this problem can be identified; 1. Improving material efficiency of cement, 2. Phasing out mortar and concrete, 3. Recycling steel, 4. Retrofit and adaptation of buildings. Difficult to provide a clear explanation of all these four parts together. Diversity of problem points means no overall agreement. Technological complexity, with having to find ways for improving efficiency, steel recycling and retrofit and adaption of buildings. Organisation to coordinate actions. No overarching viable solution.

Stakeholder Difficulty Overview

Undebatable that multiple parties required for approaching problem in its entirety, as knowledge split between stakeholders. Some basic knowledge of stakeholders involved with problem. Due to diversity in problem, stakeholder factors difficult to determine.



Step 3: Problem Extent – How big is the problem?

Problem Factors	Impact on problem extent	Stakeholder Factors	Impact on stakeholder extent
Structural Complexity	Medium	Knowledge Fragmentation	Medium
Knowability	Medium	Interest differentiation	Medium
Knowledge Framing	Medium	Power distribution	Medium

Overview: From a technical perspective, stopping use of mortar and concrete is possible, this has a low complexity and is only in the responsibility of the manufacturers of these materials. Improving material efficiency of cement becomes more complex, along with steel recycling and retrofitting of buildings. Secondary problem of skilled workforce for retrofit of buildings. Some knowledge for a timeline of all houses being EPC C by 2035 (HM Government, 2021).

Overview: Various stakeholders involved with different aspects of the problem, indicating knowledge fragmentation. Power distribution limited regarding stopping use of mortar and concrete. More extreme power can be exerted when it comes to setting up standards, such as the EPC C by 2035 (HM Government, 2021).

Table 4.14 Complexity Classification Card Problem 11: Manufacturing

4.3.12 Problem 11: Manufacturing

Outline: Material supply contracts, goods made with 50% of material, new design and manufacturing practices.

Associated CO_2 Emissions: 81.59 Mt CO_2 in UK in 2021 (UK Government Climate Change, 2023).

Step 1: Summary Evaluation

Regarding manufacturing, it is expected that in the future material supply will contract, requiring an improvement in material efficiency. Goods are to be made with 50% of materials and to last twice as long, involving new design and new manufacturing practices as well as no reduction in output. Parts of this problem are somewhat contradictory. When it is planned to have no reduction in output, but make materials that last twice as long, it is inevitable that this is not economically sustainable in the long term and would lead to a secondary problem in this. Furthermore, this is subject to consumer behaviour adjusting along with this. Some parts of this are clearly understandable as problems, such as a contracting material supply, where other parts are solutions proposed for this: material efficiency, making goods with 50% of materials, new design and new manufacturing practices. To implement these solutions, there are some secondary problems and several stakeholders involved. For making goods with 50% of materials, it is important that designs are developed for these goods with the associated manufacturing practices. This cannot be done from one day to the other and requires time, as these processes span a large supply chain so are subject to a transition period and hence identifiable as transition problems.

Step 2: How Complex is the Problem?

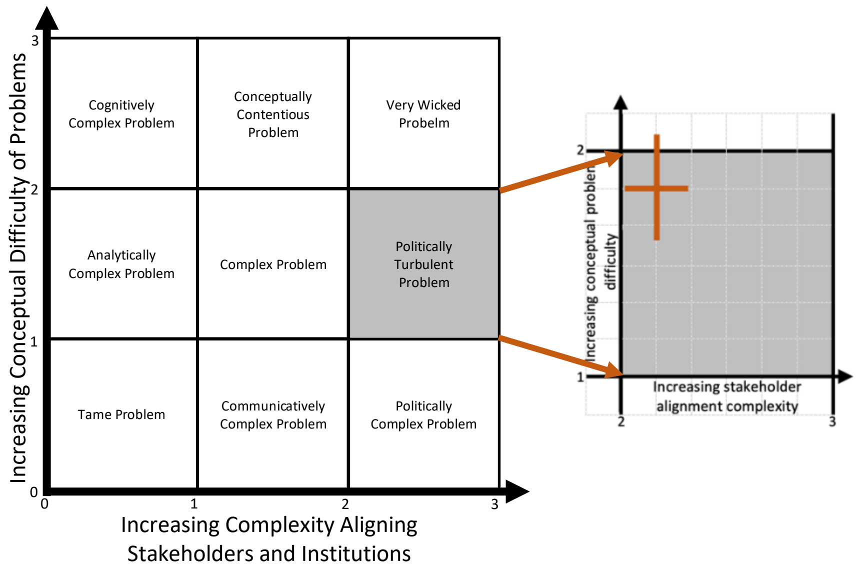
Problem complexity criteria	Problem complexity slider (Low – High)	Stakeholder difficulty criteria	Stakeholder difficulty slider (Low – High)
Clear and unambiguous definition	X	Stakeholders developing solution cooperating	X
Stakeholder agreement and acceptance	X	Stakeholders to accept and implement solution known	X
Technological problem	X	Stakeholders to accept and implement solution cooperating	X
Organisational and Leadership problem	X	Knowledge for resolving problem in one party	X
Beyond technology organisation and leadership	X	Multiple parties needed to address problem	X
Viable solution	X	Diverse values in decision makers	X
Solution agreed	X	Conflict in assumptions and beliefs	X
Defined relationship between actions & outcomes	X	Shared values	X
Relationship between cause and effects	X		

Problem Complexity Overview

Several parts to the problem: material efficiency, improved design of goods and adapted manufacturing processes, developing goods lasting twice as long. Controversy in producing products lasting twice as long, but having no reduction in output. Efficiency and improvement of manufacturing processes dependent on process in question, with technological challenges. Beyond technology and organisation due to dependence on consumers for using products twice as long.

Stakeholder Difficulty Overview

Limited collaboration of stakeholders in the entire manufacturing industry. Difficult to determine full list of stakeholders due to diversity of manufacturing processes that are incorporated. Multiple parties required to approach this problem. Disparities in values and beliefs expected.



Step 3: Problem Extent – How big is the problem?

Problem Factors	Impact on problem extent	Stakeholder Factors	Impact on stakeholder extent
Structural Complexity	Medium	Knowledge Fragmentation	Medium
Knowability	High	Interest differentiation	Medium
Knowledge Framing	Medium	Power distribution	Medium

Overview: Primary problem with medium structural complexity; producing products with 50% of materials has severe technical challenges, including developing more efficient and improved manufacturing and design practices. Secondary problems around this exist of having the resources to stem this change, with a high dependency on manufacturing indicating a high structural complexity. Limited knowledge on problem, with major challenge stemming from lack of skilled workforce, indicating secondary problems.

Overview: Lack of visibility to consumers of more environmentally friendly products that are often more expensive. Some elements of power distribution given, with manufacturers holding a key responsibility in the adaptation of manufacturing processes. Background work necessary with new product designs available for products using only 50% of materials conventionally.

Table 4.15 Complexity Classification Card Problem 12: Electricity

4.3.13 Problem 12: Electricity

Outline: Wind and solar grow as quick as possible, non-electrical motors and heaters phased out, all energy supply by 2050 will be non-emitting.

Associated CO_2 Emissions: 44 Mt CO_2 in UK in 2023 (Office for National Statistics, 2024).

Problem Complexity Overview

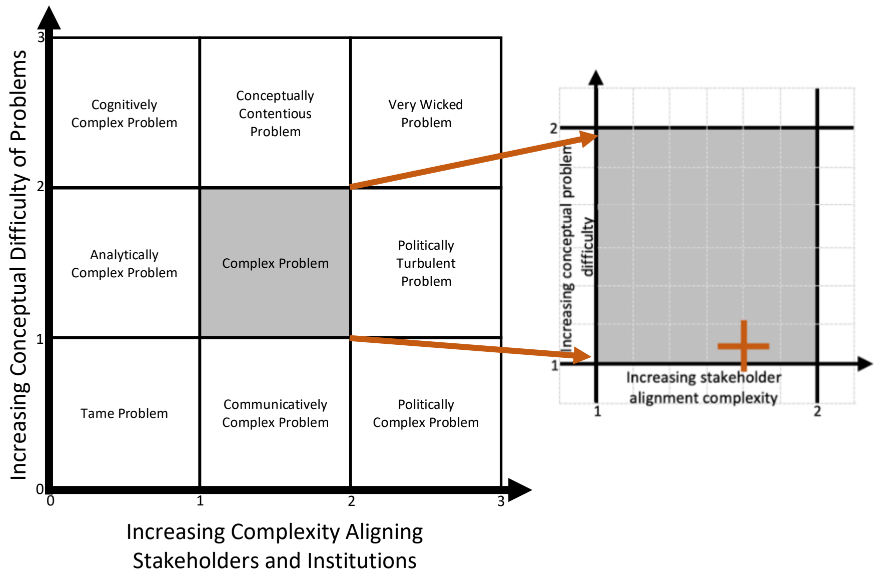
Anticipated that problem is based on emissions of energy. Discussion on renewable energy increase taking place outside of *Absolute Zero* indicating some form of agreement on the issue. Technological aspects to the problem and organisational elements come in regarding distribution. Currently not possible to meet energy demand with renewable sources of energy. Nuclear energy planned in the UK to fill this gap between supply and demand.

Stakeholder Difficulty Overview

Change in whole electricity system required involving different aspects, where no universal agreement will be established. Knowledge available on stakeholders involved. Secondary problems around skilled workforce. Knowledge for solving problem spread across stakeholders. Work for renewable energy uptake happening, indicating low diversity in values.

Step 1: Summary Evaluation

Several parts make up this problem around electricity. For reaching absolute zero, wind and solar energy grows along with the storage and distribution associated with this. Renewable energy increases four-fold by 2050, with all energy supply being non-emitting by then. Non-electrical motors and heaters will be phased out. This rather proposes solutions than outlining problems. There is a consideration of secondary problems for increasing wind and solar energy around the storage and distribution for this, important to make use of this increase of energy produced. There are further secondary problems for this around the resources for developing wind and solar energy farms, highlighting the diversity of stakeholders involved for this. This point can be classified as a prerequisite for other problems mentioned in *Absolute Zero*, as there is a high reliance on electrification.



Step 2: How Complex is the Problem?

Problem complexity criteria	Problem complexity slider: Low	Problem complexity slider: High	Stakeholder difficulty criteria	Stakeholder difficulty slider: Low	Stakeholder difficulty slider: High
Clear and unambiguous definition	X		Stakeholders developing solution cooperating	X	
Stakeholder agreement and acceptance	X		Stakeholders to accept and implement solution known	X	
Technological problem		X	Stakeholders to accept and implement solution cooperating	X	
Organisational and Leadership problem		X	Knowledge for resolving problem in one party		X
Beyond technology organisation and leadership	X		Multiple parties needed to address problem		X
Viable solution	X		Diverse values in decision makers	X	
Solution agreed	X		Conflict in assumptions and beliefs	X	
Defined relationship between actions & outcomes		X	Shared values	X	
Relationship between cause and effects		X			

Step 3: Problem Extent – How big is the problem?

Problem Factors	Impact on problem extent	Stakeholder Factors	Impact on stakeholder extent
Structural Complexity	Medium	Knowledge Fragmentation	Medium
Knowability	Low	Interest differentiation	Low
Knowledge Framing	Medium	Power distribution	Medium

Overview: Technical complexity around supply of all energy with renewable solar and wind energy, indicating medium problem complexity. Secondary problems exist for this around resources, such as material availability of producing solar and wind farms, indicating a high complexity. Knowledge available on renewable energy sources, with a clear view on the lack of capacity to meet energy demand. Other energy production should also be focused on, as it is expected wind and solar will not suffice to meet demands by 2050 (Allwood et al., 2019).

Overview: Knowledge for this somewhat spread amongst stakeholders. Elements of power distribution acknowledged regarding implementation of standards by authorities.

Table 4.16 Complexity Classification Card Problem 13: Fossil Fuels

4.3.14 Problem 13: Fossil Fuels

Outline: Fossil fuels phased out, development of carbon capture and storage may allow resumption of use of gas and coal for electricity.

Associated CO_2 Emissions: 312.7 Mt CO_2 in UK in 2022 (Department for Energy Security & Net Zero, 2023).

Step 1: Summary Evaluation

Phase fossil fuels out by 2050 as they are not compatible with absolute zero when Carbon Capture and Storage is not deployable on a large scale. Focus on the solution of phasing out fossil fuels rather than explaining what the problem behind this is. Reviewing the previous 12 suggestions put forward in *Absolute Zero,* if they are all successfully approached, it can be argued that the use of fossil fuels would no longer be an issue as it would not be necessary to use them. It is clear that fossil fuels are a large contributor to climate change, which justifies the need to phase them out for absolute zero. Before phasing out fossil fuels it is important to ensure that alternatives are available to back up the demand of energy that was previously met by fossil fuels. This is a significant secondary problem for this point. Another secondary problem is that of establishing supply chains for materials reliant on fossil fuels, such as plastics, which are biproducts of the oil and gas industry.

Problem Complexity Overview

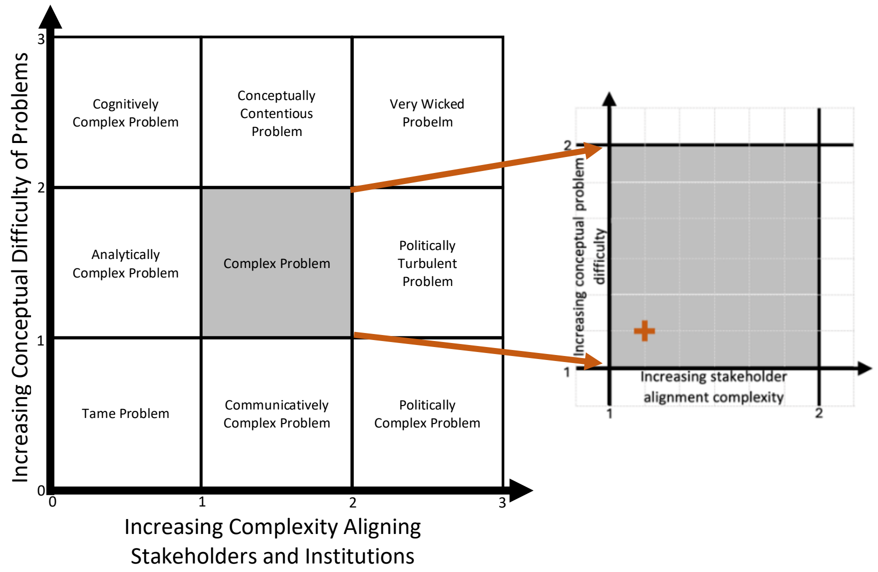
This point rather provides a solution of phasing out fossil fuels without a clear explanation on the problems with these. Based on this, an agreement of stakeholders on this proves difficult. Stopping use of fossil fuels is neither a technological nor an organisation problem. Secondary problem arising from this when having to replace fossil fuels to meet energy demand which has a technological and organisational complexity.

Stakeholder Difficulty Overview

Cooperation to cut fossil fuels is not required, so conflict also limited with no direct effect. Fossil fuels used across industries, where acceptance to cut these would have to be accepted. This acceptance will be limited based on high reliance on them, without equivalent alternative. Knowledge for cutting fossil fuels rests with one party, no requirement of multiple parties for addressing the problem. Different regarding development of carbon capture and storage which requires cooperation across stakeholders.

Step 2: How Complex is the Problem?

Problem complexity criteria	Problem complexity slider: Low	High	Stakeholder difficulty criteria	Stakeholder difficulty slider: Low	High
Clear and unambiguous definition		X	Stakeholders developing solution cooperating		X
Stakeholder agreement and acceptance		X	Stakeholders to accept and implement solution known		X
Technological problem	X		Stakeholders to accept and implement solution cooperating	X	
Organisational and Leadership problem		X	Knowledge for resolving problem in one party		X
Beyond technology organisation and leadership	X		Multiple parties needed to address problem		X
Viable solution		X	Diverse values in decision makers	X	
Solution agreed		X	Conflict in assumptions and beliefs	X	
Defined relationship between actions & outcomes		X	Shared values	X	
Relationship between cause and effects		X			



Step 3: Problem Extent – How big is the problem?

Problem Factors	Impact on problem extent	Stakeholder Factors	Impact on stakeholder extent
Structural Complexity	Low	Knowledge Fragmentation	Low
Knowability	Low	Interest differentiation	Low
Knowledge Framing	Low	Power distribution	Low

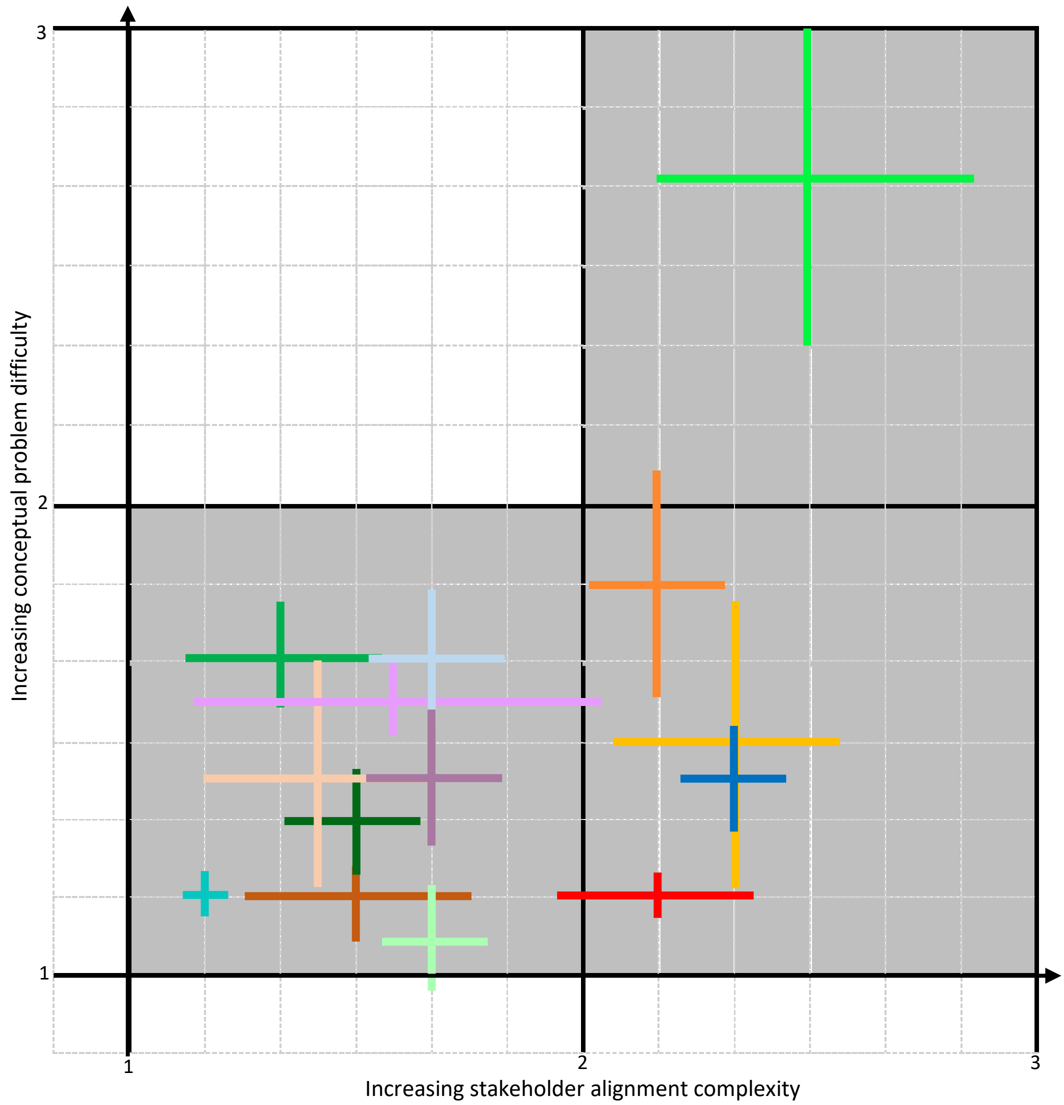
Overview: From a technical perspective it is possible to stop the use of fossil fuels without notice, there is a low structural complexity around this. When regarding the impacts this would have, it can be concluded the complexity is high. These include fossil fuel supply chains extending into some geopolitically difficult parts of the world where a sudden change would be very disruptive and lead to instability. Therefore, this can be described as a transition problem. This stems from the thought that demands previously met by fossil fuels must be met in other ways. Impact of fossil fuels on the environment known, with a high reliance on them.

Overview: Knowledge for implementing stop of fossil fuels rests with one stakeholder group, so knowledge fragmentation is limited, with knowledge framing having little impact on this. With uptake of carbon capture and storage this is different, where knowledge would be spread across stakeholders.

4.3.15 Step 4: Is there room for progress?

Step 4 is concerned with the comparison of problems against each other. In Appendix 2 you can see the comparison of the CO_2 impact of each of the 13 measures of *Absolute Zero*. For most of the 13 measures, numbers from the UK could be found and if this was not possible, the search was expanded to not solely focus on the UK. Furthermore, not all the numbers were exactly matching the scope of the 13 measures. A context of the numbers is provided alongside this which provides further details on the CO_2 impact. Figure 4.1 below shows the position of problems compared to each other based on the analysis above, including the position of absolute zero. All of the problems from *Absolute Zero* fit into the complex problem and the politically turbulent problem categories. Absolute zero itself fits into the very wicked problem category. There is no direct correlation between the CO_2 emission associated with the actions and their complexity rating. For example, the emissions associated with Fossil fuels are high, yet the wickedness of the problem is low. This indicates that working on this action would have a positive effect in the move towards net zero in a limited time period.

There are further questions to consider for comparing the importance of problems with each other. A key part of this is the interconnectedness of problems. Due to this, the first section of the analysis on step 4 discusses the interconnectedness of problems. Please see Appendix 3 for a figure to show the problems along with their secondary problems and the key themes of interconnectedness in this.



Key:

Absolute Zero	7. Food
1. Road Vehicles	8. Mining Material Sourcing
2. Rail	9. Materials Production
3. Flying	10. Construction
4. Shipping	11. Manufacturing
5. Heating	12. Electricity
6. Appliances	13. Fossil Fuels

Figure 4.1 Problem Positioning Comparison

4.3.15.1 Interconnectedness of Problems

This section focuses on providing examples of interconnectedness amongst the 13 actions and their secondary problems.

Resources Availability:

Absolute Zero Actions Interconnected: Road Vehicles, Rail, Heating, Appliances, Materials Production, Construction, Manufacturing and Electricity

- Eight out of the 13 actions are identified as affected by this secondary problem, indicating the severity of this.
- Includes availability of resources in terms of material, human, i.e. workforce and development of workforce, and land.
- UK FIRES stems from the origin of resource efficiency at the heart of future industrial strategy with resource availability being a key factor for resource efficiency and a strong limiting factor for the development on problems.
- Example:

  Rail and Food - availability of land is a prerequisite, more land will be required

  Material Production, Construction, Manufacturing and Electricity – skilled workforce for working with new products and processes, workers need to acquire new skills

Infrastructure:

Absolute Zero Actions Interconnected: Road Vehicles, Rail, Mining Material Sourcing, Materials Production and Electricity

- Operationalisation of changes not viable without supporting infrastructure.
- Strong interconnectedness between individual development of infrastructure for supporting move forward across *Absolute Zero* actions.
- Example:

  Material Production and Mining and Material Sourcing – steel recycling and development of supply chain for metal scraps with metal scraps supply chain laying foundation for steel recycling. Most casting and forging facilities already internally recycle or reuse waste material that they produced on site. In these cases, the grade of material is known. A challenge arises from the material that left their facilities. Some schemes are in place for this already though. For example, Rolls-Royce has established that 95% of a used aero engine can be recycled and around half of this can be used to make a new engine because the recovered material is of such high quality (Rolls-Royce, 2017).

Electricity Supply for Electrification:

Absolute Zero Actions Interconnected: Road Vehicles, Appliances and Materials Production

- Increase in electrification as a key solution for enabling net zero, where supply of electricity required to meet increased demand.
- Example:

  Renewable energy development under electricity action from *Absolute Zero* expected to support with secondary problems of electricity availability

Reduction in Size:

Absolute Zero Actions Interconnected: Road Vehicles and Appliances

- Potential to support electricity supply critical problems, linking to cutting use of energy.
- Example:

  Smaller vehicles and appliances expected to use less energy.

Cutting use of energy:

Absolute Zero Actions Interconnected: Rail, Appliances, Food

- Energy for cooking and transporting food as well as appliances use of energy to be reduced to 60%
- Example:

  Using rail over shipping and appliances developed with using 60% of energy support food problem to reduce energy to 60%. Link with food imported by train

Material efficiency:

Absolute Zero Actions Interconnected: Construction and Manufacturing

- Initial step before complete phasing out of materials

- Example:
  Some prerequisites for this, such as development of methods for securing primary use quality with secondary design and processes

This analysis of the interconnectedness of problems shows that there are different forms of decomposition that could be used for *Absolute Zero*. As it is written, *Absolute Zero* is structured around industry sectors all with broader implications that are problematic. Writing *Absolute Zero* based on the interconnectedness problems would also be a possibility. However, this would be less impactful with secondary problems around sectors and their way of approaching the problems.

The overview of the interconnectedness of problems helps to approach the points of analysis for step 4.

4.3.15.2 Discussion of Absolute Zero with Step 4 Analysis Criteria

The first point of analysis focuses on whether the problems are generic or focused on a specific company or industry, with the potential impact of this. The *Absolute Zero* Report aims to provide a holistic outline of actions necessary to reach absolute zero, bringing forward 13 issues to be worked on across companies and industries. There is no direct focus for the problems which is further emphasised by the arising of secondary problems. Based on this it can be concluded that the problems are generic. This has both positive and negative consequences. It is positive in the respect that developments in the individual problems will be an advantage overarchingly, as shown by the interconnectedness; if there is an improvement in one problem, the problem connect to it may also be approached. The downside to this is the degree of complexity remaining when there is no definitive focus for the problems, this makes the approach to it challenging.

A further consideration adding to the degree of complexity is the stakeholders involved with the problems and their solution and whether they see challenges that are potentially difficult to overcome. Stakeholders approaching the issues brought forward all hold a key responsibility for enabling the implementation of them. Various problems are formulated as direct solutions without providing details on the problem pain points. As mentioned in previous analysis steps, it must be noted that some of the problems are not planned in reality, such as entirely stopping flying and shipping. Generally, the issues from the *Absolute Zero* report are of a highly provocative nature and formulated in a rather exaggerated manner to spark interest and thinking in readers. As such, determining the criticality of stakeholders and their view on the difficulty of overcoming challenges in this is complicated. However, when considering the importance of the interconnectedness of problems again, it becomes clear that stakeholders in the individual problems can indirectly support progress of other problems through this interconnection.

This leads to whether impacts of the primary application can be leveraged and diffused beyond this. The interconnectedness of problems indicates the impacts of them beyond their primary focus. Several of the problems in *Absolute Zero* are dependent on the implementation of each other, indicating that advancements of individual problems cannot be sustained in the long term without the support of advancements in other problems. The breakdown of the *Absolute Zero* problems into their secondary problems emphasises the complexity of them and indicates leaders to focus approaches and actions on the secondary problems to work towards the overall approach of the bigger primary problem.

The final consideration under step 4 is whether past research provides a foundation and can act as a starting point. As introduced previously, it must be noted that the purpose of the *Absolute Zero* Report is providing a clear outline with the use of current technologies to work towards absolute zero. As such, past research to provide a starting point of developing the approach is not applicable for this analysis. However, when thinking about the impact of the problems beyond the Report, it can be noticed that part of the issues raised are planned for implementation and development with some key advancements already. Two examples of this are road vehicles and electricity. The secondary problems raised in the current analysis for road vehicles and electricity around infrastructure and uptake of renewable energy sources with available materials, are points that are limiting the further implementation and move towards them. When reviewing the interconnectivity of problems with road vehicles and electricity, it can be noted there is a high interconnectivity with other problems and they are in fact positioned as part of the lowest with respect to the problem aspect in the 9-box model. Especially with regards to electricity, various of the problems in *Absolute Zero* indicate the goal of moving towards electrification. This is dependent on the successful progress of the problem point of electricity.

4.4 Observations and Implications

Step 2 and Step 3 of the analysis have provided an overview of where the problems are positioned on the 9-box model along with the extent of them. The analysis in both of these steps examined the problems in *Absolute Zero* according to the criteria around the two aspects of problems important to consider: the problem itself and the stakeholders involved with it. From this it has been revealed that most problems sit in the complex category, with some fitting into the politically turbulent category. The interconnectedness of problems has dominated the analysis in step 4. It can justify why no single problem is classified as a tame problem based on the dependence of developments outside of the individual problem. Compared to the positioning of absolute zero in the very wicked problem category, it is shown that decomposing this into the 13 problems supports the approach and decreases the wickedness.

A frequent issue that is present throughout the analysis of *Absolute Zero* is that of transition problems. Various points raised in *Absolute Zero* have a secondary problem in which the move towards the solution provided is dependent on a transition period. An example of this is the problem around heating with switching gas boilers to electric pumps. Another example of a transition problem is that around food with stopping consumption of beef and lamb. The transition period associated with these two examples vary, and the behavioural change of individuals plays a large factor in this. This is especially the case for stopping the consumption of beef and lamb. This could happen instantly but is highly dependent on every single individual to go along with this change and adapt their habits, so the behavioural change plays a large role in this. The transition period for switching gas boilers to electric heat pumps clearly has a much longer lag associated with it due to their manufacture and installation. These examples suggest that secondary problems and transition problems are a feature of most problems that can be analysed using this methodology. They fit well enough into the nine boxes but may need further decomposition to eliminate the secondary and transition problems.

Another recurring theme in the analysis of the 13 problems in *Absolute Zero* is that several problems are formulated more as solutions rather than outlining the problem. However, a category where a solution has been outlined but a problem has not been defined cannot be detected on the 9-box model. Despite this, they have been positioned on the 9-box framework as appropriately as possible and based on the criteria outlined. Furthermore, the problems are formulated in an exaggerated way, with no implementation planned outside of the *Absolute Zero* Report, so there is no degree of stakeholder alignment on this. This leads to an adaptation of the 9-box model by adding a row and a column to reflect the lack of classification enabled previously.

There is one category missing in the problem complexity criteria, with a natural extension of the logic in this, a fourth combination is recognised of cases where a solution but no problem is outlined. The analysis of *Absolute Zero* shows that these are situations that can occur and therefore should be integrated into the framework, adding an extra row.

Furthermore, the model would benefit from adding a column for the stakeholder aspect describing problems defined for stimulating debate without intention of execution. This can be justified on the basis that exaggerated situations exist which are put forward for provocation of stakeholders rather than aiming at providing a solution, as shown in the analysis of *Absolute Zero.* This extreme treatment of stakeholders explains that an extra column is necessary. Secondary Problems and Transition Problems do not form a basis on the amendment moving towards the 16-box model because mechanisms that enable a positioning on this new model, as will be explained in further sections.

Adding boxes in this way leads to seven boxes complementing the previous model and making contribution to knowledge, moving towards a 16-box model which is shown in Figure 4.2 below. The seven additional boxes are named: 1. Provocation, 2. Realisation, 3. Call to Action, 4. Supportable Opportunity, 5. Challenging Opportunity, 6. Paradigm Shift and 7. Ignored Issues. An explanation of the new boxes added to the model as well as an example of a problem that would fit in the category is provided in Figure 4.2 and Table 4.17 on the following pages. Based on the analysis of *Absolute Zero* and it being a report developed in the research domain the applicability of the further boxes can be seen in this environment with the possibility of extension to be applicable more generically subject to further investigation.

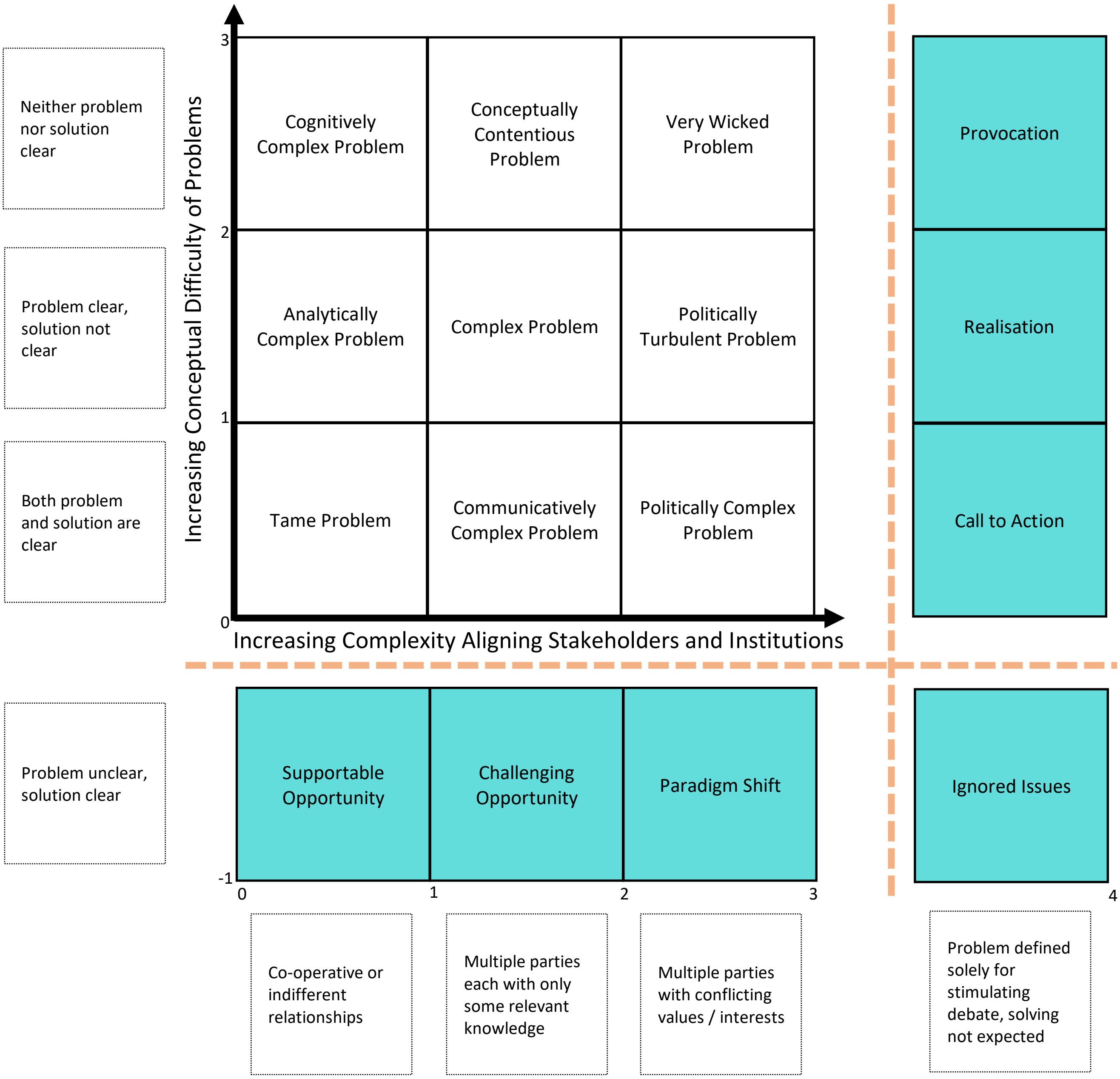


Figure 4.2 16-Box Model

Table 4.17 Description of New Boxes	
New Box Title	Example Approach
Provocation: A general issue is raised as a burning platform for action, without any consideration of potential mitigations	Activism, direct action, campaigning
Realisation: Evidence of the issue is presented and published without any proposal or speculation on solutions.	Awareness raising, Challenge based innovation
Call to Action: A call to adopt a solution which is available but for the most part unacceptable at the human or social level	Technology adoption initiatives, banning certain forms of behaviour
Supportable Opportunity: An area where research is interesting and sufficiently well aligned to available funding models to be well supported.	Digitalisation of manufacturing
Challenging Opportunity: An area with potential for development, but not well aligned to themes supported by funders	Remanufacture
Paradigm shift: An area of potential Research and Development and potential major breakthrough which is contrary to accepted thinking	Early pioneering work on quantum physics or chaos theory
Ignored Issues: Situations that only become problems because they are not discussed based on unacceptability of discussion in an area, or the belief that a particular topic is taboo in some way.	The reason behind the taboo nature of the issue needs to be understood and could make it difficult for individuals to make progress, however the proposed approach would start with getting the issue onto the discussion table in a form which minimises emotional attachment

The new 16-box model is brought forward as a model encompassing the requirements of a research report such as *Absolute Zero.* Based on this, it will be used in the following section analysing the roadmap of the FEMM Hub, which can also be defined as a report developed in a research environment.

4.5 Refining Framework

The purpose of this chapter is the testing of the framework and its refinement based on the analysis of *Absolute Zero*. Some advancements within the general set-up of the model have been undertaken by moving towards a 16-box model shown above. When taking a closer look at the steps in the analysis, it has been noted that some criteria in step 2 are continuously ranked as being of neutral importance. This indicates that the criteria do not provide further value for the determination of the problem classification and are therefore taken out of further analysis. The criteria removed from the problem complexity side are: 1. defined relationship between actions and outcomes and 2. relationship between cause and effects. This leads to the following problem complexity criteria established within the analysis steps:

1. Is there a clear and unambiguous definition of the problem?
2. Is the nature of the problem agreed and accepted by all stakeholders?
3. Is the problem accepted as a technological one?
4. Is the problem accepted as one of organisational and leadership setup?
5. Does the problem extend beyond technology, organisation and leadership?
6. Is the viable solution available?
7. Has a clear and accepted solution or approach been agreed?

In the stakeholder difficulty criteria 1. diverse values in decision makers and 2. conflict in assumptions and beliefs are mostly ranked as being of neutral importance for problem positioning. Therefore, they are removed from the framework analysis criteria leading to the following criteria establishing within the stakeholder difficulty aspect:

1. Are the stakeholders involved with developing the solution acting in cooperation?
2. Are the stakeholders who will need to accept and implement the solution known?
3. Are the stakeholders who will need to accept and implement the solution acting in cooperation?
4. Does the sum of knowledge needed to resolve the problem reside within a single party?
5. Are multiple parties, with potential or actual conflicts of interests, needed to address the problem?
6. Do people share underlying values which can drive common perspectives and alignment in their actions?

Regarding step 3 of the analysis, the point on knowledge fragmentation is similar to a point mentioned in the Step 2 of the framework around stakeholder complexity regarding whether knowledge is split amongst stakeholders. Therefore, this point is removed from step 3. As it is already considered in the second step, it is not necessary to focus on it again in the third step. As a result of this, it has been removed from step 3.

The new set of considerations for the third step are the following:

Structural complexity: inherent intractability of the technical (i.e. non-stakeholder-related) aspects of the problem.

Knowability: Not only is there little knowledge about the issue, but the nature of the problem or its solution means that: relevant information is hidden, disguised or intangible; it comprises multiple complex variables; its workings require action to discover causal links and outcomes.

Knowledge-framing: some of the knowledge receives either too much or too little attention because of the way it is framed, thereby distorting our understanding.

Power-distribution: There is a dysfunctional distribution of power among stakeholders.

Interest differentiation: The various stakeholders have interests (or values) which are substantially in conflict with those of others.

In step 4 the position of the problems is checked again on their relative position to each other and the two axes. Some of the criteria points are not clear though.

The point raised on leaders in organisation engaged in the project taking action or forming teams to take action regarding the issues addressed does not provide a deeper understanding for the classification of problems onto the framework. In the analysis of *Absolute Zero* it suggests the approach of the secondary problems. Furthermore, it is a basis for action to work in groups. The stakeholder aspect is mainly around the aspect of collaboration for projects to be approachable. Due to this, having an extra factor for pointing out whether someone is acting on the projects or whether they are forming teams to take action is redundant. This is the basis in the approach for wicked problems. This leads to the discarding of this factor for the step 4.

1. Are the issues generic (rather than specific to one company or industry) and what is the potential impact?
2. Are critical stakeholders engaged in the problem and / or its solution?
3. Do people involved foresee difficult change issues (seem impossible to surmount)?
4. Can the impacts be leveraged and diffused widely beyond the primary application?
5. Does past research provide a foundation of prior theory, acting as a starting point?

4.6 Summary

The analysis of *Absolute Zero* using the framework provided an overview of how decomposing the overall problem of absolute zero down into 13 actions has helped decrease in wickedness as shown by the 13 problems being placed in categories on the 9-box model ranked lower in wickedness. Furthermore, this analysis provided a basis for refining the model that has been provided by Alford and Head (2017) and moving it forward towards a 16-box model. This provides a clear contribution to knowledge by testing the model with the framework and advancing it. There are several key points to take away from this chapter. The *Absolute Zero* report formats points as solutions rather than highlighting the reasons for them with no indication of a problem. It has been found that secondary problems are a major part of the 13 problems within *Absolute Zero*, which can hinder the effective deployment of solutions for this. Transition problems can be seen as a type of secondary problems where a time frame is required for successful implementation of the problem. Furthermore, it was found that decomposing problems based on interconnectedness provides a practical way of decomposition which would reduce the thought-provoking aspect of the *Absolute Zero* Report though. Overall, the framework has been refined to the questions of analysis providing a deeper insight for positioning problems onto the framework, with the 16-box model being more encompassing of the needs for problem positioning of cases such as *Absolute Zero*.

4.6.1 Contributions to Knowledge and Key Findings from Chapter 4

In summary, the following can be considered as the contributions to knowledge and the key findings from this chapter.

Contributions to Knowledge:

- Moving the Alford and Head (2017) 9-box model forward to the 16-box model
- Providing a way to classify problems onto the model through the complexity classification card, this has been refined as part of this chapter
- Contribution to practice by using framework to run through data and to come out with a better understanding of the challenges and actions

Key Findings:

- Secondary Problems are a major part of the *Absolute Zero* Actions, which can hinder the deployment of solutions
- Transition problems as a part of secondary problems where a transition period is required for implementation
- Decomposing based on interconnectedness as a practical way for decomposing

Chapter 5 – Case Study: FEMM Hub Roadmap

5.1 Introduction

The previous chapter on testing the 9-box model, originating from the research of Alford and Head (2017) along with the four steps of analysis, showed that the steps could be refined. Furthermore, the chapter led to the development of a 16-box model, which addresses a wider range of situations linked to the research space. This will be validated within this chapter by applying it to a roadmap for electrical machines developed by the Future Electrical Machines Manufacturing (FEMM) Hub. Some differences between the *Absolute Zero* Report and the FEMM Hub roadmap have to be highlighted: The *Absolute Zero* report focuses on the behavioural change whilst the Roadmap is focused on engineering and technology change. The underlying thought behind both is similar though: the move towards net zero.

5.1.1 FEMM Hub Introduction

The FEMM Hub is a seven-year research programme across several Universities in the UK that started in April 2019, with the aim to play a lead role in electrification in the UK Manufacturing environment (FEMM Hub, 2023a; Ward et al., 2023). The Universities involved in the FEMM Hub are: University of Sheffield, Newcastle University, University of Strathclyde, University of Bristol. The research centres involved with the FEMM Hub are: National Manufacturing Institute Scotland (NMIS), Advanced Manufacturing Research Centre (AMRC), High Value Manufacturing Catapult (HVMC).

It focuses on manufacturing challenges for producing electrical machines for the energy, automotive, aerospace and premium consumer sectors (FEMM Hub, 2023a). The hub supports the UK Manufacturing environment to provide value in the electrical machine supply chain, develop the industrial productivity, bring environmental benefits and sustainable growth to the core of the UK's industrial strategy (FEMM Hub, 2023a).

The research activities of the FEMM Hub are divided into two phases with two grand challenges; 1. Manufacturing-led innovation in electrical machines and 2. process innovation, monitoring and simulation, there are also several cross-cutting themes (FEMM Hub, 2023b). The two phases of the research agenda focus on the seven-year spread (FEMM Hub, 2023b).

For the first half of the research period, the FEMM Hub had to provide a clear research programme, the first phase. The second phase of the research programme was developed in agreement with the advisory boards (FEMM Hub, 2023b). These research activities are described within the electrical machines roadmap.

Roadmaps can be used as a form of communication (Daim and Oliver, 2008). Communication is especially important for net zero where electrification plays a significant role, in order to provide clear goals and milestones, align stakeholders and facilitate collaboration (Barras, 2021). Due to this, the analysis of the FEMM Hub roadmap will form a case study to further apply the previously discussed framework and test its applicability to roadmaps. The analysis of the *Absolute Zero* Report in the previous chapter led to a development of the 9-box model into a 16-box model. The analysis of the FEMM Hub Roadmap will be used to validate this new 16-box model. The Roadmap and the Report are similar in some ways, but different in others. They have a different approach for communication of achieving sustainability which is expected to show a difference in the applicability of the framework. The FEMM Hub Roadmap is more focused on the development for electrical machines whilst the *Absolute Zero* Report provided a holistic agenda of achieving net zero by 2050. The key difference is the approach of the roadmap being more engineering and technology focused, whereas the Report does not work with changes in technology but rather on transition problems where behavioural changes are in focus. Another systematic difference between the Report and the Roadmap are the time they were created within the programme timeline. The *Absolute Zero* Report was produced at the very start of the UK FIRES research programme, whereas the Roadmap was produced at the mid-term stage of the FEMM Hub research agenda. As such it can be argued that the Roadmap potentially suffers from having to fit established content into a framework rather than serving as a planning basis for the programme. Nevertheless, the FEMM Hub Roadmap is a suitable case study to test the new 16-box model for assessing the applicability of a roadmap for approaching wicked problems, especially that of Net Zero, where electrification plays a central role.

5.1.2 Roadmap Introduction

The roadmap is a collective piece of work produced by FEMM Hub investigators and researchers using information available in the public domain, research publications, workshops and discussions with FEMM Hub industrial partners (Ward et al., 2023). There are industrial partners with different backgrounds that have contributed to the roadmap and the work for the FEMM Hub in general. For example, from the renewable energy side there is Siemens Energy, from the Aerospace side there is GKN Aerospace and UTC Aerospace Systems, and from the Automotive side there is ZF (FEMM Hub, 2023a). Further partners of the FEMM Hub and contributors to the Roadmap are: Aerospace Technology Institute, Airbus, Carpenter Technology, Collins Aerospace, Dyson, GKN Automotive, Hexagon, Höganäs, McLaren, Motor Design Limited, National Physical Laboratory, Protean, Rolls-Royce, Rotary Engineering, Tannlin, Twinn (Ward et al., 2023). The performance of and market demand for electrical machines are the key focus of future electrical machines in the transition to net zero and as a result they are also in focus for the roadmap (Ward et al., 2023). The roadmap uses the net zero goal and works back from this to define the significance and requirements of this for electrical machines manufacturing in the future (Ward et al., 2023). There are several key points that this is made up of, which can be divided into a set of lists around: 1. High Level Needs, 2. Supply Chain Responses, 3. Technical improvement factors, 4. Product Features and 5. key characteristics of a future electrical machines factory (Ward et al., 2023). These will be the focus of the following sections.

5.2 Roadmap Key Points

The roadmap was assembled in 2022-2023 and first looks at the policy side of net zero. This is set in a time of a Conservative UK Government, post Brexit and post Covid. The transition to net zero and the economic benefits in committing to this early on were seen as strategic imperatives for the UK at the time. The roadmap decomposes the net zero issue for electrical machines into four key areas for future electrical machines, described as high-level needs (Ward et al., 2023: p.15):

1. *"The provision of step change technologies for both machine performance and manufacturing resource efficiency*
2. *Making machines better to perform better*
3. *Materials supply, potential replacement for scarce materials, and enablement of a circular economy approach which supports anticipated market growth with known limits to availability and capacity of materials*

4. *The ability to support radical growth in demand for certain classes of product, component and material, coupled with substantial uncertainty over the magnitude of that growth."*

The high-level need on *making machines better to perform better* can be unclear with its meaning. Performing better here can refer to the efficiency, power to weight and end-of-life of electrical machines.

However, when using the policy environment for net zero, several issues arise due to a lack of technology that can be operationalised at the current time. To respond to this, the FEMM Hub has developed a roadmap around four principles (Ward et al., 2023: p.16):

1. *"The need for flexibility*
2. *Identifying solutions with broad applicability*
3. *Place a continued emphasis on tracking future trends in policy, industry, and research and proactively seeking out opportunities which help address the net zero challenge*
4. *Work with industrial clients and meet their needs where possible"*

When projecting around 30 years ahead to the year 2050, there are significant uncertainties around the requirements of electrical machines. As part of the roadmap, several supply chain responses have been formulated that will need to be provided in a future electrical machine supply chain, which are applicable nonetheless (Ward et al., 2023: p.26):

1. *"Step change in production volume for high performance applications*
2. *Flexibility in physical supply chains and in the product development process*
3. *New circular economy provisions to support material availability under increased volume*
4. *And, especially to enable market disruption, substantial cost reduction"*

In addition to the needs and supply chain responses that are applicable, overarching across the development of electrical machines for 2050, there are some technical improvement factors for product, manufacturing and supply chain performance to work towards 2050 (Ward et al., 2023: p.27):

1. *"Power and torque density*
2. *High efficiency operation*
3. *High-speed operation*
4. *Reliability and robustness*
5. *Sustainable lifecycle*
6. *Cost."*

The roadmap document of the FEMM Hub provides details around each of these improvements with some suggestions on how to approach them by illustrating them through the use case studies. In terms of the power and torque density, it is suggested to reduce the structural mass of electrical machines which can be done through several ways (Ward et al., 2023). High efficiency operation is correlated to energy consumption which is expected to decrease with increasing efficiency of electrical machines (Ward et al., 2023). Reducing ohmic losses and reducing iron losses are discussed as the main forms of improving efficiency (Ward et al., 2023). The next point on reliability and robustness describes reliability with regards to dependability of products performing and robustness as the product being able to operate under varying conditions (Ward et al., 2023). Sustainable Lifecycle is a key point for sustainability of electrical machines in the long-term due to the reliance on them for electrification for net zero. The factors on reliability and robustness, sustainable lifecycle and cost are different to the first three on power and torque density, high efficiency operation and high-speed operation which focus more on the functionality of electrical machines and improvements in efficiency of them, rather than the further impacts of electrical machines. Overall, the technical improvement factors are all encompassing in nature, considering many factors which are not all addressed within the FEMM Hub Programme.

Using electrical machines does not cause direct emissions and hence has little impact on CO_2 emissions. However, they do rely on a source of electrical power that is not addressed as part of the roadmap, implying that net zero power generation is dealt with externally. Furthermore, the manufacturing processes are the focus of this point on sustainability as they need to be optimised for sustainability, for example the materials used, sourcing and extraction of materials and feeding materials back into the manufacturing at the end-of-life of products. For this to occur there is a dependency on changes, such as suppliers to uptake sustainability measures, infrastructure, economic viability and the availability of alternative solutions (Ward et al., 2023). As well as environmental aspects, economic factors like the cost, also play a significant role in the product development stage across cradle to grave as the products must build up a positive reputation and be worthy of replacing established products (Ward et al., 2023). Materials for electrical machines can fluctuate in price and increasing demand for electrical machines and therefore increasing demand in materials can have an impact on costs (Madonna et al., 2023). Furthermore, there is a limited global availability of certain materials currently needed in the manufacturing of electrical machines, such as rare earth elements. This further creates pressure on costs (Madonna et al., 2023).

Based on technological drivers of change and technical improvement factors, it is expected that future electrical machines have the following features (Ward et al., 2023: p.42):

1. *"Easier to manufacture - more automations in manufacturing electrical machines.*
2. *Tighter tolerances - better tolerance control in manufacturing and assembly.*
3. *Fewer non-active parts - less weight in structural components which do not directly contribute to energy conversion.*
4. *More integrated - more compact design and manufacture of electrical drive units, such as integrated electrical machine and inverter.*
5. *More scalable - more modular design and manufacture to enhance scalability.*
6. *Higher power density - higher power/weight ratio or power/volume ratio by higher speed designs, higher torque density designs, or better cooling designs.*
7. *Higher efficiency - more efficient energy conversion by reducing losses in windings, cores and/or magnets.*
8. *Higher process control capability - a more accurate and efficient control of complex processes in manufacturing parts.*
9. *Better service monitoring - better in-service condition monitoring of key parts of electrical machines, such as temperatures and mechanical stress of windings and magnets.*
10. *Easier to disassemble for end-of-life processing - a better design, manufacturing and assembly strategy to facilitate an effective disassembly for the end-of-life processing.*

11. *<u>More sustainable</u> - use more sustainable materials, such as non-rare earth magnets, and use more sustainable manufacturing techniques, such as remanufacture/ recycling for the end-of-life processing.*
12. *<u>Less embedded energy</u> - higher energy efficiency in manufacturing and assembly of electrical machines.*
13. *<u>Improved cooling</u> - More effective cooling techniques to facilitate a more efficient heat dissipation, such as direct cooling of windings and rotor*."

As part of the FEMM Hub research, there is also an emphasis on developing novel manufacturing systems for low and medium volume production of high value electrical machines. To be flexible with manufacturing processes, a factory for future electrical machines is expected to have the following key characteristics (Ward et al., 2023: p.45):

1. *"<u>Flexible</u> - accommodating a wide range of designs and volumes*
2. *<u>Efficient</u> - making optimal use of raw materials and energy*
3. *<u>Connected</u> - allowing data capture and exchange for traceability and quality assurance*
4. *<u>Resilient</u> - autonomously making decisions to avoid interruptions to production*
5. *<u>Semi-automated</u> - combining benefits of automation with skilled human operators*"

The technical improvement factors form the front end of the roadmap and are the areas under which other key points are structured.

The lists introduced above form the basis of the roadmap, which is shown in summarised form in Figure 5.1 below (Ward et al., 2023). The points on high-level needs and supply chain responses are overarchingly applicable. Technical improvement factors, future product characteristics and future factory characteristics are more specific. It can be argued that the main aim of the roadmap is to decompose the problem of electrical machines for 2050 in different ways. The different lists introduced above demonstrate a decomposition of the overall aim of making electrical machines ready for the year 2050.

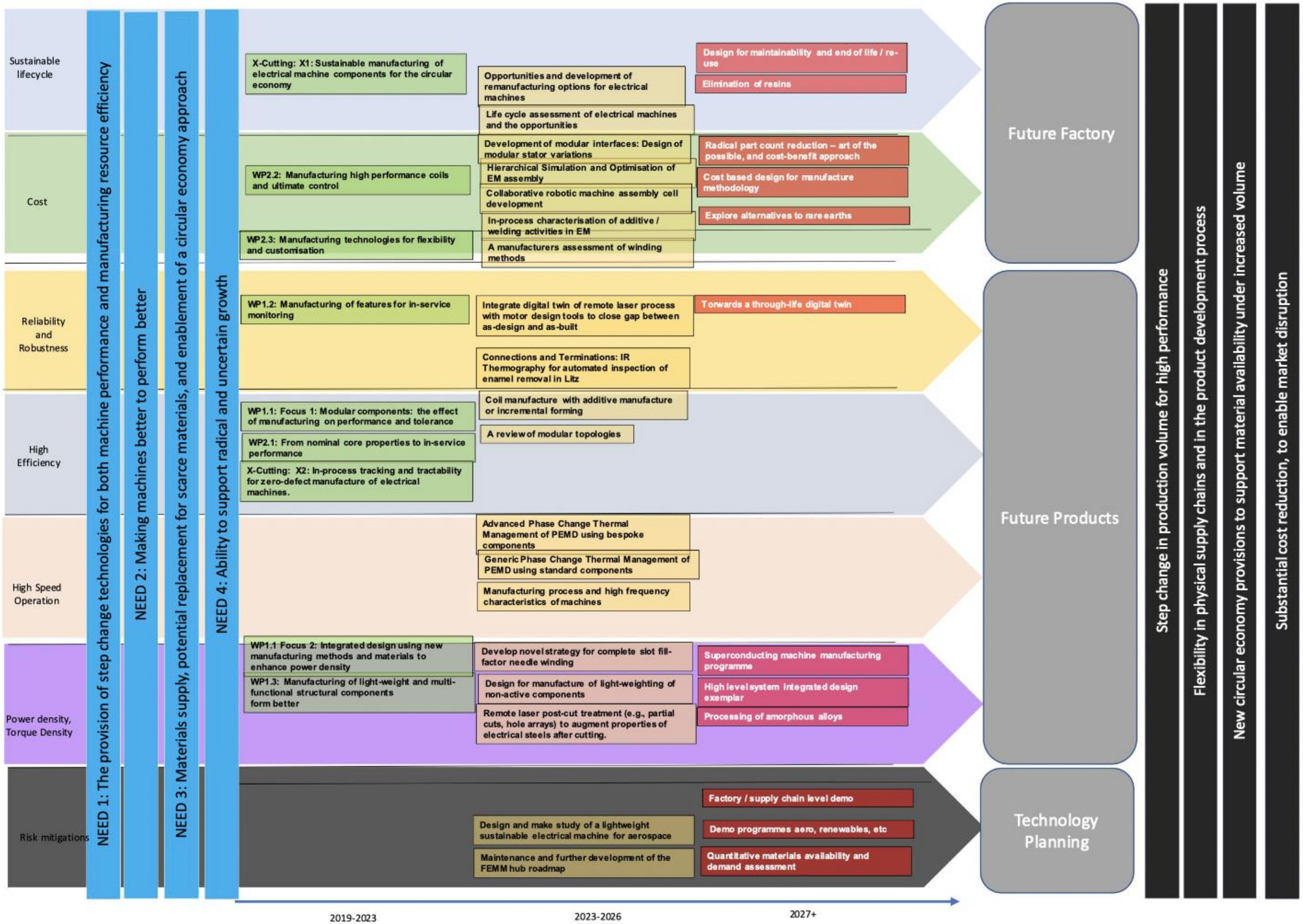


Figure 5.1 FEMM Hub High Level Roadmap

In the FEMM Hub high level roadmap the lists of different decomposition foci mentioned above are included and there is even further detail along with the FEMM Hub Roadmap Working Points and Cross Cutting Themes up until 2027 and beyond. The technical improvement factors are placed as the starting points of the roadmap and subsequently further decomposition of how to achieve these individual improvement factors is detailed. As previously mentioned, the factor around Sustainable Lifecycle plays a central role due to the importance of electrification for sustainability. From a wicked problems perspective, the Sustainable Lifecycle factor is interesting as it is anticipated that the interaction of stakeholders will determine the advances made under this improvement factor. The nature of the lifecycle of electrical machines suggests that there is a degree of interconnectedness between the stakeholders across the supply chain. This indicates that the Sustainable Lifecycle factor for electrical machines could be seen as a wicked problem where an analysis using the framework will be helpful to classify the problem and determine whether the decomposition under this factor is valuable. As a result, it has been decided to focus on this factor of sustainable lifecycle along with the decomposition factors provided in the roadmap.

5.3 Points for analysis using Wicked Problems Framework

Sustainability and the move to Net Zero is a key focus of this research. Hence, the analysis of the roadmap will also focus on points with sustainability and the circular economy which are most relevant for the analysis of wickedness.

Each of the technical improvement factors for product, manufacturing and supply chain performance are expanded on in the roadmap, giving an overview of the key considerations for them. Looking at the high-level roadmap, the points regarding sustainable lifecycle are as follows (Ward et al., 2023):

X-Cutting: Sustainable Manufacturing of Electrical Machine Components for the circular economy

- Opportunities and development of remanufacturing options for electrical machines
    - Design for maintainability and end-of-life/re-use
    - Elimination of resins

- Lifecycle assessment of electrical machines and the opportunities

As part of the analysis and for some illustration purposes along the analysis, the Sustainable Lifecycle points may be shortened and referred to in a summarised form as: Sustainable Manufacturing, Remanufacturing, Design, Resins and Lifecycle Assessment.

The points that are further indented indicate that they are considerations further in the future and further decomposed due to being more specific in their formulation. For the analysis, each of the points will be treated individually as problems to map onto the 16-box model. Furthermore, there will be a focus of the problems that are addressed by the FEMM Hub as the Roadmap has been developed within this scope. There will be some reference to the problems outside of the FEMM Hub scope.

5.4 Analysis of FEMM Hub Roadmap

Table 5.1 Complexity Classification Card Problem 1: Sustainable Lifecycle

5.4.1 Problem 1: Sustainable Lifecycle

Outline: To consider each stage of the lifecycle of a product and make changes to reduce its impact.

Step 1: Summary Evaluation

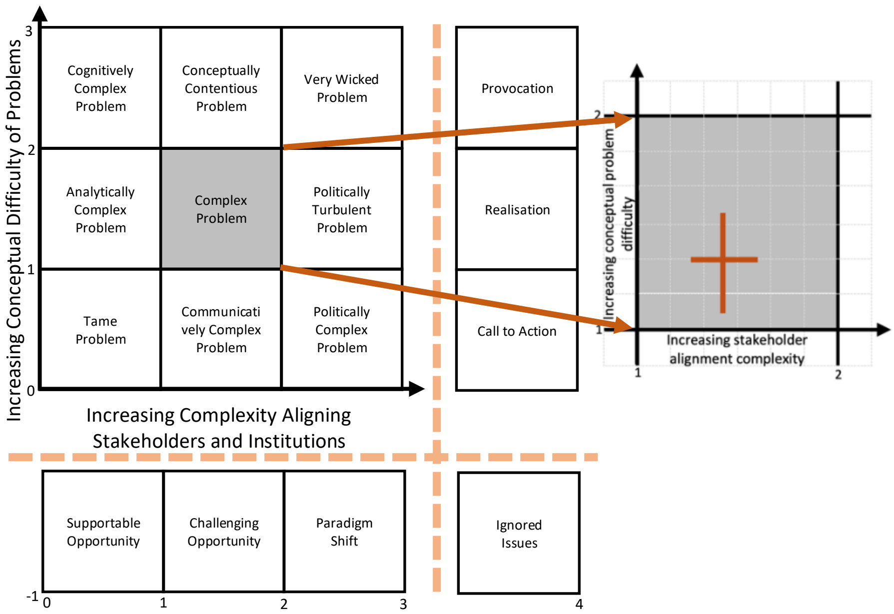
Sustainable Lifecycle is one of the technical improvement factors listed in the roadmap. The roadmap outlines product lifecycle as being considered from cradle to grave, reflecting a linear product life, or cradle to cradle, regarding a circular economy approach (Ward et al., 2023). Lifecycle impact is often measured by the amount of CO_2 emitted by a process (Ward et al., 2023). Whilst in use, emissions of electrical machines are lower than combustion engines, the manufacturing of them must improve immensely to become environmentally friendly, regarding materials, sourcing and extraction of materials, rerouting materials back into production at end-of-life (Ward et al., 2023). This is dependent on supplier sustainability, infrastructure for recovery, with a documentation of scope 1, scope 2 and scope 3 emissions providing a direction of where to focus improvement (Ward et al., 2023). The roadmap development revealed disassembly as a focus, especially designing for disassembly and elimination of resins. Secondary problems to the sustainable lifecycle problem are discussed in this chapter: design of electrical machines and elimination of resins. Some examples for designing for disassembly are provided in a case study in the roadmap, such as using reversible over irreversible fastenings, elimination of coatings, platings and resins, using modular designs and designing to allow easy access to components for operators (Ward et al., 2023). All these approaches together require time for implementation, leading towards a transition problem. Problems around resins and the difficulty of removing these from components leads to challenges for disassembly and repurposing. In the roadmap it is discussed that no clear solution has been found for producing electrical machines without resins.

Problem Complexity Overview

The roadmap discusses the use of electrical machines being sustainable with the problem being their unsustainable manufacturing. The agreement and acceptance of the problem and the solution is expected based on development in workshops with FEMM Hub Stakeholders. Clear signs of technological problem for creating a sustainable product lifecycle based on factors this is dependent on, such as designing for disassembly and elimination of resins. Leadership and organisation play a role in the coordination of designing for disassembly and eliminating resins. Not expected to extend beyond technology, organisation and leadership. Viability of solution limited based on dependency on advancements in other areas.

Stakeholder Difficulty Overview

Expected that stakeholders in FEMM Hub will cooperate for developing the solution, accepting and implementing this. The problem cannot be resolved by one stakeholder alone based on dependency on varying areas: designing for disassembly and elimination of resins for example. As a result, multiple parties are needed to address the problem. Shared values within stakeholder of the FEMM Hub are expected based on common research goal.



Step 2: How Complex is the Problem?

Problem complexity criteria	Problem complexity slider		Stakeholder difficulty criteria	Stakeholder difficulty slider	
	Low	High		Low	High
Clear and unambiguous definition	X (green)		Stakeholders developing solution cooperating	X (green)	
Stakeholder agreement and acceptance	X (amber)		Stakeholders to accept and implement solution known	X (amber)	
Technological problem	X (green)		Stakeholders to accept and implement solution cooperating	X (green)	
Organisational and Leadership problem	X (green)		Knowledge for resolving problem in one party	X (green)	
Beyond technology organisation and leadership	X (amber)		Multiple parties needed to address problem	X (green)	
Viable solution	X (green)		Shared values	X (amber)	
Solution agreed	X (amber)				

Step 3: Problem Extent – How big is the problem?

Problem Factors	Impact on problem extent	Stakeholder Factors	Impact on stakeholder extent
Structural Complexity	High	Interest differentiation	Low
Knowability	Medium	Power distribution	High
Knowledge Framing	Medium		

Overview: Technical challenges to implement solution based on dependency on advancements in other areas, such as design for disassembly and the elimination of resins. Some knowledge on solution around designing for disassembly already, including elimination of coatings, platings and resins. Knowledge on this is more developed over the specific knowledge on how to remove resins, therefore some degree of knowledge framing can be identified.

Overview: FEMM Hub Stakeholder agreement due to common goals under Hub umbrella. Elements of power distribution with each stakeholder holding key information to reach overall solution and not all stakeholders necessary for working on the same approach. Stakeholders with key expertise in specific area hold power for implementation in this.

Table 5.2 Complexity Classification Card Problem 2: Sustainable Manufacturing

5.4.2 Problem 2: Sustainable Manufacturing

Outline: X-Cutting Theme – Sustainable Manufacturing of Electrical Machine Components for the circular economy.

Step 1: Summary Evaluation

This is a cross-cutting theme of the FEMM Hub, highlighting the importance of sustainably manufacturing electrical machine components to make them work for a circular economy. This highlights a problem with the current manufacturing processes and suggests that they are incompatible with moving towards a circular economy. The process of sustainable manufacturing will be dependent on the component in question though, with each component having an individual set of stakeholders associated to them. The aspect of component dependency points towards a secondary problem and the absence of a system level view of manufacturing sustainability. A change within the manufacturing processes would have an impact across the supply chain that would need to be anticipated, based on this, various stakeholders could have conflicting interests and impede the progress of this problem. It would be advantageous to design electrical machines with sustainable manufacturing in mind from the start. With a circular economy approach, mining for component materials will decrease based on a circular economy of materials feeding back into the production for electrical machine components. This can be described as a transition problem of sustainable manufacturing. This is based on the time required for the volume of materials in circulation to reach a steady state.

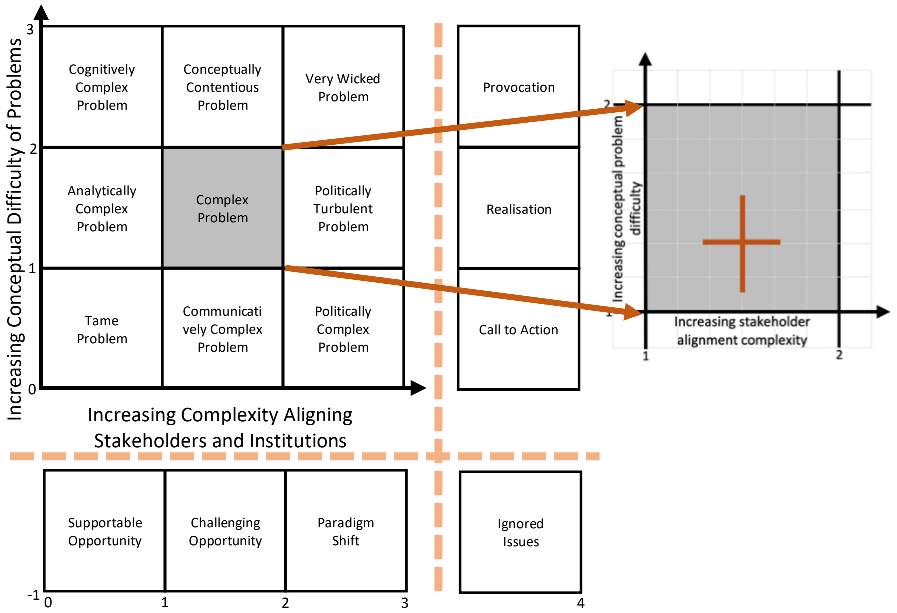
Problem Complexity Overview

Problem of manufacturing processes being incompatible with circular economy. General agreement within FEMM Hub stakeholders for cross-cutting theme.

Technical difficulties around adaptation of manufacturing processes, where organisation and leadership play a role. Not extending beyond technology and organisation. No clear ways to approach the improving of manufacturing processes given. Designing electrical machines with circular economy in mind is a prerequisite for this. Sustainable manufacturing processes is subject to advancements in technology improving processes.

Stakeholder Difficulty Overview

Stakeholders from the FEMM Hub, for example academic and industry based. This point is a cross-cutting theme of the research agenda, agreement for this across stakeholders expected along with collaboration for working towards this agenda. Stakeholders only partly representative of entire industry involved with electric machines. Knowledge for approaching problem spread amongst stakeholders of FEMM Hub, all of which are essential for implementing the solution. Some element of shared values, however diversity in industry partners indicates some disparities of values. Academic performance indicators for academic stakeholders more in focus.



Step 2: How Complex is the Problem?

Problem complexity criteria	Problem complexity slider: Low	High	Stakeholder difficulty criteria	Stakeholder difficulty slider: Low	High
Clear and unambiguous definition		X	Stakeholders developing solution cooperating	X	
Stakeholder agreement and acceptance	X		Stakeholders to accept and implement solution known	X	
Technological problem		X	Stakeholders to accept and implement solution cooperating	X	
Organisational and Leadership problem		X	Knowledge for resolving problem in one party		X
Beyond technology organisation and leadership	X		Multiple parties needed to address problem		X
Viable solution		X	Shared values		X
Solution agreed		X			

Step 3: Problem Extent – How big is the problem?

Problem Factors	Impact on problem extent	Stakeholder Factors	Impact on stakeholder extent
Structural Complexity	High	Interest differentiation	Low
Knowability	Medium	Power distribution	High
Knowledge Framing	Medium		

Overview: Technical difficulties of developing new manufacturing methods, leading to high structural complexity. Being a cross-cutting theme, knowledge is limited with work going into development of this knowledge. General knowledge on sustainable manufacturing practices available without direct application to electrical machine components. Knowledge framing difficult to determine due to specificity to components which can be described as a secondary problem.

Overview: Power distribution dependent on components. Power for changing manufacturing processes lies within component manufacturers. Constraints by external stakeholders can put pressure onto manufacturers. Development of sustainable manufacturing processes spread across stakeholders for invention and testing, leading to less exertion of power with impact. Interest differentiation limited based on common FEMM Hub agenda between stakeholders.

Table 5.3 Complexity Classification Card Problem 3: Remanufacturing

5.4.3 Problem 3: Remanufacturing

Outline: Opportunities and development of remanufacturing options for electrical machines.

Step 1: Summary Evaluation

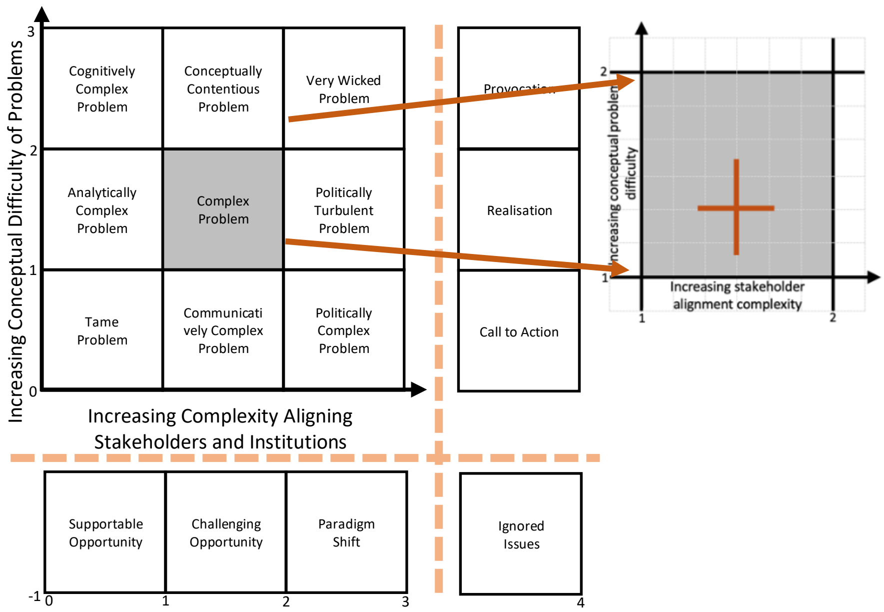
The point of remanufacturing highlights that remanufacturing options for electrical machines need to be developed and the opportunities this brings along. This supposes that there is a problem of resources, costs and environment aspects where remanufacturing is an approach to help overcome this. Remanufacturing processes are expected to be individual to the components in question. This points towards a secondary problem in this, with remanufacturing not being a one fits all solution, but rather specific to different components or materials. Stakeholders throughout the supply chain of electrical machines are affected by this, with the first process being to ensure an infrastructure making parts to be remanufactured available (Ward et al., 2023). This somewhat overlaps with the previous problem on sustainable manufacturing and the point brought forward on having a circular economy of materials. This point in the roadmap does not provide a clearly defined task on how to remanufacture.

Problem Complexity Overview

Based on roadmap development as an effort of FEMM Hub stakeholders, expected that this point brought forward has a degree of agreement and acceptance amongst stakeholders. Elements of technical difficulty and organisation and leadership for implementing solution. Moving beyond technology, organisation and leadership such as in designing and assembling electrical machines with remanufacturing in mind. This point in the roadmap does not provide a clearly defined task in how to remanufacture. Solution dependent on materials in question, therefore no unison agreement of a solution. Secondary problem of remanufacturing tailored to components.

Stakeholder Difficulty Overview

Remanufacturing processes work in progress within FEMM Hub (FEMM Hub, 2024). Implementation of solution highly dependent on industry partners and their supply chains, which is essential for this. Sum of knowledge spread amongst stakeholders, so solution cannot be implemented within one party alone. Motivations of stakeholders for this vary. Economic benefits most prominent within industry partners for remanufacturing over primary manufacturing whilst academics motivated by development of knowledge for theories of remanufacturing processes.



Step 2: How Complex is the Problem?

Problem complexity criteria	Problem complexity slider (Low – High)	Stakeholder difficulty criteria	Stakeholder difficulty slider (Low – High)
Clear and unambiguous definition	X	Stakeholders developing solution cooperating	X
Stakeholder agreement and acceptance	X	Stakeholders to accept and implement solution known	X
Technological problem	X	Stakeholders to accept and implement solution cooperating	X
Organisational and Leadership problem	X	Knowledge for resolving problem in one party	X
Beyond technology organisation and leadership	X	Multiple parties needed to address problem	X
Viable solution	X	Shared values	X
Solution agreed	X		

Step 3: Problem Extent – How big is the problem?

Problem Factors	Impact on problem extent	Stakeholder Factors	Impact on stakeholder extent
Structural Complexity	Medium	Interest differentiation	Low
Knowability	Medium	Power distribution	High
Knowledge Framing	High		

Overview: Currently remanufacturing of electrical machines, tackling problems around resources, costs and the environment, is not carried out in full (Li et al., 2024). Based on roadmap development as an effort of FEMM Hub stakeholders, expected that there is a degree of agreement and acceptance amongst stakeholders. Elements of technical difficulty and organisation and leadership for implementing solution. Moving beyond technology, organisation and leadership such as in designing and assembling electrical machines with remanufacturing in mind. Solution dependent on materials in question, therefore no unison agreement of a solution. Secondary problem of remanufacturing tailored to components.

Overview: Cooperation between stakeholders for developing solution expected based on efforts to develop roadmap together. Remanufacturing processes work in progress within FEMM Hub (FEMM Hub, 2024). Implementation of solution highly dependent on industry partners and their supply chains, which is essential for this. Sum of knowledge spread amongst stakeholders; solution cannot be implemented within one party. Motivations of stakeholders vary. Economic benefits most prominent within industry partners for remanufacturing over primary manufacturing whilst academics motivated by knowledge development for remanufacturing processes.

Table 5.4 Complexity Classification Card Problem 4: Design

5.4.4 Problem 4: Design

Outline: Design for maintainability and end-of-life/re-use.

Step 1: Summary Evaluation

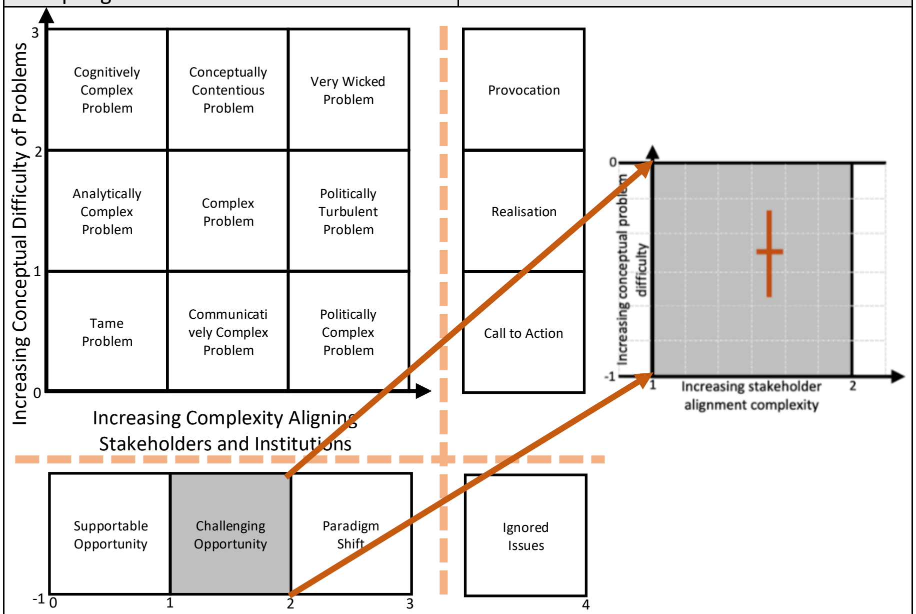
The problem around design is not clear, as the way it is written rather points towards a solution. The suggested solution is to design electrical machines for maintainability and end-of-life or re-use. This implies that electrical machines as they are currently designed do not consider maintainability and end-of-life or re-use. An explanation as to why this is necessary is not provided. This highlights a deficiency in the way the roadmap is written assuming starting preconceptions of readers that could describe this as an incompletely articulated problem. When considering the stakeholders that are involved for changing designs of electrical machines, it becomes clear that the responsibility for this lies within one group of stakeholders. However, the secondary problems of manufacturing of the changed design, for prototyping and testing, involves further stakeholders across the supply chain. Considering the previous problems introduced, it becomes clear that for electrical machines for a net zero future, design for maintainability and end-of-life or re-use is a foundational element for enabling this.

Problem Complexity Overview

Problem formulated as solution – designing electrical machines for maintainability and end-of-life or re-use. Implies problem with current designs not enabling maintainability and end-of-life or re-use. Agreement and acceptance of solution by stakeholders based on mutual development of point in roadmap. Technological complexities associated with secondary problem of new designs that need to be prototyped and tested prior to manufacturing. Some elements of organisation and leadership for solution based on managing difficulties of constraints for electrical machines. Design aspect indicates extension beyond technology, organisation and leadership. Solution requires some prerequisites for implementation as a transition from designing to final operationalisation of electrical machines takes time. Changes in design process not clearly defined for accepting of solution.

Stakeholder Difficulty Overview

Limited cooperation expected as no clearly defined change in design. Common working goal within FEMM Hub stakeholders indicates degree of collaboration. FEMM Hub stakeholders are accepting and implementing the solution for this. Designs more in responsibility of academic partners, implementation of designs in responsibility of industry partners. Requirements of electric machines dependent on use case where collaboration between academic and industry partners is required, indicating secondary problem. Knowledge for solution does not rest with one stakeholder group but is spread amongst stakeholders. There are stakeholders from different industries in the FEMM Hub, such as aerospace, automotive and renewable energy. Whilst there is a common goal within the FEMM Hub, industry partners from similar industries have increased shared values.



Step 2: How Complex is the Problem?

Problem complexity criteria	Problem complexity slider	Stakeholder difficulty criteria	Stakeholder difficulty slider
	Low / High		Low / High
Clear and unambiguous definition	X	Stakeholders developing solution cooperating	X
Stakeholder agreement and acceptance	X	Stakeholders to accept and implement solution known	X
Technological problem	X	Stakeholders to accept and implement solution cooperating	X
Organisational and Leadership problem	X	Knowledge for resolving problem in one party	X
Beyond technology organisation and leadership	X	Multiple parties needed to address problem	X
Viable solution	X	Shared values	X
Solution agreed	X		

Step 3: Problem Extent – How big is the problem?

Problem Factors	Impact on problem extent	Stakeholder Factors	Impact on stakeholder extent
Structural Complexity	High	Interest differentiation	Low
Knowability	Medium	Power distribution	Medium
Knowledge Framing	Low		

Overview: High structural complexity as designs need to be functional. Secondary problem of adapting manufacturing processes and material availability. Constraints of design change based on final application environment, indicating secondary problem. Systematic approach to design change recommended (Stipetic, Miebach and Zarko, 2015). Importance of point on material efficiency, energy efficiency and cost efficiency (Stipetic, Miebach and Zarko, 2015).

Overview: Interest differentiation in FEMM Stakeholders limited. Power can be exerted by external parties setting requirements for re-use of products. Academic partners in FEMM Hub more powerful in the development of designs, but consideration of industry requirements and industry partners have power for implementation of designs.

Table 5.5 Complexity Classification Card Problem 5: Resins

5.4.5 Problem 5: Resins

Outline: Elimination of Resins.

Problem Complexity Overview

This is a solution to a problem not clearly defined. General understanding of problems with resins with repurposing or recycling materials at end-of-life due to difficulty of separation from other materials. More tangible solution compared to previous suggestions from the roadmap. Agreement between stakeholders based on point emerging from development of roadmap. Stop use of resins no technical difficulty in first instance. Secondary problem of finding alternatives to secure functionality of electrical machines with technical difficulty. Primary problem not with organisational and leadership elements, however present with the secondary problem. No extension beyond technology, organisation and leadership. Viability of solution limited based on lack of functionality and secondary problem. Focus agreed with workshops in FEMM Hub on dry motors.

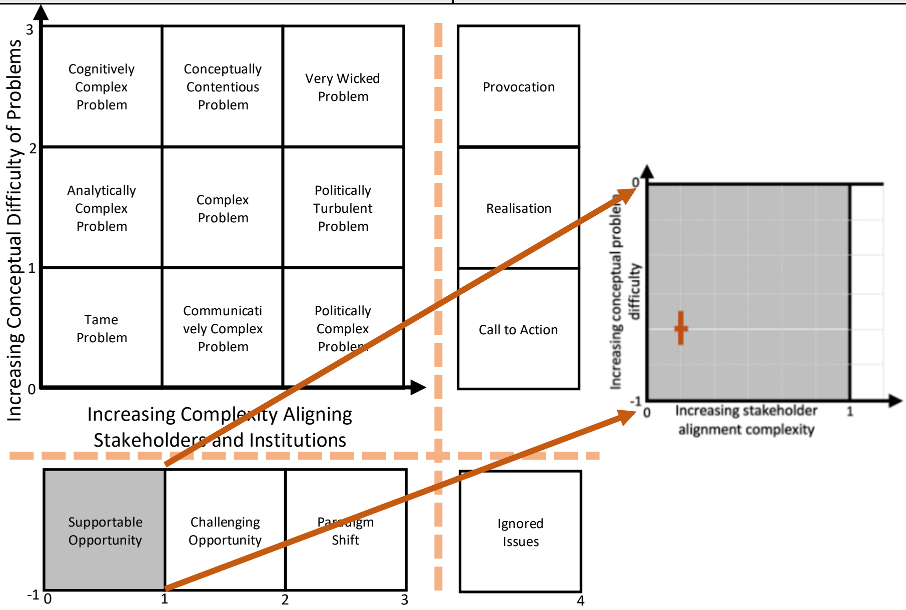
Stakeholder Difficulty Overview

Stop use of resins within one stakeholder. Secondary problem of operationalising electric machines without resins requires collaboration amongst stakeholders. Implementation of solution resting within manufacturers of electric machines. New production process with new design of electrical machines where collaboration across stakeholders is required. One party responsible for stopping use of resins. Secondary problems with manufacturing of electrical machines without resins requiring knowledge of multiple stakeholders. Shared values for primary problem having no impact based on responsibility within one stakeholder.

Step 1: Summary Evaluation

The point on resins does not provide a definition of a problem, but rather proposes a solution of eliminating resins. This can be put down to an issue with the way the problem has been formulated in the Roadmap. It is expected that this would support the overall goal of sustainable manufacturing of electrical machines for a circular economy. The responsibility for eliminating resins lies within the stakeholders handling resins, which is within only one stakeholder group. When resins are eliminated, alternatives must be found. This leads towards a secondary problem as the new designs would be required and new materials found where stock and availability need to be assured. The UK Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) has a list of substances and materials banned for use which must be considered when seeking alternatives for resins (Health and Safety Executive, 2022).

With the background in the roadmap showing that elimination of resins supports for the cross-cutting theme of sustainable manufacturing of electrical machine components for the circular economy, it highlights that this is part of the solution for achieving this overarching problem. As such, it is a decomposed element of the cross-cutting theme.



Step 2: How Complex is the Problem?

Problem complexity criteria	Problem complexity slider: Low	Problem complexity slider: High	Stakeholder difficulty criteria	Stakeholder difficulty slider: Low	Stakeholder difficulty slider: High
Clear and unambiguous definition		X	Stakeholders developing solution cooperating	X	
Stakeholder agreement and acceptance	X		Stakeholders to accept and implement solution known	X	
Technological problem	X		Stakeholders to accept and implement solution cooperating	X	
Organisational and Leadership problem	X		Knowledge for resolving problem in one party	X	
Beyond technology organisation and leadership	X		Multiple parties needed to address problem	X	
Viable solution		X	Shared values	X	
Solution agreed		X			

Step 3: Problem Extent – How big is the problem?

Problem Factors	Impact on problem extent	Stakeholder Factors	Impact on stakeholder extent
Structural Complexity	Low	Interest differentiation	Low
Knowability	Medium	Power distribution	Low
Knowledge Framing	Low		

Overview: Limited structural complexity as can stop use of resins immediately. High complexity of secondary issue on functionality of electrical machines without resins. Resins impeding disassembly at end-of-life and can reduce manufacturing costs and increase production speed (FEMM Hub, 2021; APC, 2021). To ensure functionality of electrical machines without resins, process expected to begin with design of electrical machines (FEMM Hub, 2021).

Overview: Interest differentiation between stakeholder of FEMM Hub is limited. Especially for elimination of resins, interest differentiation has little impact based on responsibility within one stakeholder. Power for this rests within manufacturers handling resins. Secondary problem of designing electrical machines without resins has more stakeholders involved where power distribution plays a different role.

Table 5.6 Complexity Classification Card Problem 6: Lifecycle Assessment

5.4.6 Problem 6: Lifecycle Assessment

Outline: Lifecycle assessment of electrical machines and the opportunities.

Problem Complexity Overview

Problem not clear, more a process or solution – creation of lifecycle assessment of electrical machines and opportunities associated with this. Opportunities part implies that lifecycle assessment reveals areas of change for improving sustainable lifecycle of electrical machines. Agreement and acceptance of solution by stakeholders expected based on bringing point forward in roadmap development. Technical knowledge for lifecycle assessment required. Organisation and leadership can facilitate required collaboration for conducting lifecycle assessment where transparency amongst stakeholders is key. No extention beyond technology, organisation and leadership. Weakness of roadmap with difficulty of quantifying material demands translated into difficulty of lifecycle assessment, impacting viability of solution.

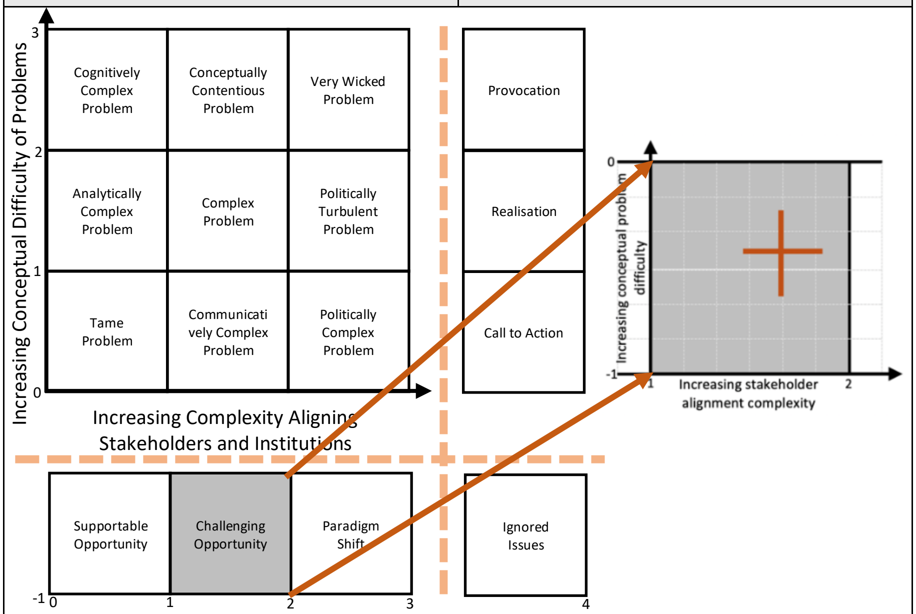
Stakeholder Difficulty Overview

Stakeholders for lifecycle assessment spanning entire supply chain of electric machines, which are not directly linked with FEMM Hub. Increases difficulty of cooperation for lifecycle assessment. Sum of knowledge spread across electric machines supply chain. Shared goal within FEMM Hub for manufacturing electrical machines for the future with sustainability as a key factor. Motivations for lifecycle assessment potentially varies by stakeholders, with some interested in economic benefits such as manufacturing companies, and others interested in the development of knowledge, such as academic stakeholders.

Step 1: Summary Evaluation

Creating lifecycle assessments of electrical machines is more a solution as opposed to defining a problem. Perhaps this is an issue of articulation of the problem in the Roadmap. The opportunities from this are not clear. Furthermore, the reason for a lifecycle assessment is not given. It is assumed that this informs stakeholders on the through life implications of ownership of electrical machines.

Stakeholders across the supply chain are required for developing a lifecycle assessment and it is expected that those under the FEMM Hub will collaborate. A weakness within the roadmap is the missing quantification of materials, as it was not possible to gather comprehensive information on this (Ward et al., 2023). This provides an indication of difficulties for making a lifecycle assessment where such information is required. This impacts the usefulness and applicability of the lifecycle assessment. Furthermore, it highlights a secondary problem element, being a transition problem where a specific transition period would be necessary to achieve a comprehensive lifecycle assessment of electrical machines.



Step 2: How Complex is the Problem?

Problem complexity criteria	Problem complexity slider: Low	Problem complexity slider: High	Stakeholder difficulty criteria	Stakeholder difficulty slider: Low	Stakeholder difficulty slider: High
Clear and unambiguous definition		X	Stakeholders developing solution cooperating	X	
Stakeholder agreement and acceptance	X		Stakeholders to accept and implement solution known	X	
Technological problem		X	Stakeholders to accept and implement solution cooperating	X	
Organisational and Leadership problem		X	Knowledge for resolving problem in one party		X
Beyond technology organisation and leadership	X		Multiple parties needed to address problem		X
Viable solution		X	Shared values	X	
Solution agreed	X				

Step 3: Problem Extent – How big is the problem?

Problem Factors	Impact on problem extent	Stakeholder Factors	Impact on stakeholder extent
Structural Complexity	High	Interest differentiation	Medium
Knowability	Medium	Power distribution	High
Knowledge Framing	Low		

Overview: High structural complexity based on high number of stakeholders involved across electrical machine lifecycle. Quantification of material important for this, which was a difficulty in roadmap development. Inactive parts good starting points of change to sustainability due to limited impact on electrical machine functionality where lifecycle assessment can guide developments on this (Boughanmi et al., 2012). No clear knowledge framing. Although inactive parts identified as quick win for development as more approachable for optimisation.

Overview: Interest differentiation potential based on lifecycle assessment relying on entire electrical machine supply chain. General agreement between FEMM Hub stakeholder, although scope for lifecycle assessment extends beyond these. Each stakeholder holds significant power for enabling fully comprehensive lifecycle assessment of electrical machines.

5.4.7 Step 4: Is there room for progress?

Step 4 is concerned with the comparison of problems against each other. Following the analysis, there are some general points that can be highlighted:

1. The problems in focus are less distinct and more overlapping compared to those in UK FIRES. This can be explained by exploring a set of problems under a specific pre-identified theme.
2. There is a recurring issue of problem articulation. The positioning of the problem on resins in the Supportable Opportunity category could potentially fall into a different category with a better description in the roadmap.
3. When looking at the breakdown of the problems from Net Zero, the problems in focus here are at a secondary and even tertiary level. This makes them more discrete but perhaps broadly applicable in several Net Zero Contexts, such as Net Zero Energy, Net Zero Flight, Net Zero Road Transport to name a few examples.

Figure 5.2 below shows the position of Roadmap problems compared to each other based on the analysis above. Sustainable Lifecycle is classified as a complex problem, along with remanufacturing and sustainable manufacturing. Resins fits into the Supportable Opportunity category and lifecycle assessment and design fit into the Challenging Opportunity category. This classification is based on the description of points within the FEMM Hub Roadmap. The wide spread of problems in the 16-box model supposes that potentially the description of problems within the Roadmap is unclear.

There are further questions to consider for comparing the importance of problems with each other. Similar to the *Absolute Zero* report, the interconnectedness of problems is a key part of this. Due to this, the first section of the analysis on step 4 discusses the interconnectedness of problems. Please see Appendix 4 for a diagram to show the problems with their secondary problems and the key themes of interconnectedness in this. This introduces the problems and their secondary problems, without aiming to be a comprehensive overview for these.

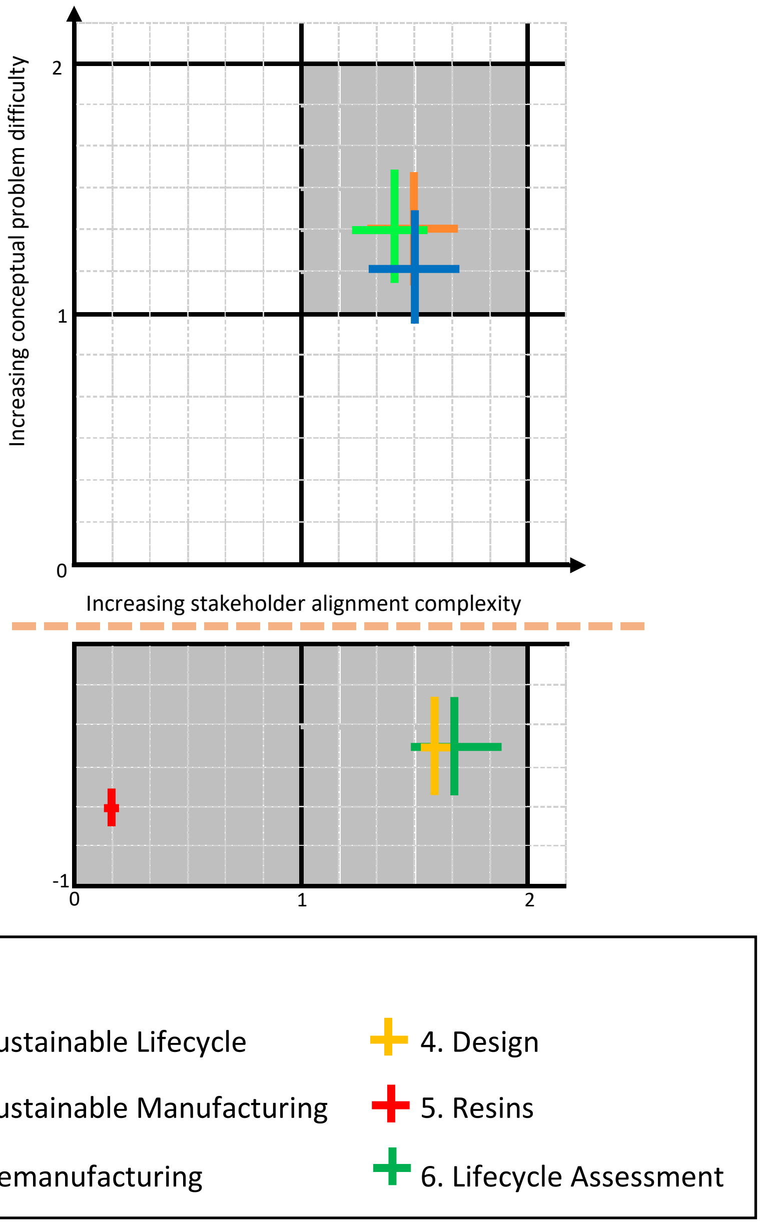


Figure 5.2 Problem Positioning Comparison

5.4.7.1 Interconnectedness of problems

With regards to the interconnectivity of the problems brought forward in the FEMM Hub Roadmap, three key themes have been identified: Component dependency, material availability and design of electrical machines. Component dependency is a secondary problem in sustainable manufacturing, remanufacturing and lifecycle assessment. The details within the component dependency problem of the primary problems vary, for lifecycle assessment the data specific to each component is important, for remanufacturing the processes are dependent on the component as the sustainable manufacturing factor. Nonetheless, the overarching element of component dependency is mutual and highlights that it is a key factor of consideration for moving towards sustainable lifecycle of electrical machines. The material availability is a secondary problem within design and resins. When designs are changed with new materials to be used, it is important to ensure these materials will be available for manufacturing. This is the same as with resins, where an alternative to resins must be found within the structure of electrical machines and this alternative needs to be available. In addition to this, design of electrical machines was a secondary problem for sustainable manufacturing, remanufacturing, resins and there was also the primary problem of design. Based on this it can be argued that if the primary problem of design is successfully approached, the problem on sustainable manufacturing and remanufacturing will be closer to fulfilment. In other words, the problems on sustainable manufacturing and remanufacturing are decomposed into the problem on design.

Furthermore, there are supplementary overlaps between primary problems that are part of the analysis and secondary problems. For example, a secondary problem of remanufacturing is the design for remanufacture of electrical machines and the fact that resins are prohibiting remanufacturing. These are two points that are also part of this analysis, and as such can be described as decomposing the points on remanufacturing into design and elimination of resins. Acceptance of remanufacturing can also be highlighted as an issue. The FEMM Hub does not deal with this as the focus of the roadmap is on technological solutions, disregarding stakeholder issues.

The technical improvement factor on sustainable lifecycle also has some secondary problems associated with it, such as design for disassembly and elimination of resins. These are two of the other problems of analysis, meaning that the sustainable lifecycle problem has been decomposed into these two problems. In other words, developing the design for disassembly point and advancing with the elimination of resins supports in the approach of the sustainable lifecycle problem.

5.4.7.2 Discussion of FEMM Hub Roadmap Sustainable Lifecycle elements with Step 4 Analysis Criteria

The roadmap from the FEMM Hub is unarguably focused directly on electrical machines. Many solutions proposed appear generic and self-evident until going deeper and asking questions of uptake and application, where the stakeholder dimension becomes important.

Even though the stakeholders of the FEMM Hub are from different industries, the overall goal is common: the development of high value electrical machines and their manufacturing to be at the forefront of the electrification revolution (FEMM Hub, 2024). Electrical Machines are the central enabler of electrification, which holds a key importance within the move towards net zero goals. Despite having this direct focus, the overall impact of developments in electrical machines can be extrapolated across industries for the purpose of electrification and therefore has a major element of genericness. The developments in the analysis points also support in this genericness based on the overall goal for the improvements in electrical machines. However, the individual points can be identified as having varying degrees of genericness:

- Sustainable manufacturing encompasses various manufacturing processes that are component specific and must be adapted.
  Increased degree of genericness.
- In contrary the point on resins has a direct focus on the removing of this.
  No genericness.
- The position of the sustainable manufacturing and resins on the 16-box model support this: sustainable manufacturing is classified as a complex problem and resins sits in the Supportable Opportunity category.
- Stakeholder complexity within the sustainable manufacturing points is higher compared to the point on resins. Design and Lifecycle assessment are positioned in the Challenging Opportunity category. They require interactivity of stakeholders.
  Elements of genericness.

- Sustainable lifecycle is directly decomposed into the points under analysis: design for disassembly and elimination of resins. It is classified as a complex problem. Advancements in Sustainable lifecycle can help overarchingly especially with further developments in the decomposed areas. Stakeholder interactivity is important for moving this forward.
  High degree of genericness.

This implies that for the successful implementation of sustainable lifecycle, sustainable manufacturing, remanufacturing, design, and lifecycle assessment, there are several critical stakeholders engaged with each being part of the solution to fulfil these points. Compared to resins, where only one stakeholder is initially in the responsibility to stop the integration of resins within the manufacturing of electrical machines. This indicates that there is a degree of complexity around several stakeholders being involved to accomplish these changes. However, based on the collaborative approach in the FEMM Hub for the development of the roadmap for electrical machines, and the common drive within the research Hub it is expected that these changes are not impossible to be effectuated.

Regarding acting upon or having dedicated teams to take action on these points, there are working groups within the FEMM Hub, especially for the Sustainable Manufacturing point which is a cross-cutting theme. The stakeholder considerations within the FEMM Hub are limited though. When looking at end-of-life and the stakeholders considered in this, it can be noted that stakeholders are not developed on and the stakeholders within the FEMM Hub are relied on. There are further stakeholders outside of the FEMM Hub environment that can affect the successful end-of-life process. Stakeholders such as recyclers play a significant role for end-of-life. It can be argued that for enabling sustainable manufacturing, there are several key activities that support this, such as developments in remanufacturing, design, elimination of resins and lifecycle assessment. Based on this, the sustainable manufacturing theme is decomposed into these points. Work focused on these decomposed areas will move the overall point of sustainable manufacturing forward, similar to sustainable lifecycle which is also decomposed into design for disassembly and elimination of resins. This is somewhat represented within the Figure 5.2 showing the overall positioning of points against each other. The point on sustainable lifecycle is identified clearly as a complex problem in the model.

Moving forward with the cross-cutting theme of sustainable manufacturing, the FEMM Hub can build on the research taking place within it. Numerous stakeholders are involved with this, where knowledge is developed in cooperation under the umbrella of the FEMM Hub work for moving towards electrification for a sustainable future. Based on this, the impacts of the successful sustainable manufacturing of electrical machines go far beyond the FEMM Hub itself given that electrification is a central pillar for the enablement of net zero. The sustainable manufacturing point in the roadmap is lacking rigour, which the analysis through the 16-box model has shown. Undertaking an assessment of problems proposed as requiring solutions in the roadmap is helpful as it shows whether real problems are tackled. Setting key issues to be addressed out as defined problems would increase the chance of successful resolution. These points highlight the importance of using the 16-box model, as it enables to better understand the characteristics of the actions in the Roadmap. Would the original 9-box model enable a similar understanding of these problems though? How does the position of the FEMM Hub points on the 16-box model compare to if the original 9-box model by Alford and Head (2017) were used for positioning? These questions will be discussed in the following section.

5.4.8 FEMM Hub Roadmap 9-Box and 16-Box Model Position Comparison

To further assess the validity of the 16-box model, the actions from the FEMM Hub Roadmap under the Sustainable Lifecycle point are positioned onto the original 9-box model and framework to compare the positioning. When starting the assessment of the Roadmap points using the original 9-box model, a constraint of the boxes available was noticed again with the lack of boxes to highlight situations where solutions are clear but the problems are not clear. Figure 5.3 below shows the FEMM Hub points positioned onto the 9-box model.

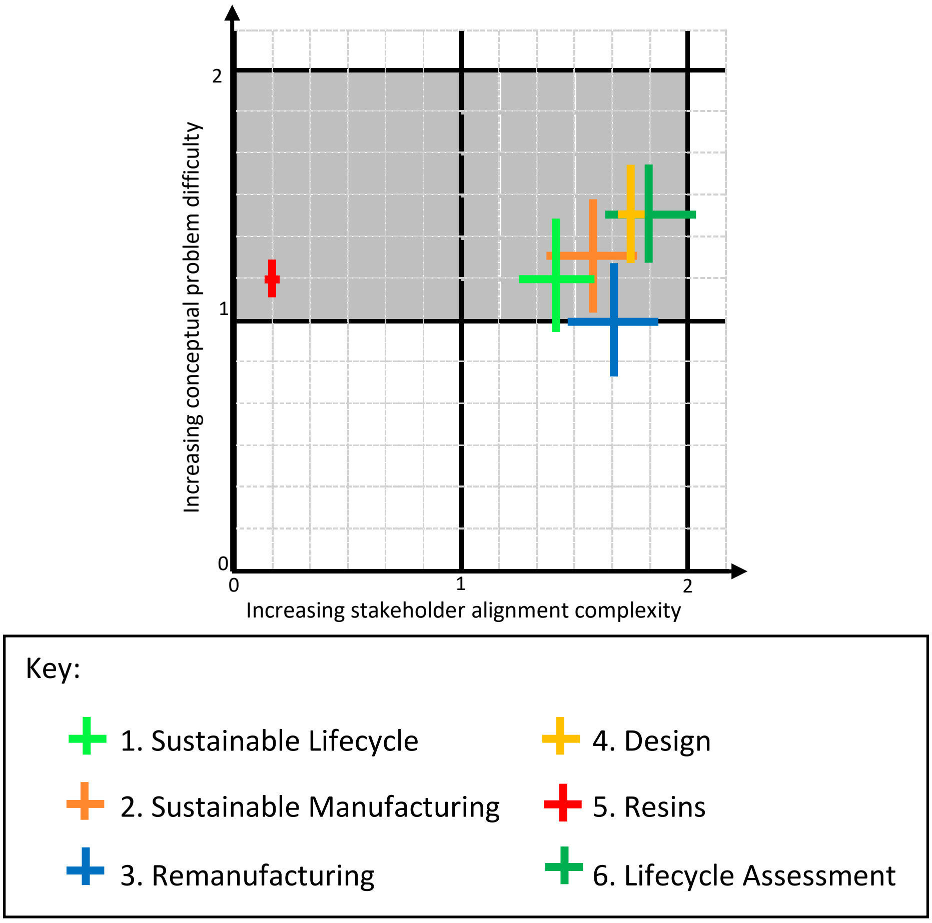


Figure 5.3 9-Box Model Problem Positioning Comparison

The positioning using the original 9-box model and framework was again a collective task amongst the research group with the supervisors for this thesis, bringing together the findings after individually carrying out the analysis. Going through the actions, a change in the position of the actions has been inevitable based on the lack of boxes to categorise situations where solutions are clear but problems are not. In the 9-box model the Sustainable Lifecycle, Sustainable Manufacturing and Remanufacturing points remained in the Complex Problem category. Design and Lifecycle Assessment have been moved from the Challenging Opportunity category to the Complex Problem category. The point on Resins has moved from the Supportable Opportunity to the Analytically Complex Problem Category. The move away from the challenging opportunity and supportable opportunity categories has been difficult, as it was sought to find a category on the original 9-box model to show the characteristics of these points within the restrictions of the 9-box model. The positioning on the original 9-box model does not reflect the true characteristics of the actions, because the complexity of the Design, Lifecycle Assessment and Resins points is not shown in the original model. The complexity of these points seems to be higher when using the new model compared to the 16-box model. This shows that there is a true value in the 16-box model for categorising situations to better understand the challenges around them. Further observations and implications of the new 16-box model and the analysis carried out in this chapter are discussed in the following section.

5.5 Observations and Implications

The FEMM Hub Roadmap has been analysed above using the four steps for positioning the sustainable lifecycle points onto the 16-box model. The positioning of problems as shown above highlights that the supplementary boxes of the 16-box model are needed for analysing documents, such as the FEMM Hub Roadmap. The new model enables an encompassing analysis of the points outlined. Based on the expression of problems within the Roadmap, the sustainable lifecycle point itself is classified as a complex problem, along with remanufacturing and sustainable manufacturing. The remaining points are classified as solutions: resins are positioned in the Supportable Opportunity category, Lifecycle Assessment and Design fit into the Challenging Opportunity category. They are classified as solutions as they do not have a clearly defined problem. This shows that the further boxes added by the development to the 16-box model are necessary. Furthermore, this points towards an issue regarding the quality of the FEMM Hub roadmap.

This adds an insightful angle to the FEMM Hub Roadmap as a document, suggesting that it is providing solutions to problems that are not there or at least the need for them does not follow logically from the analysis of needs and drivers in the FEMM Hub Roadmap. It seems to articulate the problems in a way that assumes background understanding to make it clear what problems are discussed. Providing more rigour in the introduction of problems is beneficial to avoid misinterpretation and confusion on them. This supposes that when challenges are set out in roadmaps, it is beneficial to define them accurately so they can be assessed systematically.

Overall, the analysis of individual problems becomes increasingly difficult based on their dependency on advancements in other areas. It becomes difficult to split the analysis between primary and secondary problems. However, this interconnectedness of problems helps to approach the overall sustainable lifecycle technical improvement factor for electrical machines. This means that approaching several decomposed problems in combination helps to approach the primary problem. Furthermore, the interconnectedness of the points revealed a clear line of decomposition building up on each other, with the point of resins being a result of such decomposition. This is visualised as being the less complex of the problems due to being in the responsibility of a single stakeholder group. This indicates that when problems are decomposed to the highest degree, they seem to become more approachable and support the overcoming of the initial problem. However, this highlights an issue with the sequence of problems in the roadmap. Through the analysis, it has been shown that approaching the most decomposed problem first supports the overall solving of the bigger problem. This indicates that in a roadmap timeline, the problems that are most decomposed should be positioned closer in time. As the timeline in the roadmap moves forward it should move towards the major problems, where decomposed problems stem from.

The decomposition of problems can also be identified as the root cause of a difference between the problem positioning of the FEMM Hub Roadmap and the *Absolute Zero* Report. The *Absolute Zero* Report breaks down the overall problem of absolute zero by one degree into 13 actions. The FEMM Hub goes down further decomposition steps. This is illustrated in Figure 5.4 below showing a sequence of decomposition of both the UK FIRES *Absolute Zero* Report extending into the FEMM Hub Roadmap.

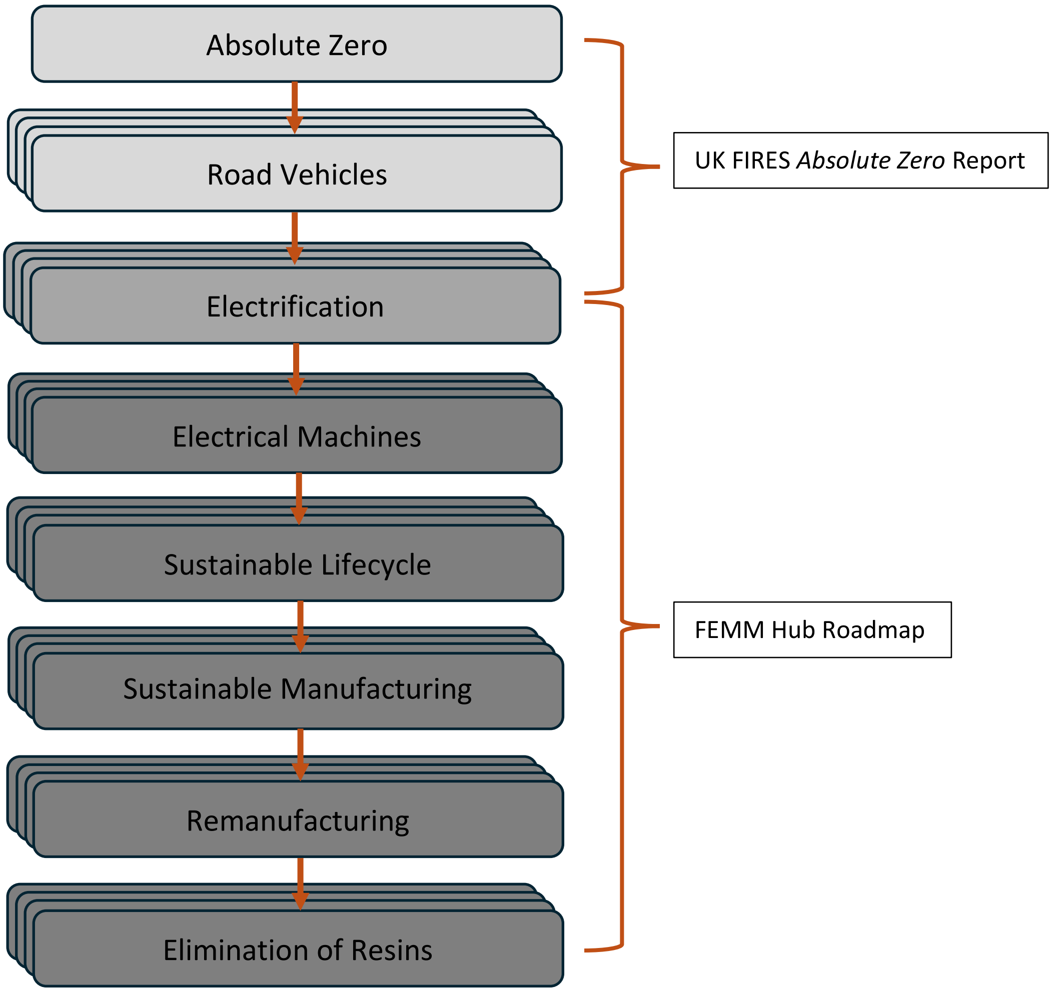


Figure 5.4 Sequence of Decomposition

The analysis of the FEMM Hub Roadmap has shown the necessity of the further categories introduced in the 16-box model and the value of these. The model can be used outside of the research environment. Staying in line with the idea of sustainability, the United Nations have brought forward 17 Sustainable Development Goals, which can form the basis of a further case study for analysing and positioning using the 16-box model. There are 17 Sustainable Development Goals for 2030 calling countries to work in global partnership to end poverty, improve education and health, reduce inequality, tackling climate change including preserving forests and oceans (United Nations, 2024).

- Goal 1: No Poverty – ending poverty in all its forms everywhere.

  This could fit into the Challenging Opportunity Category of problems, based on this entailing various stakeholders that can hold part of the information to implement no poverty and supposing the direct solution of No Poverty.

- Goal 17: Partnerships for the goals

  This potentially fits into the Supportable Opportunity category. Partnerships and Collaboration are deemed necessary and the solution for the overall sustainable development goals. Under this it would be expected that there is a cooperative environment.

Further analysis of this using the steps in the complexity classification card would be necessary to demonstrate this.

5.6 Summary

This chapter analysed the FEMM Hub Roadmap with the four steps for positioning the sustainable lifecycle points onto the 16-box model. Some of the key points of this are outlined below:

- Further boxes added in the 16-box model needed for enabling encompassing analysis of case study on FEMM Hub Roadmap. Points from the FEMM Hub are classified in the further boxes: Challenging Opportunity and Supportable Opportunity.
- Expression of problems forms the base of analysis: there is value in defining the problem accurately to minimise the opportunity for misinterpretation which could lead to a faulty analysis of problems.
- Decomposition of problems in a roadmap setting suggests working on points that are directly approachable, which have been subject to a high degree of decomposition, should take place earlier rather than later.
- Decomposition as a key factor differentiating the UK FIRES and FEMM Hub problem positioning. The FEMM Hub roadmap decomposed the overall point on sustainable lifecycle in further degrees, as opposed to one degree in the *Absolute Zero* Report impacting the overall positioning of individual problems.
- Possible applicability of 16-box model outside of the scope of this research, such as in the United Nations Sustainable Development Goals, subject to further research.

5.6.1 Contributions to Knowledge and Key Findings from Chapter 5

In summary, the following can be considered as the contributions to knowledge and the key findings from this chapter.

Contributions to Knowledge:

- Contribution in providing a framework for assessing situations to understand their characteristics
- New 16-box model validated through the analysis of the FEMM Hub roadmap which shows the necessity of the further boxes added through the model
- Applicability of a roadmap in a wicked problems setting to decompose problem and make it more approachable
- Suggesting areas of further applicability of the 16-box model, such as the United Nations Sustainable Development Goals

Key Findings:

- It has been found that providing a clear definition of the situations under analysis is necessary to enable a clear assessment of the situations
- Working on points that are directly approachable, which have been subject to a high degree of decomposition, should take place earlier rather than later.

The following chapter will further discuss and compare the two case studies along with reviewing the importance of this for the research environment.

Chapter 6 – Findings and Discussion

6.1 Introduction

The previous two chapters led to the development and validation of a 16-box model for problem classification. Some observations and implications from the analysis of the two case studies have been introduced. The findings from this will be highlighted before discussing the importance of the 16-box model and its contribution to the research domain. The research questions brought forward in the literature review will also be reflected upon as part of this chapter.

6.2 Findings

The findings of the two case studies, the UK FIRES *Absolute Zero* Report and the FEMM Hub Roadmap, will be expanded on individually. This will allow a comparison of the two case studies to be drawn in a subsequent section.

6.2.1 UK FIRES *Absolute Zero* Report Findings

The aim of Chapter 4 was to test the framework using the four steps to position problems onto the 9-box model. When starting the analysis with the initial method described, it was found that the process results in a large amount of written narrative that is difficult to interpret, thus making it difficult to implement. Hence, the steps were reviewed, leading to a summary step replacing step 1 and the three other steps remaining the same. Furthermore, to display the analysis in a more presentable way and to facilitate comprehension, a consolidated overview of the steps has been developed in the form of the Complexity Classification Card. This approach focuses on the key points from the steps and visually displays them.

The analysis of *Absolute Zero* revealed the importance of secondary problems for the successful implementation of the 13 actions. One of the challenges in undertaking this assessment of *Absolute Zero* was that the 13 actions were not posed as problems per se in the report, albeit their implementation in most cases would pose problems. Essentially several of the problems were formulated more as solutions rather than providing an explanation of the action and why there needs to be an action. However, the point of *Absolute Zero* is to establish a set of measures which, in combination, deliver absolute zero and are therefore the individual measures are elements of this solution. Nevertheless, as well as providing a basis for assessing the original framework, the analysis of *Absolute Zero* identified two important and likely generic sources of difficulty:

- Several of the problems are associated with a transition period, such as switching from gas boilers to electric pumps. It is assumed that there will be a period of transition while the preferred technology is adopted. Transition problems are subject to a time frame from the first step of approaching a problem to the full implementation of the solution, for the transformation to take full effect. Various factors affect the transition period, such as availability of resources, which is identified as a secondary problem.
- There are several secondary problems associated with the problems used in the analysis, such as for the point raised on the electrification of road vehicles. A secondary problem associated with vehicle electrification is the logistics around power supply, this includes setting up a charging infrastructure and ensuring the necessary supply of energy to meet the demand for charging. Resources are a key factor that can limit this, both from the physical resources and the human resources side. This change cannot take place from one day to the next and the successful implementation of this is exposed to a transition period.

Furthermore, the analysis revealed that interconnectedness is a major characteristic of the 13 actions. Many of the actions and their secondary problems are dependent on the successful implementation of each other. In other words, the solution to one problem will be affected by the solution to the interconnected problems. The interconnectedness of problems is also identified as a reason for none of the 13 actions of *Absolute Zero* being classified as Tame. The move away from fossil fuels is a key point for electrification of road vehicles and generating electricity. Another interconnection in the *Absolute Zero* Report is that between mining material sourcing, material production and manufacturing. Availability of materials is the basis of many of the actions from the report.

A characteristic of wicked problems that has been identified throughout the analyses is the interconnectedness of several elements, all of which need to be addressed driving political complexity.

Absolute Zero arguably serves two purposes: firstly it makes the point that Net Zero could be achieved without a 'techno-optimistic' reliance on developments that are unproven; and secondly it demonstrates the range and extent of somewhat extreme measures needed to do this. Both aspects of *Absolute Zero* are controversial and seem unlikely to be accepted at the mainstream level except perhaps in the event of a much more extreme perception of the climate crisis. They are, however, both highly provocative and perhaps aimed at stimulating thought and reaction. Based on this it can be argued that *Absolute Zero* deals with possibilities of non-techno-reliant decarbonisation, which most would not regard as practical options. Hence, a category of possibilities that may not have previously entered the consciousness as serious approaches is perceptible.

Following the analysis of the 13 actions from the *Absolute Zero* Report, it was found that the steps could be further refined, and additional boxes are needed for the classification of situations such as those in *Absolute Zero*. A category that was missing within the problem aspect focusing on the problem itself is one where the solution is clear, however the problem is not. This was deemed to be applicable to a range of research focused activities and is therefore somewhat generic. Furthermore, the actions from *Absolute Zero* have been brought forward to spark interest in them rather than specifically aiming for ones of implementation. This led to another category on the problem aspect focusing on stakeholders involved with them, with problems solely defined for stimulating debate rather than expecting stakeholders to act upon them. Based on these changes, the 9-box model was adapted to a 16-box model.

This refined framework was brought forward for the analysis of the FEMM Hub Roadmap for electrical machines.

6.2.2 FEMM Hub Roadmap Findings

The FEMM Hub operates at a deeper engineering level in comparison to *Absolute Zero*. Therefore, the nature of the areas of consideration in the FEMM Hub are somewhat different to those in *Absolute Zero*. The 16-box model developed as a result from the analysis of the *Absolute Zero* Report formed the basis of the analysis of the FEMM Hub Roadmap for electrical machines. The Analysis in Chapter 5 is used as a basis for validating the 16-box model and test it on a case that is based on a deeper engineering content. The focus of the analysis of the FEMM Hub Roadmap was placed on the factors in the roadmap concentrating on sustainable lifecycle, based on the scope of this research on sustainability and the move to Net Zero, where sustainability and the circular economy are most relevant for the analysis of wickedness.

Overall, the analysis of the Roadmap highlighted the interconnectedness of points with the potential action of climate change. It is noticeable that between the different points, there is an element of build-up, where the developments on one point will mean an advancement on another too. This can be linked to the idea of secondary problems. This suggests that some actions are win-wins such as making the product closer to the design intent that improves all other performance factors. Stakeholder acceptance provides a foundation for this, which is however not a major point of consideration in the FEMM Hub Roadmap. This would entail costs for implementation but leads to secondary benefits from secondary problems. The overview of the interconnectedness of secondary problems of the individual points from the Roadmap showed that there are mutual secondary problems. Component dependency, material availability and design of electrical machines are three of the key points of interconnectedness identified within the sustainable lifecycle points from the roadmap and their secondary problems. This is an inevitable consequence of decomposition. As such, when these points are worked on, the impact will span across various elements in support for the electrical machine's sustainable lifecycle.

Examples of this are the primary problem of design being a secondary problem of sustainable manufacturing, remanufacturing, and resins. Another example that adds to this is the primary problem of remanufacturing having the secondary problem of design and resins prohibiting this. This shows an element of decomposition of the remanufacturing point into design for remanufacture and resins. Overall, the challenges in the FEMM Hub under this sustainable lifecycle point are poorly raised being relatively unhelpful in a roadmapping context. This is reflected in the analysis of the roadmap.

Some parallels between the roadmap analysis and the literature can be drawn, whereby secondary problems around electrical machines with rare earth magnets have been recognised previously, however not named as such. Reuse and recycling of existing rare earth magnets will be important for future electrification, which is subject to setting up a supply chain to recover existing magnets for repurposing requiring collaboration and coordination (Filho, 2016).

Overall, the analysis of the points from the Roadmap showed the importance of the supplementary boxes added by the development of the 16-box model, as the discussion in section 5.4.8 *FEMM Hub Roadmap 9-Box and 16-Box Model Position Comparison* has shown. The points on resins, lifecycle assessment and design fit into the boxes that have been added to shape the 16-box model. They are classified as being brought forward as solutions as opposed to defining problems, highlighting the importance of clearly defining points to enable systematic assessment of them using the framework from this research.

6.2.3 Comparison of two case studies

Before going into a comparative discussion on the two case studies, the differences between them are outlined. The *Absolute Zero* Report works with behavioural changes, the success of the implementation of 13 actions brought forward in this is highly dependent on the behavioural changes of individuals. Therefore, we would expect more stakeholder difficulty than technical complexity. This somewhat contrasts with the FEMM Hub Roadmap, which is focused on engineering and technology, in other words: technical complexity. Although these are underlying differences, the principal idea of the Roadmap and the Report are one – moving towards Net Zero. The style and purpose of the two cases also contrasts. Arguably, *Absolute Zero* is deliberately provocative, as has been discussed previously. The FEMM Hub Roadmap, on the other hand, tries to position quite specific elements of research into categories of challenges which need to be addressed. It attempts to provide a more straightforward and less controversial approach. Overall, both cases work back from the goal of Net Zero. Reviewing the case studies and comparing them directly against each other in their set-up, it is found that the approaches almost mirror each other in their strengths and weaknesses. Arguably *Absolute Zero* is about stimulating thinking in the stakeholder community at the political level whilst failing to deal with the practicalities. The FEMM Hub on the other hand deal with the specific practicalities at the expense of stakeholder considerations with a detachment from the total problem.

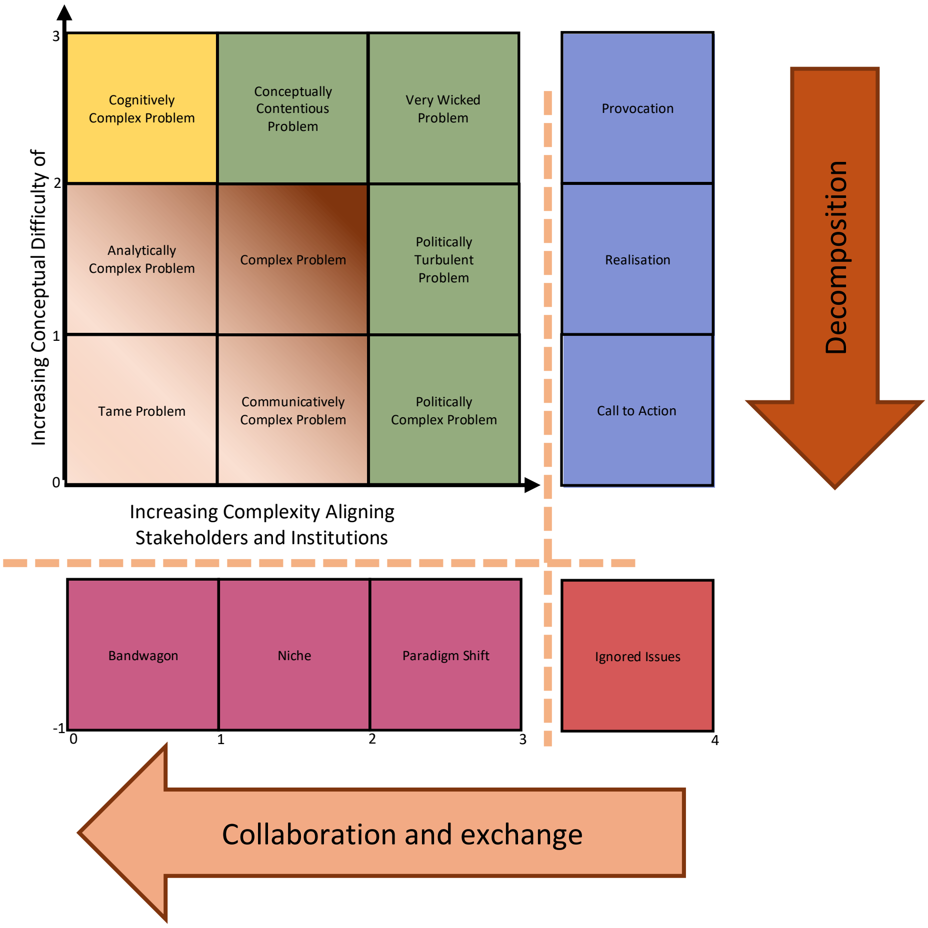
Another common element between the two case studies is the presence of secondary problems, the interconnectedness of problems and that not all of the elements of the case studies are true problem statements, but solutions posed as problems. Secondary problems are an element that can be traced back to the literature, albeit not introduced as such. Rittel and Webber outlined in their 10 characteristics of wicked problems that they can be considered a symptom of another problem (Rittel and Webber, 1973). Zellner and Campell (2015) build up on this in their research and found that further problems are uncovered in the process of approaching wicked problems. Secondary problems show the further considerations and actions necessary for achieving the primary problem in question. For example, for the electrification of vehicles, electrical machines are important, the associated materials and their supply chain that needs to be in place for this, in addition to skilled workforce for building electrical machines. The analysis through the steps for positioning points on the model pushes towards considering the further actions, such as the secondary problems, necessary for approaching primary problems. As previously discussed, sometimes the secondary problems reoccur in a primary problem identified in the case studies.

The decomposition of problems of the two case studies is different and can explain the difference between the problem positioning. Whilst the *Absolute Zero* Report takes the approach of providing an all-encompassing overview of the actions necessary for achieving absolute zero, it decomposes this by one degree into 13 actions. The FEMM Hub Roadmap takes a different approach and focuses on different elements necessary for enabling the use of electrical machines for 2050, going further steps of decomposition. This is illustrated in Figure 5.3 showing a sequence of decomposition of the *Absolute Zero* Report, extending into the points on the FEMM Hub Roadmap. From the analysis of the Roadmap, the points identified as solutions seem to be the most decomposed based on the sequence of decomposition shown in Figure 5.3. As the solutions for these are clear it supposes that the most decomposed elements of a problem are to be approached first as a clear solution seems to be available. This further suggests that to approach primary problems, there needs to be more and more decomposition until secondary problems are eliminated fully. Only then it is possible to truly approach a problem at its core.

6.3 Implications of Problem Categorisation and Approaching Mechanisms

The 16-box model and the associated steps for positioning problems onto it have been at the core of this analysis. What does the classification tell you about how to proceed with the problems though?

Decomposition has been a key element in the analysis to decrease the complexity of problems and make them more approachable. The decomposing affects the problem set up and as such influences the positioning of problems relative to the conceptual difficulty axis. This suggests that the conceptual difficulty of problems can be reduced by decomposing them. However, there is a risk that the resulting decomposed problems do not combine to address the overall initial problem. This is demonstrated by the categories of situations that are dealing with solutions and not problems. The stakeholder complexity is somewhat affected by decomposition too, by decreasing the scope of the problem in question and with that the stakeholders associated with it. Decomposing narrows down the stakeholders required for solving a problem, providing a more direct path for approaching: Political stakeholders are unlikely to engage in an engineering problem and vice-versa. However, stakeholder complexity is a factor that can be improved by setting up mechanisms to support collaboration and exchange between stakeholders. This supports transparency amongst stakeholders and encourages the working towards a common goal. Figure 6.1 indicates how to reduce overall wickedness of problems with the direction of the arrows.



Key:

Arrow to show change in position relative to conceptual difficulty based on indication

Arrow to show change in position relative to stakeholder complexity based on indication

Approaches for categories of Boxes:

- Project Management Methods
- Mediation, Secondary and Transition Problems, for driving prioritization
- Lean Startup
- Communication
- Campaigning and increasing awareness
- Curiosity Driven Research

Figure 6.1 Indications how to reduce overall wickedness of problems and approaching mechanisms

When having identified how to reduce the wickedness of problems, it is also important to understand mechanisms and methods to help approaching problems from different parts of the model. Areas in Figure 6.1 have been highlighted to provide a first indication on the types of methods that could help in these situation categories. Different types of Project Management Methods have the potential to support for approaching situations in origin of the 16-box model; *Tame*, *Analytically Complex*, *Communicatively Complex* and *Complex*. Waterfall, Agile and Hybrid methods can be used for these classifications of problems respectively. The waterfall method takes a directive approach, project demands must be clearly defined from the beginning, requirements and the sequence of discrete actions are set before starting off on a project (Albrecht and Albrecht, 2021). This makes the waterfall methodology most applicable to situations where solutions are clear, and problems are clear, such as in the *Tame* and *Communicatively Complex* situations.

The Agile Methodology somewhat contrasts with this and enables more flexibility to adapt to incidences coming up when progressing through the possibility of incorporating feedback loops, which can diminish the efficiency within the progress of a project (Albrecht and Albrecht, 2021). This matches the direction needed for more complex situations where specific requirements may change throughout the process when more information is revealed on the problem in question.

The hybrid methodology combines the practices from agile and waterfall, gathering all necessary information initially like in waterfall, but enabling flexibility and iterations throughout deployment, like in agile (Albrecht and Albrecht, 2021). This provides the basis of an approach to situations that are complex, including *Analytically* and *Communicatively Complex*.

The gradient in Figure 6.1 provides a first indication on how to approach situations categorised in the *Tame*, *Communicatively Complex, Analytically Complex* and *Complex* boxes. The light colour indicates a waterfall approach, moving towards the medium colour with the hybrid approach and the dark colour for agile. This is a first suggestion of how to deal with situations in the given boxes which is subject to further investigation for approval, which is outside of the scope for this research.

Moving further away from the origin of the original nine boxes, the boxes in green, covering the *Conceptually Contentious*, *Politically Complex, Politically Turbulent* and *Very Wicked Problems*, the analysis through the case studies showed that transition problems and secondary problems play a role in this, for driving mediation. Working through all points so that stakeholders reach an acceptance with them decreases the political complexity. This combination of mediation, using secondary and transition problems provides a basis for approaching problems in the green boxes to drive prioritisation. Knowing which of the secondary or transition problems should be approached first helps to provide a structure in the process.

In the new boxes added for creating the 16-box model, there are also some suggestions for approaching situations categorised in these. When classified as *Ignored Issues*, shown in the figure in red, situations should be dealt with through communication and increased awareness. This ensures that stakeholders are more conscious about the situation and recognise that there is value in approaching it.

Situations categorised in the bottom row of the 16-box model are ones where the solution is clear, however, the problem is not. A method that can support in situations categorised in these boxes, outside of the *Ignored Issues*, is the lean startup method. For general understanding of the lean startup method, Erik Ries developed a definition for startups: 'a human institution designed to create new products and services under conditions of extreme uncertainty' (2011: p. 8). As part of the lean startup methodology, Erik Ries (2011) argues that startups aim to develop a sustainable business, turning visions into real life products, understanding customer responses to them and subsequently deciding whether to persist or adapt. For situations in the 16-box model, this means that for solutions developed, finding the right problem for them to then solve is important, with the solution able to be adapted according to the problem if required.

In the situations classified as *Provocation*, *Realisation* and *Call to Action*, shown in blue, campaigning and raising awareness are seen to provide an adequate way forward to approaching the situations where stakeholders are ranging between oblivious, unconvinced and distrustful about them.

The final yellow box on Cognitively Complex Problems situations can be defined as curiosity driven research, with classic basic science that is unconstrained by management approaches.

The mechanisms suggested in the above to approach situations in the given boxes are initial perceptions which must be tested. Future work could explore the validity of the suggested approaches to problem types with the relevant characteristics.

6.4 Research Questions

6.4.1 Research Question 1

In what ways does problem categorisation and recognition of certain problems as complex or wicked help in driving tangible progress toward net zero supply chains and engineering solutions?

The categorisation of problems onto the 16-box model following the positioning steps highlights the key characteristics of problems with regards to the two problem aspects: 1. The problem itself and 2. The stakeholders involved with this (Alford and Head, 2017). Although, given the new set-up in the 16-box model which looks at problem and solution aspects, it can be argued that using the word complex *situations* is more inclusive for the description. As such, it can be argued that for the categorisation of complex situations, the two aspects of situations that must be considered are: 1. The characteristics on situations themselves and 2. The stakeholders involved with them.

Through highlighting the characteristics of complex situations in this way, it is possible to understand what component of the issue is missing to enable approaching this. The decomposition of issues is intended to help move towards more approachable tasks. This has been shown by the example of the FEMM Hub, where the decomposition to the highest degree led to the solution of eliminating resins for supporting the remanufacturing of electrical machines overall. Furthermore, an initial indication of how different project management approaches might be best suited to support specific categories of situations for the 16-box model has been made.

Overall, the 16-box model provides a basis for understanding complex situations in more detail and the requirements needed to approach them. Rebs, Brandenburg and Seuring (2019) argue that driving sustainable supply chain management through multi-level frameworks is adequate due to incorporating and considering the interconnectedness and complexity of supply chains. This is further supported by the work of Ward and Godsell (2019) which have focused on linking supply chains and innovation through a structured approach, that has been shown to be viable. Therefore, linking sustainability with the supply chain can profit from a structured approach, such as the 16-box model.

6.4.2 Research Question 2

Does the process of decomposing complex problems through approaches such as a roadmap change the nature of wicked problems?

For the Roadmap on electrical machines by the FEMM Hub, the focus of analysis was placed on the sustainable lifecycle point. This is decomposed across several stages in the roadmap, shown in Figure 6.2 below on the sustainable lifecycle sequence of decomposition within the FEMM Hub Roadmap. The sequence of decomposition is based on points mentioned in the roadmap under the sustainable lifecycle aspect.

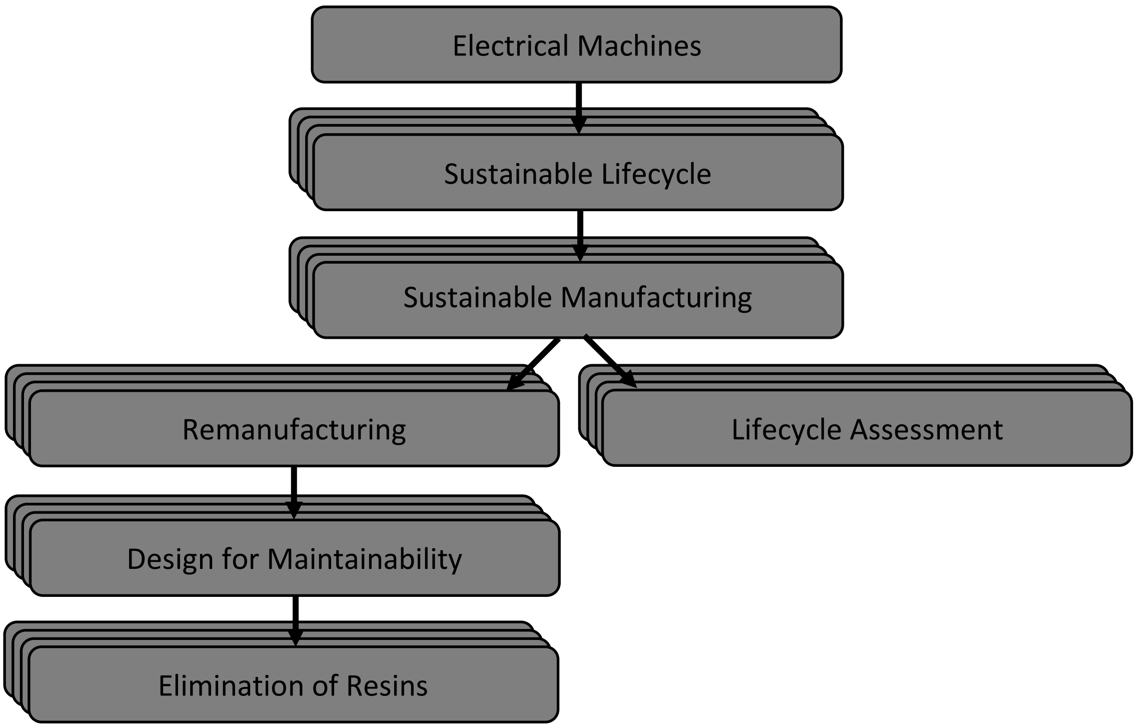


Figure 6.2 FEMM Hub Roadmap Sustainable Lifecycle Sequence of Decomposition

The decomposing of problems, such as that of electrical machines for 2050, uncovers some of the key elements necessary to approach them. As such, the nature of the wicked problem in terms of being unsolvable, is diminished. This is supported by the analysis of the roadmap and the categorisation of the decomposed elements on the 16-box model. The problems ranked higher in the decomposition sequence are also classified higher in complexity. This complexity decreases as you move down the sequence of decomposition. Although the decomposition results in a set of addressable problems, they do not combine to address the overarching wicked problem for enabling decarbonisation. Decomposing too far can be a risk, whereby the focus on the initial problem is lost.

Furthermore, decomposing draws parallels to the work breakdown structure known from project management. As part of a work breakdown structure, all tasks needed to complete a project are clearly outlined in a sequence starting with the project itself (Lock, 2013). This is where the difference between decomposing and a work breakdown structure comes in. With the work breakdown structure, the tasks required to be completed are already known from the start. Whereas with decomposing, there is no clear overview of the tasks required when focusing on the initial problem. The work breakdown structure may work for tame problems, where again, the requirements are known. With increased complexity, there are more unknown factors, so a work breakdown structure is not effective.

The FEMM Hub Roadmap has further drawbacks stemming from the decomposition method. It largely ignores political factors and therefore does not deal with implementation. Moreover, it decomposes into inadequately articulated problems which creates unnecessary separation from the primary problem.

6.4.3 Research Question 3

Is it appropriate to assume that engineering solutions in wicked problem domains are necessarily the subject of decomposition before being presented to the engineer?

Answering this question relies on drawing evidence from the FEMM Hub Roadmap. Based on the way points are formulated, the electrical machines roadmap provides some direct solutions, indicating that decomposed subjects are presented to engineers. These are the points the FEMM Hub is working on, therefore it can be stated that wicked problem parts are approached by engineers from the decomposed elements side. Yearworth (2016) found that having a clear definition of problem structuring methods would be interesting for engineers, which somewhat matches the finding in this research on engineers being presented with direct solutions. The research by Lönngren (2017) highlights that engineers need clear and structured guidance to integratively approach wicked problems, which is shown by the direct solutions being presented to engineers in the FEMM Hub Roadmap with the subjects decomposed from the Sustainable Lifecycle point. This line of thought is continued in the literature that follows this, where Schuelke-Leech (2020) argues that engineers are problem solvers for problems that are rigid and clearly defined, and their solutions are clearly outlined. This does not mean that the topics engineers are presented with are subject to the highest degree of decomposition. When an engineer is confronted with a problem that has wicked characteristics this supposes, that to proceed, colleagues from different disciplines with access to different expertise and pools of knowledge should be engaged. This adds practical recommendations for engineering education and training. This fits with the Figure 6.1 in the implications of problem categorisation sections, that suggests the wickedness of problems is decreased in the two dimensions by decomposing and collaboration and exchange.

6.4.4 Research Question 4

Is it appropriate to assume that supply and demand associated with wicked problem domains are necessarily the subject of decomposition before being presented to the supply chain?

The *Absolute Zero* Report and the FEMM Hub Roadmap start off from the wicked problem of climate change. Supply chain considerations are not clearly identifiable in the first instance when thinking about this. When decomposing climate change, as has been done by the *Absolute Zero* Report and the FEMM Hub Roadmap, the actions revealed and the secondary problems associated with them uncover a vital supply chain connection. The secondary issue of supply to meet the demand of the problem, for example by having the necessary materials available, is reoccurring throughout the analyses. Oliver and Webber (1982) have explained that the balance of supply and demand is the basis for supply chain management. Based on this and the presence of secondary issues with elements of supply to meet the demand which resulted from the analysis of the *Absolute Zero* Report and the FEMM Hub Roadmap, supply chain management plays a central role in approaching climate change. Furthermore, surplus at end-of-life material in absence of circular economy planning would lead to an obvious mismatch between supply and demand. This links to the transition problem category, where supply of materials hinders promptly implementing changes. To support this interplay between secondary problems to work towards net zero, collaboration is a key element to reduce the stakeholder difficulty. This creates a link to supply chains and their requirements for integrating sustainability, as collaboration across supply chains is key for creating an impact moving towards sustainable supply chain management, with the potential to reduce emissions through this (Abbasi and Nilsson, 2012). Vachon and Klassen (2008) have also found that collaboration across actors in the supply chain can have a positive effect on the environmental performance overall. In addition to this, the interconnectedness of problems shows the advantage of working on the supply chain issues for supporting other problems as well. An example of this is electrification and the motivation to move towards renewable energy, such as solar and wind. To set up and expand solar and wind farms, materials to build these need to be available, which is not only a secondary problem, but also subject to a transition period. The development of solar and wind farms supports the expansion of renewable energy, which in turn supports the energy requirements for electrification. Based on this, the supply chain becomes a key enabler for the implementation of the secondary problems and the associated transition problems. In other words, the decomposed subproblems are presented to the supply chain. However, the analyses conducted are insufficient to draw full conclusions on supply chain considerations.

6.4.5 Research Question 5

How does a technology roadmap impact the wickedness of the electrification problem?

The FEMM Hub Roadmap has decomposed the electrification problem with a focus on electrical machines that are a key enabler for electrification. The sustainable lifecycle point in the Roadmap has been decomposed following the steps shown in Figure 6.2. The classification of the problems indicates that the complexity of the sustainable lifecycle point decreases going down the steps of decomposition. This is reflected in the Figure 5.2 that showed the comparison of the Roadmap problems relative to each other. As such, the decomposing taking place in the FEMM Hub Roadmap impacts the electrification problem in such a way that the complexity of this is decreased, with the way of formulation providing solutions over problems. Furthermore, the degree of decomposition is directly correlated to the decrease in complexity. There is a risk of too much decomposition though.

As discussed in the literature, roadmaps can be seen as a form of communication (Willyard and McClees, 1987). This element of communication that is given by roadmaps supports in having a clear direction and collaboration across academia and industry which is necessary for growth in technology, such as electrical machines (Kajikawa et al., 2008). The categorisation of the points of the FEMM Hub Roadmap show that this can aid the decomposition and allow a decomposed problem to be relevant to the bigger problem, suggesting that roadmapping is ever more important for decomposition, impacting wickedness of situations to be more approachable.

6.4.6 Research Question 6

What is the degree of decomposition necessary for approaching problems?

As discussed as part of the previous research question, decomposition is a useful method for approaching problems by decreasing their complexity, effectively moving from a single seemingly impossible problem to several more tractable ones. In the analysis of the two case studies, it was found that despite steps of decomposition, secondary problems are overarchingly present, prohibiting the moving forward on problems. This suggests that problems need to be decomposed to a degree where secondary problems are eliminated to enable directly approaching them. Decomposition must be limited though, to avoid decomposing to an extent where the problem is eliminated by no longer dealing with the original elements of it and rather having solutions. This is where communication is key. If a level of specialism is reached in individual technology projects that is meaningless to stakeholders in the overarching problem, then decomposition has perhaps gone too far. This is demonstrated by the bottom row of the 16-box model that shows solutions but not problems. It suggests that the decomposition ending in a solution has taken the focus too far away from the actual problem and indicates that there is a limit of decomposing there, as shown in Figure 6.3 below. On one hand, decomposing on a purely technical basis, as partially seen in the FEMM Hub, might result in good theoretical solutions, but limited acceptance. On the other hand, decomposing into provocative politically loaded suggestions, as in *Absolute Zero,* ignores secondary problems which deal with practicality. The new boxes added to form the 16-box model could be indicators to look out for on this.

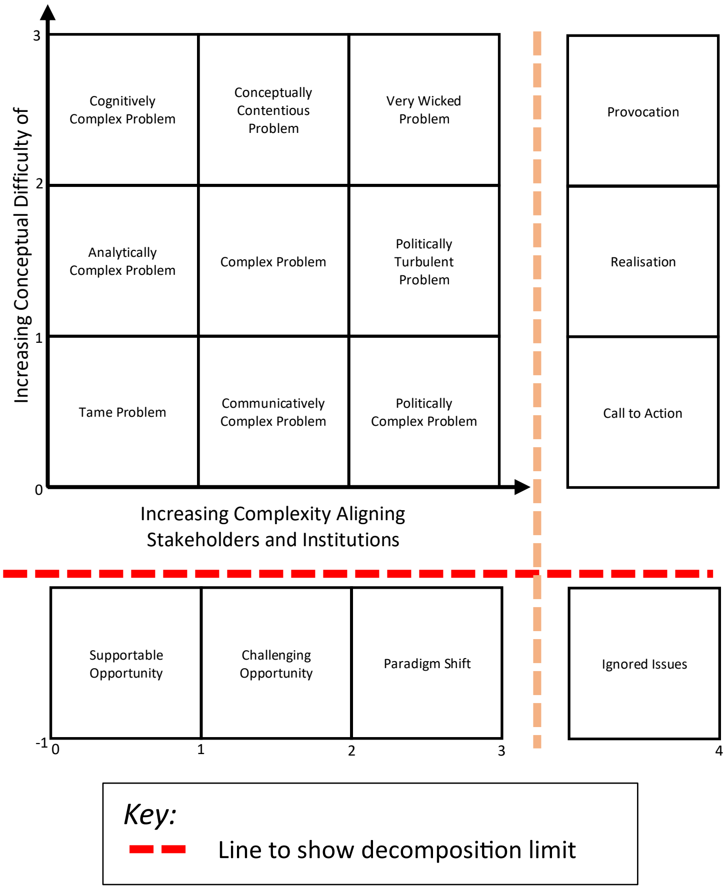


Figure 6.3 Limit to decomposition

6.5 Research Implications

The 16-box model provides a comprehensive means of classifying research domain cases identified in the *Absolute Zero* Report and the FEMM Hub Roadmap. This was not possible with the previously established 9-box model by Alford and Head (2017). By refining and expanding the 9-box model, the application domain now covers a wider range of cases. This new framework is necessary based on representing a layer within the issues side of the model focusing on solutions, which are present in the research domain. Furthermore, mechanisms to support decreasing the complexity of problems based on their classification have been identified. Decomposing supports to decrease conceptual difficulty and collaboration and exchange supports in the decreasing of stakeholder complexity. This provides an approach with clarity to wicked problems, which has previously been lacking (Zellner and Campbell, 2015).

6.6 Summary

There are several general characteristics of the 'problem' set that has been evaluated through Chapters 4 and 5:

- Decomposition:

This is a key element to making wicked problems more approachable. Through decomposition, problems are broken down into the parts that must be considered for approaching the overall problem. This decreases the complexity for addressing elements of the problem necessary to move towards problem fulfilment. Decomposition can reveal transition and secondary problems of the primary problem in question. Decomposing is different to a simple work breakdown structure. This is based on there being more unknown factors with complex problems, where the work breakdown structure is not effective as it profits from knowing tasks to be accomplished from the start. However, it is key to decompose very complex situations to a certain point for enabling project management methods to be effective.

- Transition Problems:

These indicate that some problems to be solved are subject to a transition period. This could be dependent on technologies being adapted or material supply chains being built up. They slow down the progress for problem completion until the transition period has been overcome. There is a link of this to dealing with stakeholder difficulty with stakeholders having to accept that some things need time. With transition periods a certain timeline is involved, and prioritisation would help to put an order to the tasks. However, this is contentious. For transition problems, stakeholder difficulty is a limiting factor and to overcome this, it is important to get all stakeholders to look at the problems together, addressing all issues, taking the time to negotiate a prioritised order. This could also positively affect the transition period needed. Thus, stakeholder management through engagement and managing expectation plays a central role in this.

- Secondary Problems:

Secondary problems indicate elements of problems that must be considered for ensuring to successfully addressing them. Working on the secondary problems moves forward on the primary problems in steps. However, approaching secondary problems does not always ensure that the primary problem will be solved in its totality. When looking at the elements of problems through secondary problems, an interconnectedness can be noticed between them.

- Interconnectedness:

Interconnectedness of problems can have positives and negatives. The analysis of the *Absolute Zero* report and the FEMM Hub Roadmap revealed the interconnectedness of primary problems and secondary problems. The positive around this is that when approaching a part of a problem in one area, there are elements of other problems that will move forward towards completion too. This is likely to be an important basis for prioritisation. Addressing the secondary problems that help with many primary problems provides a meaningful order to prioritisation and delivers an outcome to solving primary problems faster. This also provides a foundation of dealing with stakeholder difficulty.

- Non-Problems, including solutions without clear problems and 'possibilities' aimed at simulating discussion:

The 16-box model has extended the range of situations that could be explored through the Alford and Head (2017) 9-box model. This new model allows two important categories of situations to be considered. Situations where the solution is clear but the problem is not can be seen to exist where specific expertise is promoted irrespective of its fit with any problem. Situations where problems are posed for the sole purpose of stimulating debate can be linked to contrarian thinking and are important in challenging received wisdom. These categories do not relate to problems as such, but they do represent a logical extension of the Alford-Head problem space. Inclusion of these 'non-problems' in the framework has proved necessary in categorising the situations seen in the engineering research space and moving towards ways of dealing with them.

- Inadequate Definition of Problems:

The point above on non-problems brings forward situations as seen in the FEMM Hub Roadmap. Part of the problems under analysis have highlighted that poor and inadequate articulation of the problems can hinder adequate categorisation of problems. This highlights the importance of providing clearly outlined situations for categorisation.

- Value of the model in directing action:

The 16-box model as introduced in Figure 6.1 provides an indication on what to do to decrease the wickedness of problems, through decomposing and collaboration and exchange. In addition to this, first methods for approaching problems classified in different areas of the model have been introduced. Lean Startup, Mediation, communication, campaigning and increased awareness, curiosity driven research, waterfall, hybrid and agile methods, could help to move problems towards completion, subject to further investigation.

Chapter 7 – Conclusion

7.1 Conclusions

Considering decarbonisation in the supply chain and engineering research context led to a focus in this thesis on wicked and complex problems. Wicked problem thinking is clearly applicable to decarbonisation because of the interplay between stakeholder and technical challenges. Engineering research has been a fundamental part of highlighting the intersection between stakeholder and technical challenges, emphasising the importance of it for addressing climate change. In addition to this, decarbonisation can be seen to meet almost all criteria that have been put forward within wicked problem definitions. Considering this within the context of the supply chain implications of engineering research and its eventual deployment resulted in a focus on structured approaches to wicked problems. In particular the approach of Alford and Head (2017) had promising characteristics, for example through highlighting problem characteristics and enabling the positioning of problems through classification in different categories of wickedness based on this. This 9-box model by Alford and Head (2017) has been developed into a 16-box model through the analysis of case studies from the research domain:

1. the *Absolute Zero* Report by UK FIRES and
2. the Electrical Machines Roadmap by the FEMM Hub.

The 16-box model was developed as a result of the analysis in Chapter 4 on the UK FIRES Report *Absolute Zero* because the initial model did not suffice to meet the requirements of situations identified in the case studies. A broader range of situations are discussed in the Research and Development space which can be handled in similar ways, even when not classified as problems. The 16-box model now enables the classification of these types of situations, which has been approved by the analysis of the FEMM Hub Roadmap in Chapter 5.

Structured approaches are found to be suitable here because as well as providing a basis for categorising problems, they suggest the possibility of targeting approaches to particular problem types. This is an approach which would seem fitting in situations of decomposition, where a problem has been effectively broken down into smaller ones.

Supply Chains and Engineering formed a part of the case studies analysed in this thesis. Several of the secondary problems identified throughout the analysis in Chapter 4 and Chapter 5 are rooted in supply chains. The engineering focus is given with the case study of the roadmap in electrical machines from the FEMM Hub. It can be argued that technical solutions to climate change seem to emerge in secondary problems around supply chains. Engineering developments have the possibility to mitigate some pressures on the supply of scarce materials, highlighting an interplay between supply chains and engineering solutions. The case studies have been found to decompose complex situations into smaller more approachable tasks. In the *Absolute Zero* Report, the goal of absolute zero was decomposed into 13 actions. In the Electrical Machines Roadmap, decomposition across several areas took place. The focus of the thesis was on the sustainable lifecycle point that was decomposed more concretely. This decomposing has been identified to support in moving forward on the overall wicked problem. With the advancement in the approaching of wicked problems that has been provided through the 16-box model and framework, work on supply chain sustainability will be progressed.

The research carried out in the thesis has supported the broadening of the knowledge for wicked and complex problems, and with that the global net zero goal.

7.2 Academic Contribution

7.2.1 Contribution to Knowledge

Through the development and testing of a structured approach to complex and wicked problems, this thesis has revealed several contributions to knowledge.

1. 9-Box Model in Engineering and Research Context

   Whilst there have been some approaches of wicked problems in an engineering context, this has not been done with a structured approach such as that of Alford and Head (2017). It is the first time the 9-box model by Alford and Head (2017) is applied to the climate change, engineering and supply chain context. Furthermore, previous work on wicked problems and engineering focused on educational needs of engineers (Lönngren, 2017).

2. Four Steps of Positioning Problems

   A set of four steps has been developed from the literature to enable positioning of problems onto the model by Alford and Head (2017). Based on the analysis of the *Absolute Zero* Report in Chapter 4, the steps have been amended to reflect clarity of analysis.

3. 16-Box Model

   One of the major contributions from the thesis is the 16-box model that incorporates the two important aspects of situations: the situations themselves and the stakeholders involved with them. The model was developed as a result of the analysis of the *Absolute Zero* Report in Chapter 4 and tested for validity in Chapter 5 using the electrical machines roadmap. Situations can be classified onto the model based on the positioning steps that have been adapted from previous research. This classification helps to understand the characteristics of situations and provides an indication of approaches necessary for advancing on them.

4. Complexity Classification Card

   A complexity classification card has been developed in Chapter 4 for a consolidated overview of the analysis criteria. This was done based on the finding that a narrative on the positioning steps is extensive. Through the complexity classification card, the criteria are displayed visually and concisely and enables patterns between different situations to be spotted at ease for comparison.

5. Mechanisms to approach wicked problems

   Following the positioning steps and based on the resulting classification of situations on the model, mechanisms to decrease the wickedness of situations have been outlined in Chapter 6, section 6.3, where Implications of problem categorisation and approaching mechanisms are discussed. The methods outlined include: Lean Startup, Communication, Campaigning and increased awareness, Mediation, Curiosity Driven Research, Waterfall, Agile and Hybrid Project Management Methods. For decreasing the conceptual difficulty, decomposition has been found as the solution. Stakeholder complexity is decreased by collaboration and exchange between stakeholders.

6. Applications of the framework in the research domain
   The model put forward has been used in two research case studies from EPSRC funded research projects. It has been shown that the 9-box model was insufficient for encompassing the requirements of the full range of situations seen in the research domain case studies, including stronger engineering focus in the Roadmap analysis.

7. Terminology
   When conducting this research on wicked problems, some terminology has emerged as omnipresent: secondary problems, transition problems, interconnectedness and decomposition. These are four core elements of wicked problems to be cautious about for future research in the field. Furthermore inadequately articulated problems have emerged as skewing the positioning of problems.

7.3 Practical Considerations

As well as the somewhat abstract categorisation of problem and situation types, there has also been a preliminary attempt to illustrate how this can be used to direct action. Based on the categorisation on the model, there are methods for moving forward which have been described previously and these are:

- Communication
- Mediation
- Lean Startup
- Project Management Methods
- Curiosity Driven Research
- Campaigning and Increasing Awareness

These suggestions are subject to further investigation. Figure 7.1 summarises and describes the methods.

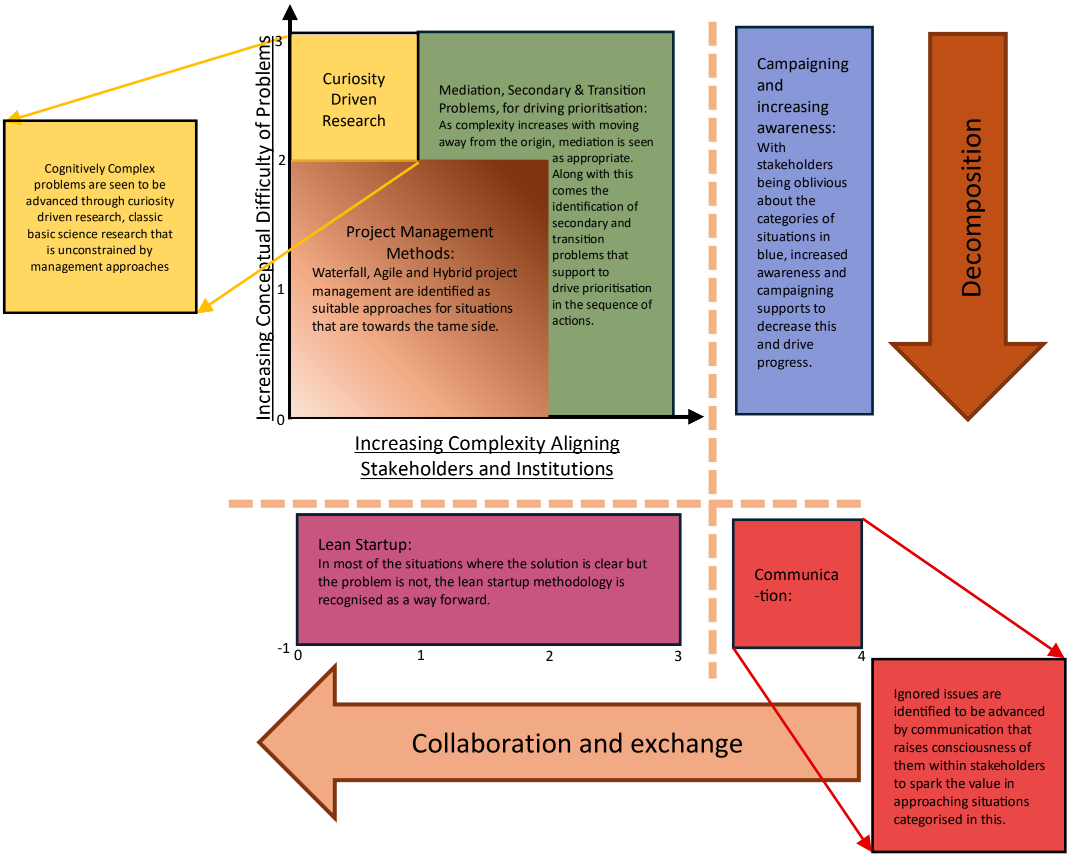


Figure 7.1 Indications how to reduce overall wickedness of problems and approaching mechanisms

7.4 Limitations and Further Work

7.4.1 Limitations

The thesis provides further knowledge in the field of wicked problems and approaching them. However, there are inevitably a number of areas that could be improved through further work.

1. One of the most obvious limitations of the wicked problems approach in engineering is that it is very abstract and could be seen to have limited practical value. Using a structured approach mitigates the risk of this because characterising problems in a systematic way suggests the possibility of common approaches to solutions. Some approaches have been suggested, and while they seem reasonable this is a very early-stage analysis that would need to be tested. Even with this mitigation in place, the application of wicked problems thinking in this space could still be considered quite

theoretical and abstract in nature until it can direct meaningful and distinctive responses. These might include responses around team formation, education and training of engineers, and new planning approaches

2. The approach developed here has been focused around case studies in the domain of research aligned to decarbonisation. Whilst the approach has the potential to be generically applicable, at least in the wider research space, this has not been tested.

3. The initial intent of the thesis was to explore supply chain management issues related to climate change on a somewhat general level. The characterisation approach, especially for decomposed problems can be seen as creating a bridge between very high-level problems at the level of supply chain management and more tractable and actionable work programmes. The implications of this on supply chain management have only really been considered at the level of supply and demand mismatches for scarce materials and minerals.

4. The challenges around decomposition and the extent to which this creates a mismatch between active programmes and the core wicked problems has been discussed at some length. While several considerations have been made, this is still an open question and one which is vital in the potential for any managed approach to addressing complex problems (or at least the engineering and supply chain solutions to them).

5. The FEMM Hub case study illustrates the potential connection between a roadmap approach and wicked and complex problem analysis. It also clearly highlights some of the difficulty in articulating rather vague 'non-problems' as aspirations in a roadmap context. However, the FEMM Hub roadmap is not typical of technology roadmapping work as it was undertaken on a retrospective basis and attempts to fit already committed work into a strategic context. As a result, drawing full conclusions on the connection between roadmapping and wicked problem categorisation is limited.

To progress on the limitations to this research, further work can be supportive, which will be discussed in the following section.

7.4.2 Further Work

To mitigate the limitations from this work, further work along different routes can be fruitful.

1. *Limiting abstraction of research and testing actions based on problem classification*
   The indications and suggestions of how to deal with situations classified in given boxes is subject to further investigation to validate them. The thesis provides some first indications of what actions can be useful once the classification of situations is known. Further work in this area will support to confirm the actions necessary for moving forward, which would limit the abstractness of the work and increase its practicality. Further work examples include: the FlyZero Roadmap by the Aerospace Technology Institute (Hadnum, Pacey and Milne, 2022), or the sustainable plastics roadmap by Lux Research (Schiavo, Willard and Hua, 2022).

2. *Application of Model*
   The thesis uses two case studies from the research environment to develop and validate the 16-box model. The applicability of this outside of the research environment was out of the scope for this research. It is assumed that for wicked problems in other areas, the model can prove to be a useful approach, which is subject to further work. As well as testing the framework outside of the research environment, choosing research outside of the engineering and supply chain scope is a way forward.

3. *Supply Chain Management for Climate Change*
   The work in thesis provides some insight into supply chain issues related to net zero and climate change. However, there is potential in testing the framework with supply chain sustainability to draw conclusions on the applicability of it in this field and understand the implications.

4. *Decomposition*

   Decomposition has been a major component of this research. To establish the complete understanding on the impact this has on the fulfilment of overall wicked problems, diving deeper directly on decomposition is important.

5. *Roadmapping and Wicked Problems*

   The FEMM Hub Roadmap has not been a typical example for technology roadmapping. More typical roadmapping studies would need to be explored before a full set of conclusions can be drawn about the connection between roadmapping and wicked problem categorisation.

6. *Using the 16-Box Model at the portfolio level*

   Investigating the 16-box model at the portfolio level, coupled with management of individual decomposed problems with appropriate project management tools could provide a further insight into the applicability of the model. This could be a useful mechanism for connecting the challenges of technology pull, from tame problems, with technology push, from earlier stage and speculative research.

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Appendices

Appendix 1 – Example of Analysis Using Positioning Steps

Road Vehicles

<u>Step 2:</u>

Absolute Zero Action: Stop development of Petrol and Diesel Engines, new vehicles must be compatible with absolute zero, all new vehicles electric, reduced in size.

<u>Problem Complexity:</u>

1. *Is there a clear and unambiguous definition of the problem?*

The problem is around the switch of petrol and diesel engines to electric vehicles. It could be argued that there are two parts to the problem: one is with the stop in development of petrol and diesel engines and the other focuses on new vehicles that must be compatible with absolute zero through being electric and possibly reduced in size. Regarding the technical level, these are rather solutions than problems though. In terms of adoption and behavioural changes, this does pose problems as consumers must be willing to use electric vehicles.

2. *Is the nature of the problem agreed and accepted by all stakeholders?*

There are different stakeholders involved with this problem, such as original equipment manufacturers and their suppliers. It is understood that for absolute zero, the automotive industry needs to advance the developments of electric vehicles.

According to the Climate Change Committee, the transition to electric vehicles is clearly set out, with a goal of all newly sold vehicles being electric by 2032 (Wills, 2020).

3. *Is the problem accepted as a technological one?*

Stopping development of petrol and diesel engines is not a technological issue, as it would be possible to stop the work on petrol and diesel engines immediately. With regards to the behavioural aspect, it is not straight forward to stop use of petrol and diesel engines without further notice. The development of net zero compatible electric vehicles could be described as a technological challenge where improvements are sought. Secondary problems associated with the development of electric vehicles compatible with net zero could also be classified as technological. This can be explained through the necessity of new materials to produce electric vehicles and the requirements for charging electric vehicles. Further challenges include the scaling up of the production of electric vehicles from the relatively low volume, high-cost vehicles they are today to the high volume, lower cost vehicles they need to be to reach mass adoption.

Whilst electric vehicles are made up of fewer parts compared to conventional petrol and diesel vehicles, a new challenge for manufacturers comes with the manufacturing of battery cells and the question of subcontracting the manufacturing and setting up supply chains for this or producing battery cells in-house (CCC, 2020). For example, the batteries require specific materials, such as rare earth elements, where a rate of supply needs to be arranged to meet the demand for electric vehicles as well as clarifying what will happen to batteries at end-of-life and the possibilities for recycling of batteries (Wills, 2020). Currently there is not sufficient capacity to reach the required rate at a suitable price.

Another technical challenge for successfully using electrical vehicles on a wide scale is the lack of electricity available. This can be classified as a secondary problem. It is expected that by 2050, only 60% of the electricity required will be available. This will impact the electricity available to charge electric vehicles, indicating that adjustments need to be made with the cars or more electricity needs to be made available (Allwood et al., 2019).

4. *Is the problem accepted as one of organisational and leadership setup?*

Due to the secondary problems associated with the road vehicles action in *Absolute Zero*, there is an indication that organisational and leadership aspects are important in the setup for coordination. Organisational and leadership aspects are also relevant in coordinating costs associated with the uptake of electric vehicles and the supporting network for enabling their usage.

5. *Does the problem extend beyond technology, organisation and leadership?*

In this analysis it is not recognised that the problem extends beyond technology, organisation and leadership.

6. *Is the viable solution available?*

The solution of just stopping the development of petrol and diesel engines is possible and viable. However, this has several implications and follow on tasks result from this. Different types of electric vehicles are already available on the market now and are also a viable solution. The switch towards having only electric vehicles entails the background work for ensuring the production of electric vehicles and enabling the use of these vehicles.

A major barrier to the transition is the requirement of significant amounts of electricity for a charging infrastructure, meaning that it is necessary to address where this increase in electricity should come from (Wills, 2020). Along with the question on the supply of electricity for this, there are also associated cost implications. Feeding into this is the lack of a charging infrastructure, which incurs significant costs in the development and the improvement of the network capacity for the development of the electricity grid (Wills, 2020; HM Government, 2022). Providing charging opportunities for electric vehicles is necessary for a full transition for consumers to know that there is a possibility of charging wherever they wish to drive, especially for long distances, as this is currently a factor holding back buyers (Wills, 2020; HM Government, 2022).

The UK government has put in place grants to promote the purchase of electric vehicles, which currently are set at a higher price range than conventional combustion engine cars. For example, there are grants in place to set up charging points (UK Government, 2023). It is not an uncommon approach to make grants available and assumes a build-up of momentum for electrical vehicles. It raises a question about confidence in this build-up.

7. *Has a clear and accepted solution or approach been agreed?*

The solution is understood for the development of electric vehicles to enable the phasing out of petrol and diesel engines. Car manufacturers are announcing their move towards only producing electric vehicles, which indicates that there is a clear understanding of the need for this change and a degree of acceptance for this. With that being said, it is important to note that throughout the manufacturing of electrical vehicles the consumption of resources and energy is high, with high CO_2 impacts too that can be brought down to the manufacturing of the required batteries (Bieker, 2021; Franzò and Nasca, 2021).

8. *Is there a known / defined relationship between actions and outcomes?*

The switch from petrol and diesel engines to electric vehicles indicates that during the use of the vehicles the emissions are decreased being positive for decarbonisation, as long as the electricity comes from non-emitting sources. However, this decarbonisation in favour of electric vehicles during their use is not reflected in the manufacturing process. For the new vehicles compatible with net zero, that are electric and smaller in size, the size factor might be relevant to a certain degree in terms of mitigating embodied carbon during manufacturing. The IEA published a comparison in the greenhouse gas emissions across the lifecycle of electric vehicles and internal combustion engine vehicles (2021a). This revealed an emission of 11.7 tCO_2e (metric tonne of carbon dioxide equivalent) per vehicle lifetime for Electricity in electric vehicles compared to an emissions of 35.9 tCO_2e per vehicle lifetime for fuel cycle in internal combustion engine vehicles (IEA, 2021a). It must be noted that the source of data for this figure of 11.7 tCO_2e gives a range of values for a low carbon energy mix (50gCO2-eq/kWh) through to a high carbon mix (800gCO2-eq/kWh). Overall, this shows that switching from petrol and diesel engines to electric vehicles can lead to a reduction of 24.2 tCO_2e per vehicle lifetime only during the use phase. When considering the emissions in the production phase on top of this, electric vehicles are expected to result in 19.7 tCO_2e across their lifetime, compared to 41.9 tCO_2e for internal combustion engine vehicles (IEA, 2021a). This highlights the potential of this switch in vehicles to significantly contribute to reducing emissions.

9. *Is there a clear and demonstrable relationship between assumed cause of the problem and resulting effects?*

The problem with the switch to electric vehicles is that consumers must be willing to accept to purchase and use these new electric vehicles. It is anticipated that if this change in behaviour can be achieved, this will be a positive step towards net zero. The numbers on vehicle emissions highlighted in the answer to the previous question already introduce that the use of electric vehicles can help to reduce emissions in road vehicles significantly.

Stakeholder Difficulty Factors:

1. *Are the stakeholders involved with developing the solution acting in cooperation?*

It is recognised that for the transition to electric vehicles to work, stakeholders need to work in cooperation (Wills, 2020). Determining the cooperation across stakeholders on this cannot easily be determined. However, there are consortiums in which vehicle manufacturers come together where a sense of cooperation for developing solutions in the move to electric vehicles can be exchanged on (SMMT, 2024).

2. *Are the stakeholders who will need to accept and implement the solution known?*

There are various stakeholders involved with the transition to electric vehicles, e.g.: Vehicle manufacturers, battery manufacturers, charge point manufacturers, raw material suppliers, electricity providers, charging infrastructure providers as well as governments. For the transition of electric vehicles to work effectively it is necessary for all stakeholders in this environment to work together (Wills, 2020). They share the same driver for making vehicles more environmentally friendly for net zero in mind and keeping up a competitive environment. The level of conviction among stakeholders is questionable. As economic times have got harder, net zero commitments have been let down and put on hold.

Social acceptance of electric vehicles by consumers plays a key role in their adoption. In a comparison on the social acceptance of electrical vehicles in Germany between 2011 and 2020 based on the factors of acquisition cost, security concerns, limited range, long charging time, poorly developed charging infrastructure and more polluting it has been found that there is a significant change in acceptance between 2011 and 2020 (Burkert, Fechtner and Schmuelling, 2021). The biggest change in acceptance has been in the security concerns factor with a decrease of concern by 75% between 2011 and 2020 (Burkert, Fechtner and Schmuelling, 2021). Factors around high acquisition cost and limited range limit the acceptance of electric vehicles in 2020 the most, followed closely by the poorly developed charging infrastructure (Burkert, Fechtner and Schmuelling, 2021). It has been argued that technological improvements increased the acceptance of electric vehicles, especially due to advancements with batteries (Burkert, Fechtner and Schmuelling, 2021). There is a concern around the environmental impacts of electric vehicles, where sometimes it is argued they are more polluting (Burkert, Fechtner and Schmuelling, 2021). This can be brought back to the impact that manufacturing has with regards to greenhouse gas emissions.

3. *Are the stakeholders who will need to accept and implement the solution acting in cooperation?*

The cooperation between stakeholders for the development of electric vehicles is limited in terms of the car manufacturers working individually on the development of their electric vehicles to increase pressure in the market. However, consortiums in which several stakeholders of the industry come together drive collaboration for electric vehicle development. The implementation of this comes down to the individual car manufacturers.

4. *Does the sum of knowledge needed to resolve the problem reside within a single party? (i.e. can the problem be addressed within a single organisational unit (team, plant, company, etc.)?)*

The knowledge for stopping the development of petrol and diesel engines rests in one place, with the automotive original equipment manufacturers. In contrary, for the adoption of net zero compatible cars more stakeholders are involved and the knowledge to approach this is spread across the stakeholders.

5. *Are multiple parties, with potential or actual conflicts of interest, needed to address the problem? (where multiple parties are required is there inherent difficulty in co-operation?)*

As the knowledge to provide a solution to the problem and the secondary problems associated with it is spread across stakeholders, multiple stakeholders are required for the addressing of the problem.

6. *Are there diverse values, mental models, aspirations among decision makers?*

It can be argued that the Covid-19 Pandemic has led to a change in the direction that decision makers take. Before the pandemic there was a lot of focus on moving to sustainable modes of transportation such as increasing use of public transport. This has shifted in the pandemic due to the interest of using private vehicles to decrease risk of infection (Budd and Ison, 2020). Following the pandemic, the efforts for moving towards net zero have picked up and there is more focus on this again.

7. *Does deep conflict exist in assumptions, beliefs and assumptions?*

Support of electric vehicle adoption and the social acceptance varies. Policy plays a strong part in the adoption of electric vehicles, where weak policy indicates a low acceptance of electric vehicles and stronger policy leading to higher acceptance of electric vehicles (Hardman, 2019; Sierzchula et al., 2014; Rietmann and Lieven, 2019).

8. *Do people share underlying values which can drive common perspectives and alignment in their actions?*

The problem with petrol and diesel engines is widely recognised as well as the need to switch to electric vehicles.

Step 3:

Problem Focused Criteria

1. *Structural complexity: Is there inherent intractability of the technical (ie non-stakeholder-related) aspects of the problem?*

Technical solutions exist and are widely available at the one-off level, so for individual consumers. The primary problem complexity is low. If all consumers switched to Electric Vehicles, then there are secondary problems that arise, for example around charging, the power supply and material and product supply chains. The switch to electric vehicles cannot happen instantaneously due to factors like this and will take time to be fully implemented (Hill et al., 2019). The secondary problem complexity can be classified as high.

2. *Knowability: Is there little knowledge about the issue? Is relevant information hidden, disguised or intangible? Does it comprise multiple complex variables? Do its workings require action to discover causal links and outcome?*

The knowability of the problem surrounding electrifying vehicles is clear at first. For reducing emissions around transport, electrifying vehicles is the solution. However, there is more implications of electrifying vehicles for supply chains and infrastructure for example. For consumers to switch their behaviour from buying traditional petrol and diesel engine cars it is important to make this decision to switch to electric vehicles as easy as possible. A clear barrier for the adoption of all electric vehicles is the limited availability of charging infrastructure (IEA, 2021b). This again points towards a secondary problem with the adoption of Electric Vehicles. The Covid-19 Pandemic slowed down the pace of building new chargers that are accessible in public (IEA, 2021b). Another factor prohibiting the adoption of electric vehicles is the initial high cost of purchase (IEA, 2021b).

3. *Knowledge-framing: so Does some of the knowledge receive either too much or too little attention because of the way it is framed, thereby distorting our understanding?*

There is an overall focus on moving towards electric vehicles, along with the secondary problems this involves. Not one clear area is focused on more than others for this as all the individual factors, e.g. the charging infrastructure, the power supply and material and product supply chains, play together for enabling the switch to electric vehicles.

Stakeholder Focused Criteria

4. *Knowledge fragmentation: Is the available knowledge fragmented among multiple stakeholders, each holding some but not all of what is required to address the problem?*

Surrounding fragmentation of knowledge, it is understood by car original equipment manufacturers that with the goal of net zero emissions there needs to be a restructuring of the industry. It is expected that the 2020s will be the decade of change for the automotive industry with 18 of the 20 largest OEMs increasing model availability and production for electric vehicles (IEA, 2021b). This forecast matches with the current developments in the car industry, with increasingly new models of electric vehicles becoming available.

5. *Interest-differentiation: Do the various stakeholders have interests (or values) which are substantially in conflict with those of others?*

The interest differentiation brings in a different perspective to this. There are various stakeholders involved which could have conflicting interests when it comes to switching to electric vehicles. Examples of stakeholders are the governments, original equipment manufacturers, energy companies, suppliers and customers. However, specific policies can support in this aspect and help stakeholders to work towards a common goal.

6. *Power-distribution: Is there a dysfunctional distribution of power among stakeholders?*

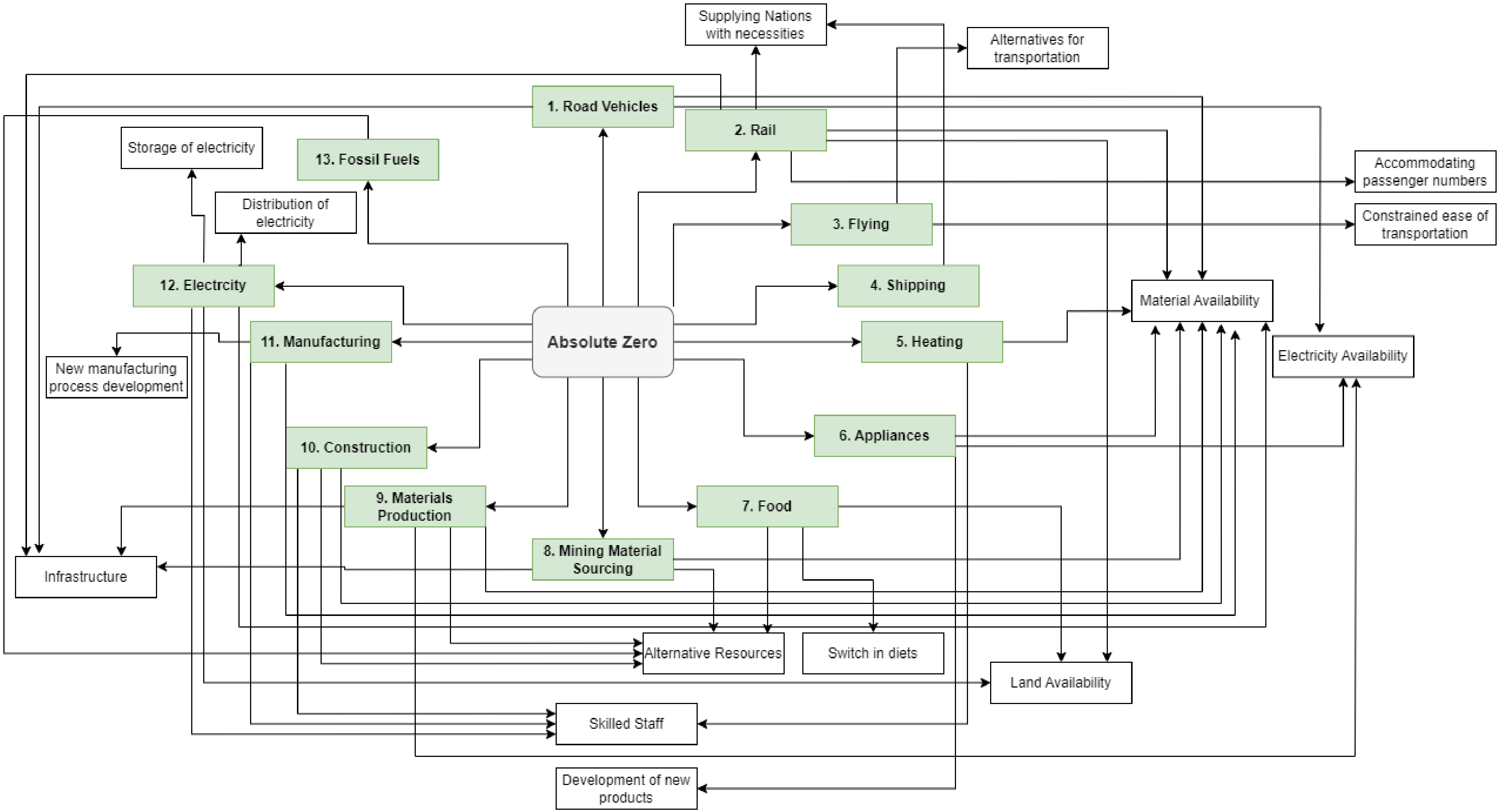
Another consideration is the power distribution amongst stakeholders. Consumers rely on the developments of the car manufacturers for purchasing a vehicle. Consumers also play a part in the successful move towards using electric vehicles, as their purchasing behaviour will determine whether these cars are in demand and will be in use in the future. However, like conflicting interests, policy can help to limit the power distribution for this.

Appendix 2 – *Absolute Zero* Actions and their CO_2 Emission Context

***Absolute Zero* Action**	**CO_2 Emissions in UK (Mt CO_2) in Year**	**Context**	**Source**
Road Vehicles	99 (2021)	Emissions of domestic transport in the UK. Includes numbers on: cars and taxis, HGVs, vans, buses, motorcycles and mopeds and other road transport.	Department for Transport, 2023b
Rail	2.21 (April 2022 – March 2023)	Includes emissions for passenger and freight train journeys.	Office of Rail and Road, 2023
Flying	32 (2023)	Counts emissions of flights departed from the UK airports	Transport and Environment, 2024
Shipping	5 (2021)	Emissions of domestic transport in the UK	Department for Transport, 2023b
Heating	76 (2021)	Emissions of heating by UK households	Department for Environment, Food & Rural Affairs, 2024
Appliances	2,872.3 (2022)	Appliance emissions from residential and services sector.	International Energy Agency, 2023
Food	158 (2019)	Provides GHG emissions that are connected with production and consumption of drink and food across their entire value chain.	Forbes, Fisher and Parry, 2021
Mining material sourcing	17.18 (2021)	Source provides overview of CO_2 emissions by industry in 2021.This number focuses on Mining and Quarrying.	UK Government Climate Change, 2023
Materials Production	6,380 (2016)	Emissions of materials production globally	Hertwich, 2021

Construction	10.2 (2021)	Source provides overview of CO_2 emissions by industry in 2021.	UK Government Climate Change, 2023
Manufacturing	81.59 (2021)	Source provides overview of CO_2 emissions by industry in 2021.	UK Government Climate Change, 2023
Electricity	44 (2023)	Territorial emissions on electricity supply	Office for National Statistics, 2024
Fossil Fuels	312.7 (2022)	Considers territorial CO_2 emissions, including fuel used for electricity generation	Department for Energy Security and Net Zero, 2023

Appendix 3 – Interconnectedness of *Absolute Zero*



Appendix 4 – Interconnectedness of Roadmap