# A HOLISTIC APPROACH FOR AMELIORATING THE EFFECT OF ‘VALLEY OF DEATH’ IN TECHNOLOGY ASSIMILATION

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# Abstract

Technology assimilation is an increasingly important topic in modern manufacturing industries. Successful technology assimilation not only supports the development of better products, but also can provide a competitive edge in fast-moving markets, such as the automotive industry. Technology assimilation is a complex process, with a high failure rate, with technologies that seem promising in the research phase, failing to be assimilated into the final product. This high failure rate for technology assimilation is costly, in both time and other resources, and so has resulted in the effect of the ‘Valley of Death’. Tools and methods for technology assessment are essential enablers of successful product development, a process that requires collaboration from both engineering and business professionals to be successful.

This thesis presents research that was aimed at ameliorating the ‘Valley of Death’ effect during technology assimilation, particularly in the environment of the automotive Original Equipment Manufacturers (OEMs). The research was undertaken in close collaboration with Jaguar Land Rover Limited. Such collaboration provided first-hand information and direct engagement that supported and enabled this research.

A review of the relevant theoretical concepts and the process of technology assimilation was undertaken, with a focus on the tools and methods that have been applied. The literature review resulted in an identification of the gaps and challenges among current technology assimilation approaches. This work also resulted in a conceptual model being developed to represent three different viewpoints that it is argued are essential to understand for successful technology assimilation, namely:

Natural Technological Viewpoint, Social Technological Viewpoint and Human Technological Viewpoint. These three viewpoints were then further elaborated in a Hexahedron Model of Technology, alongside consideration of technology assimilation complexity, capability of technology and the contribution of a potential technology, allowing six different perspectives to be considered during the process of assessing if a specific technology is suitable for assimilation into a complex product.

In this thesis, the Hexahedron Model of Technology, as the name suggests, allows consideration of six different facets for successful technology assimilation, and can be further elaborated to include more aspects of technology based on the future work. This model can also support an enterprise to understand how to develop the technology in a direction that might increase the likelihood of successful assimilation.

The approach to technology assimilation presented in the thesis first sets out a Technology Assessment Framework and methods for populating and applying it. The Hexahedron Model of Technology provides a structural platform for assessing the subjective factors that need to be considered during technology assimilation in a structured way. This process helps to reduce the number of technologies that are considered for assimilation; by pre-eliminating some relatively weak technologies and taking forward only those more likely to succeed. A Technology Refinement and Modification Algorithm was then developed that provides suggestions, at a high-level, for the direction for technology improvement to help make the technology better match the requirements. This algorithm hence helps to further increase the chances of successful technology assimilation.

The Technology Assessment Framework and Technology Refinement and Modification Algorithm were applied to two case studies. One of these cases was conducted to demonstrate the process of the proposed approach whereas the other one was part of a real-world project in collaboration with the Jaguar Land Rover Limited. Overall, this research demonstrates a two-step holistic approach to technology assimilation that first reduces the number of technologies considered for assimilation and then establishes the direction for development of new technology to improve the likelihood of successful technology assimilation.

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## Glossary

| | |
|---|---|
| 3C | Complexity, Capability and Contribution |
| ADAS | Advanced Driver-Assistance Systems |
| ADS | Autonomous Driving System |
| AHP | Analytic Hierarchy Process |
| CI | Consistency Index |
| COT | Commercialization of Technology |
| CR | Consistency Ratio |
| DOD | United States Department of Defense |
| ECU | Electronic Control Unit |
| EPSRC | Engineering and Physical Sciences Research Council |
| ER | Enterprise Requirement |
| ERM | Enterprise Requirement Matrix |
| GWM | Gateway Module |
| HMT | Hexahedron Model of Technology |
| HTV | Human Science Associated Technological Viewpoint |
| IRLs | Integration Readiness Levels |
| IT | Information Technology |
| JLR | Jaguar Land Rover |
| MCDA | Multi-Criteria Decision Analysis |
| MTRs | Midterm Reviews |
| NASA | National Aeronautics and Space Administration |
| NHTSA | National Highway Traffic Safety Administration |
| NPD | New Product Development |
| NTV | Natural Science Associated Technological Viewpoint |
| OEMs | Original Equipment Manufacturers |
| PhD | Doctor of Philosophy |
| PI | Principal Investigator |
| PSi | Programme for Simulation Innovation |
| R&D | Research and Development |
| $R\&D^3/DD$ | Research and Development Degree of Difficulty |
| RI | Random Indices |
| ROI | Return-on-Investment |
| ROSE | Relational-Oriented Systems Engineering |
| SRLs | System Readiness Levels |
| STV | Social Science Associated Technological Viewpoints |
| SysML | Systems Modeling Language |
| TAF | Technology Assessment Framework |
| TCM | Technology Contribution Matrix |
| TF | Technology Feature |
| TFM | Technology Feature Matrix |
| TRLs | Technology Readiness Levels |

| | |
|---|---|
| TRMA | Technology Refinement and Modification Algorithm |
| TTS | Technology Trade Space |
| UML | Unified Modeling Language |
| V2V | Vehicle to Vehicle |
| V2X | Vehicle to Infrastructure |
| V&V | Verification and Validation |

# 1 Introduction

The origin of this PhD research came from the difficulties that automotive original equipment manufacturers (OEMs). e.g. Jaguar Land Rover Limited (JLR) face in assimilating new technologies into products (1–7). The assimilation of evolving technologies into complex products and systems presents increasingly more complex challenges such as creating new ways of working, examining decision-making processes and redesigning the governance structures for the production lines and supply chains (8–12). New technologies, when successfully assimilated into products and systems, can provide new functionalities and features to the products that help to maintain competition advantages (13–15). Moreover, the capability of technology assimilation of enterprises, in terms of how fast and how well technologies can be assimilated, has become essential to the companies in automotive industry for its influences on the quality of systems and products that could potentially lead to bigger market share. (16–18).

The importance of technology assimilation has been demonstrated and proven through decades of research. Research has shown that being unable, or unwilling to embrace new technology can be a cause of companies losing market share (6,12,13,15,18). An example of this is that Sony Entertainment failed to replace its Minidisc with the MP3 format in time and eventually lost the market entirely back in the 90’s (19). Moreover, the rapid development of products (systems) is one of the cutting-edge topics in current manufacturing industry and technology is recognised as a key driver behind new product development (7,20,21). More importantly, technology assimilation also influences the delivery schedules and risks associated with new product development (22,23).

However, most of the applications of technology assimilation are conducted based on various of methods and approaches that lead to unpredictable results of technology assimilation (1,10,24–27). As part of the Programme for Simulation Innovation (PSi), a joint five-year research programme between Jaguar Land Rover Limited and the Engineering and Physical Sciences Research Council (EPSRC)[1], this research has been conducted with close collaboration with Jaguar Land Rover Limited. The author has been invited to meetings held by Jaguar Land Rover Limited with regard to the technology assimilation. Such meetings and involvements have provided first-hand experiences of the methods and approaches of technology assimilation applied in the automotive industry. The observations and analyses of such meetings are included in Section 2.9 of this thesis. One of the most important assumptions from these experiences is that, as also acknowledged by the engineers and managers engaged in this work, the methods and approaches automotive OEMs applied are either not sufficient in certain ways or not being applied consistently throughout the projects. These experiences underpin the importance and the need for research in this area and are a motivation for this PhD research.

The aim of this research is stated as follows: ‘to develop a holistic approach to technology assimilation for ameliorating the effect of ‘Valley of Death’ in the environment of automotive OEMs’. The detail explanations of the aim of this research is presented in Section 3.2. This research has resulted in a holistic approach to technology assimilation that supports the practical reality of designing and developing complex products and eventually ameliorates the problem of low likelihood of successful technology assimilation that is often referred to as the effect

[1] This work was sponsored by the Programme for Simulation Innovation (PSI), a partnership between Jaguar Land Rover Limited and UK EPSRC grant EP/K014226/1.

of ‘Valley of Death’. First, a framework namely Technology Assessment Framework (TAF) is introduced to support decision-making about which technologies should be considered for assimilation. The purpose of this phase of the approach is to reduce the Technology Trade Space (TTS) (i.e. number of technologies) that are fully considered for assimilation, and direct effort and resource at only those technologies that are likely to be successfully assimilated. Second, an algorithm, namely Technology Refinement and Modification Algorithm (TRMA), is presented that supports the enterprise in planning the general directions of improvements of the selected technologies in a forward-looking manner, which should further benefit the overall fulfilment of the requirements and so increase the likelihood of successful assimilation.

The overall structure of this thesis is illustrated in Figure 1.1. Chapter 1 introduces this research and outlines the scope of the work. Chapter 2 mainly discusses literature related to technology assimilation, as well as methodologies that applied in this research. This is followed by an analysis of the state-of-the-art methods and tools involved in technology assimilation in practice, revealing the insufficiency and inadequacy of such methods and tools. The analysis of the literature includes an expanded definition of ‘technology’ for the purpose of this research that takes account of a broad range of perspectives. In addition, the observations and lessons learnt from real world technology assimilation are included in this chapter to support the findings from literature review. In Chapter 3, the aim and objectives of this research are set out following the identification of the research problem. Moreover, in Section 3.4, the methodology of this research is presented. This section mainly focuses on explaining how to apply methods (previously discussed in Chapter 2) to conduct this research and ameliorate the effect of ‘Valley of Death’ in technology assimilation. In Chapter 4, the Technology Assessment Framework (TAF), which is developed based on a Hexahedron Model of Technology discussed in Section 4.1, is presented from the beginning of the conceptual design all the way to the detailed explanations of each component of TAF. In Chapter 5, the Technology Refinement and Modification Algorithm (TRMA) is presented. This chapter explains the details of the algorithm with a conceptual example and a workflow. In Chapter 6, two major case studies are conducted that contain the comparative assessments of two pairs of technologies by applying both TAF and TRMA. The main purpose of this chapter is to demonstrate TAF and TRMA. In addition, both case studies serve as preliminary verifications and validations of the proposed approach in this research. Case study 1 is conducted based on hypothetical situations and applies information gained from both literature and Jaguar Land Rover Limited. The results from this application of TAF demonstrate a clear ranking of the technologies under consideration, and show which technology has more potential to be successfully assimilated. The TRMA analysis is only applied to the technology that shows good potential for assimilation after the TAF assessment results have been analysed. Case study 2 contains information from a real world project conducted by Jaguar Land Rover Limited. The assessment results from TAF in this case study are hence not as clear as the first case study. Therefore, TRMA is applied to both technologies to further analyse the potential for assimilation. The results from TAF and TRMA are combined to provide the final suggestion on which technology should be considered to assimilate. In the Chapter 7, the conclusions and future works of this research are presented.

Overall, the contributions of this PhD research are summarized hereafter. First, this research presents a review of the literature in the scope of technology assimilation including, but not limited to the concepts of technology, the tools and methods of technology assessment and the environment of technology assimilation to identify the gaps and research problems involved in the technology assimilation. Second, this research provides evidence to support the identification of such gaps and problems through close engagement with the industry and hence increasing the potential impact and benefit of this research for both academia and industry. Third, this research proposes a holistic approach for ameliorating the ‘Valley of Death’ effect in technology assimilation. This approach contains a Technology Assessment Framework (TAF) and a Technology Refinement and Modification Algorithm (TRMA). Finally, this research conducted two case studies applying of the proposed holistic approach for ameliorating the effect of ‘Valley of Death’ in technology assimilation; these cases preliminarily verified and validated TAF and TRMA through engagement with the Jaguar Land Rover Limited. The outcomes of these two case studies both suggest that, by applying the proposed approach of this research, the effect of ‘Valley of Death’ in the automotive OEM environment can be ameliorated. The approach facilitates the identification of technologies that would fail to meet the business requirement and enables the identification of that will have a better surviving chance through ‘Valley of Death’.

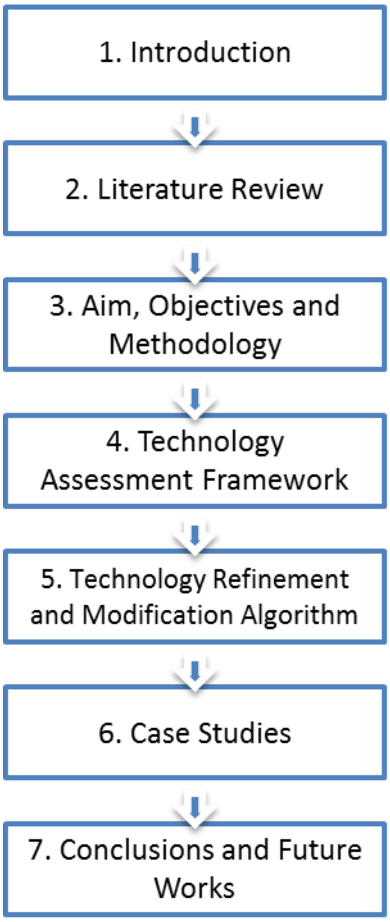


**Figure 1.1 Structure of Thesis**

## 1.1 Research Scope

This research focuses on undertaking technology assimilation and technology assessment in the automotive industry especially in automotive OEMs. There is also literature on technology assimilation in the health care industry and medical industries (26–30), but for this research, the scope was limited to technology assimilation in the automotive OEMs for the reasons explained hereafter.

First, the automotive OEMs are recognised as technology-oriented industry by the Standard Industrial Classification published by the Office for National Statistics as well as literature (31,32). Therefore, technology assimilation is a process of vital importance to automotive OEMs. Moreover, since the development of an approach that includes methods and processes that facilitate different viewpoints and concerns involved in technology assimilation is one of the major tasks of this research, automotive OEMs represent an ideal environment for studying technology assimilation due to the fact that they have to respond to the market while maintaining a balance among the different expectations of a variety of stakeholders (33–35). Technology assimilation, as a complex problem in automotive OEMs, requires the collaboration of many different teams and multiple viewpoints in order to tackle it successfully (16). Technology assimilation problems in automotive OEMs should be solved by collaboration among different departments of automotive OEMs rather than by engineering departments alone, which are discussed in Chapter 2 and Chapter 4 of this thesis.

In addition, as stated previously, this research is funded by the Engineering and Physical Sciences Research Council (EPSRC) through collaboration with Jaguar Land Rover Limited. This provides opportunities for this research to access cutting-edge approaches to technology assimilation, and such close engagement between this research and this automotive OEM enables the opportunity for preliminary verifications and validations of the research outcomes.

# 2 Literature Review

Figure 2.1 illustrates the structure of this chapter of literature review.


**Figure 2.1 Structure of Literature Review**

The main purpose of the literature review in this thesis is to study current technology assimilation processes and methods in order to identify the gaps. However, one thing needs to be noted is that this literature also includes reviews of applied methodologies in this research. The methodologies reviewed in this chapter are mainly focused on understanding what such methodologies are and explaining the reasons of them being applied in this research whereas the Methodology section (Section 3.4) in Chapter 3 focuses on explaining how these methodologies are applied in this research.

This literature review is divided into ten sections. In the first section, different definitions of technology are reviewed in order to propose the expanded definition of technology in this research. In addition, some related terms and concepts of technology are studied and reviewed for their importance to technology assimilation. Most importantly, three technological viewpoints are defined in this section that are further elaborated in Chapter 4 to propose the Hexahedron Model of Technology, which is the foundation of both TAF and TRMA.

In the second section of this literature review, the differences between concepts such as technology adoption, knowledge transfer and technology assimilation that are similar yet have different meanings are reviewed. The purpose of this section of literature review are 1) to distinguish such similar terms so that the disambiguation can be achieved and 2) to define the scope of technology assimilation in this research.

In the third section of this literature review, the general scenarios of technology assimilation are assumed based on reality and observations from the engagement with Jaguar Land Rover Limited namely technology-driven technology assimilation and requirement-driven technology assimilation. The differences between these two general scenarios of technology assimilation are identified, and the requirement-driven technology assimilation is selected as the focus of this research. Therefore, the scope of this research is further narrowed down.

In the fourth section of this literature review, one of the major arguments of this research is presented. Here it is argued that in order to conduct a better technology assessment, the methods and tools should facilitate comparative assessments. As one of the foundations of the development of the Technology Assessment Framework (TAF), this argument is rooted in the understanding that the quality of technology is a relative term. The idea is that there is no ‘best’ but only ‘better’ technology to assimilate given a certain situation. Therefore, comparative assessment of technologies under same criteria and situation is required to suggest a ‘better’ technology.

In the fifth section of this literature review, the relationships between technology assimilation and its environment are reviewed. More specifically, the influences of technology assimilation on Research and Development (R&D) and New Product Development (NPD) as well as marketing are studied and reviewed. The purpose of this section of the literature review is to explain the importance of technology assimilation in current automotive OEMs. In addition, a Vee model of technology assimilation is assumed based on the literature review in this section in order to better define the process of technology assimilation.

For the sixth section of this literature review, the technology assessment processes and the approaches to decision making in technology assimilation are reviewed. In addition, this research reviews the cutting-edge methods and tools for technology assessment and decision-making in order to identify their strengths and weaknesses. Such strengths and weaknesses are further elaborated into the requirements of the development of TAF in Section 4.2 of Chapter 4.

The seventh section of this literature review focuses on the ‘Valley of Death’ theory and the the effect that causes technology assimilation failures. For the ease of read purpose, a brief introduction of the ‘Valley of Death’ and its effect is included here. A more comprehensive discussion of this topic is presented in Section 2.7. In general, the ‘Valley of Death’ is a metaphor employed in many domains but mostly with reference to new things or ideas such as inventions, technologies or start-up businesses that could not survive for various reasons through logical time (36,37). In technology assimilation, ‘Valley of Death’ refers to a concluded phenomenon where a technology fails to reach the market because of the inability to advance from the technology's demonstration phase to the commercialization phase (38). Failure to bridge the ‘Valley of Death’ is often due to a resource gap between R&D laboratory and commercialization within an enterprise. As explained in detail in Section 2.7, the original theory of ‘Valley of Death’ highlights an important phenomenon but does not address how to move projects from the laboratory to New Product Development (NPD) via individual and organisational level decisions (38–40). Existing methodologies for bridging the ‘Valley of Death’ and reduce the negative effect of it are explored and elaborated in to the approach proposed in this thesis in Chapter 4 and 5.

In the eighth section of this literature review, major applied methodologies in this research are reviewed. This is to study what they are and how they could benefit the development of the proposed approach in this research. As explained previously, how these methodologies are applied to this research is explained in a later chapter (Section 3.4 of Chapter 3).

In the ninth section of this chapter, the technology assessment in real world situation is studied and reviewed based on the engagements of the author with Jaguar Land Rover Limited. The observations from such engagements are presented and are followed by the analyses of lessons learnt that are approved by the Jaguar Land Rover Limited. This section provides an alternative source of understanding of the problems other than literature.

In the last section, the summary of this literature review is presented. This section summarises the gaps identified in this literature review and identifies the essential features that the proposed approach in this thesis should have in order to ameliorate the ‘Valley of Death’ effect in Technology Assimilation. Such features are further included and elaborated to the identification of the requirements and specifications of TAF development in Section 4.2 and 4.3 of Chapter 4.

## 2.1 Definitions of Technology and Related Terms

Over the years, research has been conducted to reveal the true nature of technology and the relationships between technology and science. There is a popular viewpoint that recognizes technologies as applications of science (41). Also, technology is defined as the practical implementations of intelligence by Ferre (42). These two definitions echo with each other as technology can be recognized as either implementation or application of human knowledge or science. A relationship and transformation can be identified between the technology and human knowledge or science. Therefore, this research elaborates on these viewpoints and defines technology based on different branches of science and further proposes the technological viewpoints.

There are different classifications of science in the literature. For example, Simon defines science into two classes that are Natural Science and Design Science (43). Also, one of the popular classifications divides science into Natural, Social and Human Science. However, the point here is not to find the 'right' classification of science. Instead, knowing that there are different classifications of science establishes that there are different viewpoints on how people understand science. As mentioned, there is a relationship, either implementation or application, can be identified between science and technology. Therefore, this research argues that there are different viewpoints on how people understand technology.

In this research, the classification of science that divides science into Natural, Social and Human Science is adopted and further elaborated to define different classes of technologies.

Figure 2.2 illustrates the mapping between the adopted science classification and technology classifications.

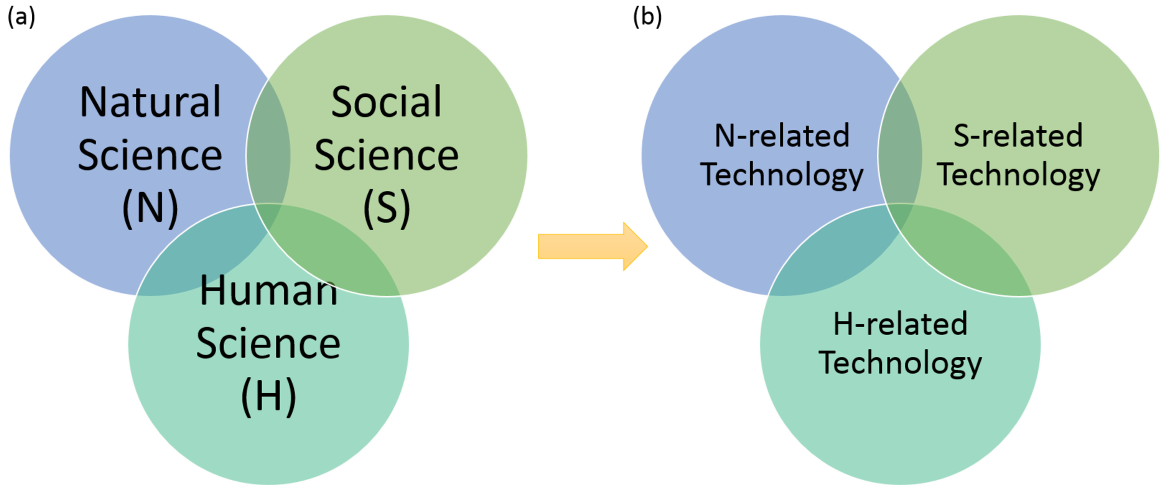


**Figure 2.2 (a) Classification of sciences based on their natures. (b) The associated mapping of different types of technologies onto the classification of sciences as in (a).**

As shown in Figure 2.2, in general, a relationship between science and technology can be understood as a mapping between two classes where science (S) is being applied to technology (T). Mathematically, there is a mapping,

**Equation 1 Mapping between Science and Technology**

$$f : \mathcal{S} \to \mathfrak{T}$$

This mapping is an abstraction of how sciences have been applied or implemented to create a technology.

Figure 2.2 (a) illustrates a general classification of science, based on the natures of the scientific fields, as Natural Science, Social Science and Human Science (also known as Humanities). The overlapping areas between each pair of fields are inter-disciplines. The overlapping areas indicate that the sciences in these classes are jointly dependent on each other. For example, this research believes that the mathematical modelling of finance is a Natural-Social Science; the studies of music and musical instruments using physics is a Natural-Human Science; law can be regarded as a Social-Human Science; and, arguably, System Science is a combination of sciences in all three classes in the present days. As shown in Figure 2.2, there is a possible way to express science as a set by,

$$\mathcal{S} = \{N,S,H,NS,NH,SH,NSH\}$$

Where N,S and H represent Natural, Social and Human Science respectively. Combining with the mapping, there is then an associated set of technologies,

$$\mathcal{T} = f(\mathcal{S}) = \{f_N(N), f_S(S), \ldots f_{NSH}(NSH)\}$$

In practice, this is a good approximation when only considering the major contributions of branches of knowledge in developing of a particular technology, i.e. this research neglects the fact that the boundaries between scientific disciplines are blurred rather than sharp.

**Table 2.1 Examples of Technology Assimilations**

| **Science** | **Technologies** | |
|---|---|---|
| | ***Existing technologies*** | ***Assimilation examples*** |
| Natural Science (N) | Engine calibration design of experiments | Engine calibration and aftertreatment systems integration environment |
| Social Science (S) | Static enterprise resource planning based on emission legislation | Self-organizing enterprise resource planning |
| Human Science (H) | Driving behaviour static modelling | Driver in the loop (dynamic behaviour modelling) |
| Natural-Social-Human Science (NSH) | System trade-offs; Pareto Optimality | Systems of system trade-off methodology |

In Table 2.1, some existing technologies and possible technologies for assimilation (derived from respective classes of sciences in the automotive industry) are shown as examples.

Overall, based on the classification of science, a general classification of technology can be identified. However, this research acknowledges the fact that technologies are not easily classified and that this classification of technology does not precisely cover all technologies.

Nonetheless, the mapping between science and technology reveals an important fact that different technological viewpoints are necessary in order to obtain better understanding and analysis of technologies. Therefore, definitions of different technological viewpoints are presented hereafter.

As mentioned previously, the term ‘Science’ has many definitions and classifications. This part of the literature review does not focus on science, so that arguing about the classification of science is simply to point out that there is a vast amount of knowledge that can be seen as science apart from the Natural Sciences. During this PhD research, one of the findings is that insufficient attention is paid by automotive OEMs and technology-oriented industry to the technologies that belong to the overlapping parts shown in Figure 2.2 (b), which can be very influential to the fate of the enterprises (44).

Normally, the modern technology-based firm acknowledges the technology only as the Natural Science-related technology and sometimes ignores other kinds of technology (44–46). This fact causes some solutions of engineering problems to be limited from the beginning. It is not rare that some technologies are discarded because they do not belong to the category of Natural Science-related technology, as shown in Figure 2.2 (b), when technology assimilation is the solution of some business problems even though these technologies have the potential to solve such business problems.

In fast-moving manufacturing environments, new technologies are being integrated onto existing platforms (47–49). When 'non-traditional' technologies are not considered from the initial stage because of the limited vision of technology, companies can lose their competitive edges.

Moreover, different types of technology based on the classification of Figure 2.2 (b) have different ways to be integrated (47). It is always better to have a forward-looking plan when different types of technology need to be integrated together. Such forward-looking plans should be based on a unified view of technology.

For example, a new driving model of a (car) driver (a technology which can be categorised into the combination of Human Science-related and Natural Science-related technologies) needs to be integrated with a virtual model of a vehicle (a technology which can be categorised as a Natural Science-related technology) under the constraints of different market models (technologies which can be categorised into the combination of Social Science-related and Natural Science-related technology) is an example of such integration of different types of technology according to the classification of Figure 2.2.

Moreover, not only there are different types of technologies, there are different aspects of technology that should be analysed and assessed by different technological viewpoints in order to achieve a holistic understanding of the technology and hence increase the probability of successful technology assimilation. As one of the major arguments of this research, the technological viewpoints that derived from different classifications of science are presented and explained in next section of this literature review.

### 2.1.1 Technological Viewpoints Derived from Different Classifications of Science

This section of the literature review serves to explore the different technological viewpoints that derived from different classifications of science. The identification and definition of the technological viewpoints are recognised as one of the novelties of this research and are proven vital important for technology assimilation in later chapters.

#### *2.1.1.1 Natural Science Associated Technological Viewpoint (NTV)*

Analyzing a technology from a Natural Science associated viewpoint is perhaps the most common and default way in modern automotive OEMs based on the experience acquired from the engagement between the author and Jaguar Land Rover Limited. The understanding and analysis derived from this viewpoint often treat the technology in a straightforward manner. Often, through the development of technology, and through technology employment, engineers aim at solving the problem directly. This viewpoint works particularly well when the problem can be clearly narrowed down to specific engineering requirements, such as the improvement of a particular system element, and is backed up by ongoing scientific research. However, when systems are very complex and may have multiple stakeholders, and outcomes of the technology assimilation project that only relies on this viewpoint are unpredictable. This viewpoint is often referred to as Natural Technological Viewpoint in later chapters.

#### *2.1.1.2 Social Science Associated Technological Viewpoint (STV)*

This viewpoint is concerned with the effects of a technology on the management of the corporation and organisational level rather than looking at how the technology solves engineering problems directly. Often, through better management, the cost of technology assimilation can be significantly reduced, the quality of the assimilated technology can be improved, and the time to market can be reduced. However, different technologies have different levels of difficulty in terms of organisational management. Moreover, the assimilation projects of some technologies may affect the structure of the enterprise and require cross-departments collaboration that increase the overall complexity of the project (16). This technological viewpoint can be applied to reveal the difficulties brought by a given technology in the organisational level.

For example, in automobile industries, companies often have many departments, each of which is responsible for a particular system of the vehicle, such as the engine department and the after-treatment department due to the differing nature of the underlying engineering characteristics. During an assimilation project for an emission-related technology, ineffective management could lead to a lack of cooperation between the two departments or could overburden one department compared with the other. Eventually, this could lead to a delayed technology assimilation process and a significant loss of market share. Without the Social Science Associated Technological Viewpoint, such risks are easily overlooked. This viewpoint is often referred to as Social Technological Viewpoint in later chapters.

#### *2.1.1.3 Human Science Associated Technological Viewpoint (HTV)*

This technological viewpoint can be used to reveal the potential influences of a technology on the end users and stakeholders and vice versa. Instead of focusing on the technology, HTV emphasizes the relationship between the technology and human, especially the people (end user) who will eventually use the technology or the product that contains the technology, and focuses on the aspects of technology that affect or affected by the end user. By learning such end user behaviors and how they affect a technology life cycle as well as learning how a technology could potential affect the end user, the technology is then improved based on the study outcomes. For example, user behavior analysis is a particular approach to enhance the acceptance of products and technologies from HTV (50). This approach aims to analyze the user behavior when using the certain product and technology and therefore provides improvement suggestions for product and technology with regard to their user acceptance.

Another example of how human affect the technology assimilation in automotive industries is product positioning. Different groups of end users prefer different products and features of products. For example, expensive technologies such as fancy entertainment systems and Advanced Driver Assistance Systems (ADAS) on high-end vehicles would not be appropriate features of a vehicle product aiming at low-end vehicle market for the potential increased cost. When assessing technologies from HTV, the consideration of such product positioning should always be included. A fundamental argument of this PhD research, which is further explained in Section 2.4, is that the quality of technology is a relative term. In the content of HTV, especially in the scope of product positioning, this means that the most advanced technology may not be the right choice of assimilation when considering the product positioning of the product it will be assimilated into. The positioning of the product greatly affects the decision making of technology assimilation in terms of which technology should be considered to be assimilated (51). This viewpoint is often referred to as Human Technological Viewpoint in later chapters.

In order to support the above mentioned three technological viewpoints, this research has also reviewed the work of Linstone (52). There are three perspectives been identified and defined by Linstone namely technical perspective (T), organizational perspective (O) and personal perspective (P) (52). These perspectives echo with three technological viewpoints defined in this research.

Based on the work of Linstone, the O and P perspectives are recognised as complements instead of replacements of T. Similar to Natural/Social/Human associated technological viewpoints; this provides the various ways of thinking of complex problem. As Avison et al argued, for all complex problem and situation, all three perspectives will be required to be adopted for analysing inevitably (53). This argument supports the fact that companies would be harmed if ‘non-traditional’ technologies are not considered from the initial stage because of the limited vision on technology in current fast-moving manufacturing environments where new technologies are being integrated onto existing platform.

### 2.1.2 Complexity of Technology and Technology Assimilation

One of the main challenges when designing automotive products is the significant level of complexity both within and between the component systems. This complexity presents automotive OEMs with significant challenges and directly impacts on the outcome of technology assimilation.

There are generally two approaches that have been used to define the term ‘complex’. The first approach has been to define ‘complex’ as consisting of many varied interrelated parts (54)(55). The second approach defines ‘complex’ as ‘complicated, involved and intricate’(55). Based on the work of Johnson (54), complexity is defined here as ‘the phenomena which emerge from a collection of interacting objects’. This definition of complexity highlights the fact that interaction among elements is one of the key contributors to complexity. Moreover, based on the work of Tani and Cimatti (56), the aspects of the term system complexity are identified.:

1. *‘Number of elements or sub systems’.*
2. *‘Degree of order within the structure of elements or sub systems’.*
3. *‘Degree of interaction or connectivity between the elements, sub systems and the environment’.*
4. *‘Level of variety, in terms of the different types of elements, sub systems and interactions’.*
5. *‘Degree of predictability and uncertainty within the system’.*

The first aspect is the number of elements or sub systems which is easy to understand as the number of elements or sub systems increases, the potential interactions among them also increase. This research believes that the aspect number two to four focus on the internal reasons of complexity as they explain the different causes of different interactions. The fifth aspect of complexity identified by Tani and Cimatti is believed as the other major aspect of the term complexity as the unpredictability and uncertainty of the system truly distinguish the term complex and complicated (56).

In this research, by elaborating on the above-mentioned works, the technology complexity is defined as follow:

*'The degree of which the interrelationships and (or) interactions of a technology's components and (or) features cause difficulties for the observer to gain a holistic understanding of the technology.'*

With this definition, the technology complexity is understood directly associated with the number and degree of the interrelationships/interactions among a certain technology. And also, this definition is based on a subjective point of view as the complexity is also directly associated with the observer meaning that to a specific technology, different observer could have different perceived complexity based on their different knowledge and profession background.

Moreover, after elaborating on such definition of complexity of technology, the complexity of technology assimilation can be assumed as follow:

*'The degree of which the interrelationships and (or) interactions of the stakeholders and entities involved in a technology assimilation project combining with the complexity of technology cause difficulties for the observer to gain a holistic understanding of the technology assimilation and management.'*

As suggested by the definition of the complexity of technology assimilation in this thesis as well as the title of this sub-section, there are two levels of complexity that need to be dealt with during the process of technology assimilation. Overall, gaining a holistic understanding as well as predicting the complexities that may be encountered during the technology assimilation are crucial to industry.

### 2.1.3 Capability of Technology

Similar to the term complexity, there is no universal definition of capability that is agreed by all disciplines due to the huge amount of different viewpoints regarding the term ‘capability’.

According the literature, many types of capability have been identified. In Oxford Dictionary, the word ‘capability’ is defined as ‘the power or ability to do something’ (57). In literature, for example, an enterprise is recognised to have dynamic capabilities if it is able to identify and respond to the changes within the environment (58). Similarly, the business capabilities, though belonging to different business management sections, refer to activate, use and maintain resources for specific business activities. Moreover, the Information Technology (IT) capability is defined as the ability of an enterprise to acquire, deploy, combine, and reconfigure IT resources to support and enhance the business strategies and work processes (58–60). Arguably, the discussions of capability focus on capabilities of enterprise. However, this research elaborates on such understandings and definitions of capability and shifts the focus from the capabilities of enterprise to the capabilities of technology.

In this research, the capability of technology is understood directly associated with the requirements of technology assimilation. A technology has a certain capability only if this technology has the ‘power or ability’ to fulfil a certain requirement, and by assimilating this technology, the enterprise acquires this capability. This understanding of capability highlights the dynamic nature of the term capability meaning that a certain technology can be acknowledged as providing great capabilities to a company or project but at the same time be acknowledged as providing fewer capabilities to other companies or projects that have different set of requirements. Therefore, a technology may provide different capabilities to different enterprises, and this fact enables the technology assessment based on the capabilities of technology.

Also, as the capabilities of technology are directly associated with requirements it needs to fulfil, the importance of different capabilities of technology can be distinguished by the importance of different requirements. This understanding will be further elaborated in Chapter 4 where the development of Technology Assessment Framework is stated and discussed.

### 2.1.4 Contribution of Technology

The contribution of technology is one of the ‘3C’ (Complexity, Capability and Contribution) aspects of technology that are included in the proposed Hexahedron Model of Technology later in Section 4.1. The reason this aspect of technology is worth defined and identified is that it highlights the overall reward of technology assimilation from a holistic viewpoint.

The word ‘contribution’ is defined as ‘*The part played by a person or thing in bringing about a result or helping something to advance*’ according to Oxford Dictionaries (61). Based on this definition, the contribution of technology can be understood as the ‘part’ played by a technology in bringing about a result. This understanding is supported by a similar statement in the research of IT technology contribution where the contribution of IT technology is associated with the achievement of the business objectives (62).

As later discussed in Section 2.3.2, the basic scenario of the technology assimilation that this research is focused on is the requirement-driven one. Therefore, in the scope of this research, the ultimate objective of technology assimilation is to fulfil the requirements of technology assimilation. Based on this ultimate objective and the understanding of contribution, the contribution of technology is defined as follows: ‘The contribution of technology in the scope of requirement-driven technology assimilation is the degree of which a technology in bringing about the result in terms of fulfilling the overall requirements of the technology assimilation’.

The contribution and the capability of technology are related to each other. The capability of technology, as discussed in previous section, is defined based on the fulfilment of individual requirement using a ‘white-box’ viewpoint whereas the contribution of technology is defined based on the fulfilment of overall requirements using a ‘black-box’ viewpoint.

The contribution of technology is an aspect of a technology that can be directly associated with the ‘reward’ of technology assimilation. The details of how this aspect is utilised and transformed into a criterion in the proposed holistic approach is later explained in Chapter 4.

## 2.2 Disambiguation of Technology Assimilation

The term technology assimilation in this thesis may give rise to some ambiguities, for there are similar terms such as technology adoption, technology diffusion and technology integration. This section serves to study the differences of these terms so that disambiguation can be achieved.

Arguably, technology integration is a more popular term in engineering than technology assimilation (5,24,25,47,63–66). Based on the experience of the author, practitioners and managers in the environment of automotive OEMs often misunderstand the difference between technology assimilation and technology integration. In this research, technology integration is defined as the process that brings together the target technology into one system or product resulting in the technology functioning together with the existing system as a whole (67–69). Technology integration is recognised as a process only from engineering viewpoint in this research.

Furthermore, technology adoption and technology assimilation are confusing concepts as well. However, according to the research of Wei, Lowry and Seedorf, technology adoption refers to the physical acquisition or purchase of a technology. This term does not refer to the deployment or similar action (70).

There is also the concept of technology diffusion that occasionally causes ambiguity to the understanding of technology assimilation. In this research, technology diffusion is recognized as the process by which a technology spreads across a population of organizations (70–74).

The term ‘assimilation’ is defined as follows in the Oxford dictionaries: ‘The process of taking in and fully understanding information or ideas’(75). This term better fits the expanded definition and understanding of technology that is explained in this thesis. The technology assimilation is, therefore, a process of taking in and fully understanding a technology and consequently fully utilising the said technology to better fulfil the requirements of the enterprise.

More specifically, in this research, technology assimilation is understood as series of stages from initialisation of a project, through assessment of both project and technology at pre-adoption to the formal technology adoption and finally to full full-scale test and deployment that excludes technology diffusion.

Figure 2.3 represents the scopes of these above-mentioned concepts.

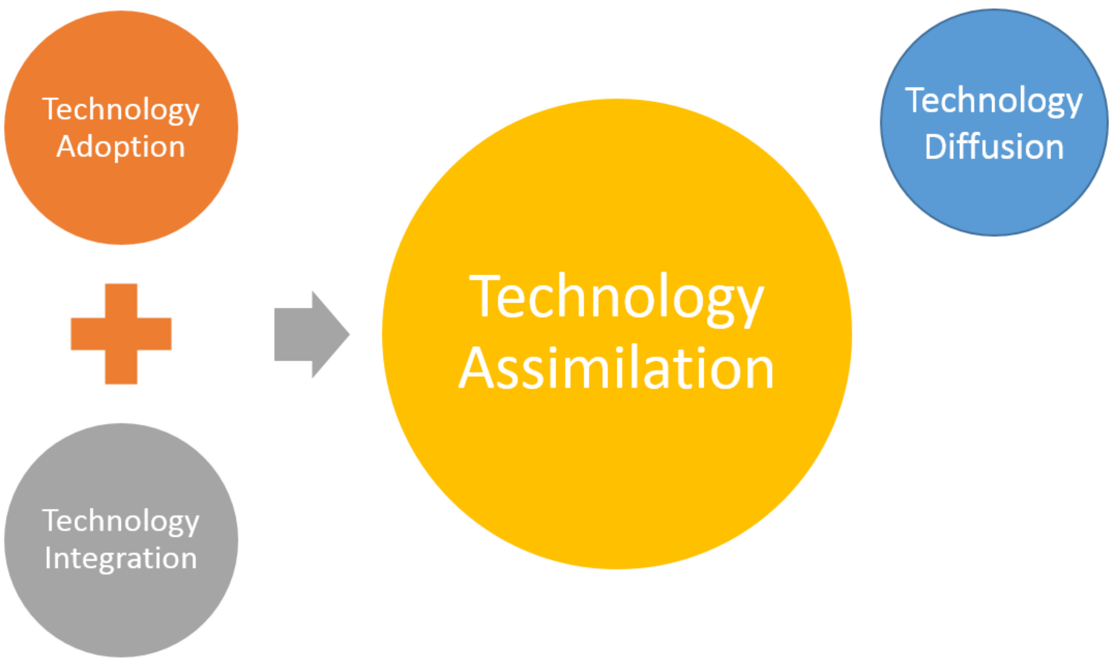


**Figure 2.3 Scopes of Technology Assimilation related Concepts**

From the Figure 2.3, it can be seen that the scope of technology assimilation does not include technology diffusion. According to literature, technology diffusion as a concept contains the concept of psychological acceptance of technology from individual perspectives (76,77) and therefore is excluded from this research. In terms of technology assimilation, this process can be broadly subcategorised into three logical steps. The first step is the evaluation or assessment of the maturity, the risk of absorption and the cost of the whole assimilation of the particular technology to support the executive decision-making process. The second step is to push the assimilation through the resource shortages stage, where many failures of technology assimilation happen which also known as the ‘Valley of Death’, by investing in resources (not only money investment but also human resource and time). The last step is to put the assimilated technology into production or application (47,78,79). The general steps of technology assimilation are further discussed in Section 2.5 of Chapter 2.

From these three steps of technology assimilation, there are two concerns that needed to be addressed which are (1). How to conduct accurate technology assessment that supports the executive decision on technology adoption and (2). How to improve the likelihood of success of selected technology passing through ‘Valley of Death’. This research believes that the likelihood of success of technology assimilation will be increase after these two concerns are addressed.

Therefore, the literature of technology assessment and ‘Valley of Death’ theory (including its effect) is also reviewed and discussed to reveal the gaps of current approaches in Section 2.6 and 2.7 respectively. However, in next section, the technology assimilation is studied from holistic viewpoint to understand the relationships between technology assimilation and its environment.

## 2.3 General Scenarios of Technology Assimilation

In a later section, a Vee model of technology assimilation is assumed to conclude the study of current technology assimilation process. However, in this section, the topic is broader, which is the general scenarios of technology assimilation. There are two scenarios of technology assimilation have been identified based on the experience of engaging with automotive OEMs in this research which are technology-driven technology assimilation and requirement-driven technology assimilation. These two scenarios are introduced and explained hereafter.

### 2.3.1 Technology-driven Technology Assimilation

The first scenario of technology assimilation is called technology-driven technology assimilation which is caused by the emerging of a technology that is either a result of a scientific breakthrough or a focus of the industry for any reason. For example, after Apple launched the first generation of iPhone and surprised the market, the touch screen became a differentiating technology of the smart phone industry. Other smart phone manufactures have assimilated this technology and launched their products with this technology ever since. These kinds of technologies are believed to have the potential to reshape the industry or restructure the market. Therefore, it is of great interest for any enterprise to assimilate this kind of technologies as fast as possible before other competitors in the market.

In this scenario, the need for assimilation of this particular technology is nearly absolute. However, the assimilation process is assumed to be built around this technology and the enterprise needs to adapt for the technology assimilation. Therefore, this research argues that this particular scenario is rarer compared to the one that will be explained in next section.

### 2.3.2 Requirement-driven Technology Assimilation

The second scenario of technology assimilation is named requirement-driven technology assimilation in this research which is normally started by certain set of requirements that cover from enterprise strategy level requirements to detail engineering level requirements. When such requirements are settled and defined, enterprise, especially for a technology driven enterprise and industry such as automotive OEMs, may consider assimilating certain technologies as a means to fulfil these requirements

In this scenario, there may be several candidate technologies that are under consideration for assimilation. Therefore, an enterprise can rely on the results of technology assessments to decide which technology is the best choice in terms of fulfilling that certain set of requirements. Moreover, the technology that is selected for assimilation may be modified or refined after so that a better fit can be achieved.

The technology assimilation process in the first scenario, as explained, is normally built around a certain technology and is rarer. In order to develop a general approach to ameliorate the difficulties in technology assimilation, in the scope of this research, the current focus is the second scenario explained above that is believed to represent the majority of technology assimilation cases.

## 2.4 The Relative Nature of Quality of Technology

In this research, one of the fundamental ideas is that there is no absolute ‘good’ technology for every enterprise to assimilate due to different situations of enterprise (80–82). A wide range of technologies should be assessed before one is selected for assimilation into an enterprise and a product in the scope of requirement-driven technology assimilation.

A technology that has been successfully assimilated into an enterprise is not necessarily a good choice for a different enterprise. The reason behind this is obvious that every enterprise and every project are different in some ways that result in different requirements of technology assimilation and different standards and criteria of technology assessment. Also, different enterprises have different business strategies, different leaderships and different levels of resources that can be allocated onto technology assimilation projects (22,80,83–86). Therefore, the assessment of technologies where the suitability of technologies to enterprises or projects is analysed and assessed is critical to the success of technology assimilation.

This idea can also be interrelated in a different way that there should be no absolutely ‘best’ technology to assimilate but only a ‘better’ technology to assimilate. The quality of a technology is a relative term that only meaningful when comparing with other technologies. Therefore, this idea leads to the understanding that the technology assessment approach should support comparative assessments and analyses. Several technologies that have potential to fulfil a set of requirements or a project should be assessed in the same contexts and criteria to decide which one is the better choice. This research believes that simply assessing one single technology and considering that technology the best choice is not an effective way of conducting technology assessment.

Moreover, the suitability of a technology also depends on the nature of enterprise and project. The assessment of technology should be conducted based on clear understanding of the environment of technology after assimilation. Therefore, the technology assessment should include the concerns of Social (organisational) and Human (user) aspects of technology that may, for example, influence the working practice of employees, the product positioning and customer perceptions of product (22,70,80,83–89).

## 2.5 Technology Assimilation and Environment

In this section of the literature review, the environment where technology assimilation takes place is reviewed based on publications in different fields of researches which include but not limited to Business, Requirements Engineering and Systems Engineering.

In the first part of this section, the necessities of the terms 'enterprise requirement' and 'technology feature' in this research are explained. In the Second part of this section, a Vee model of technology assimilation that follows systems engineering principles especially the standard Vee model of Systems Engineering are assumed based on literature and real-world engagement. This serves to provide a holistic view of technology assimilation.

### 2.5.1 Enterprise Requirement and Technology Feature

#### *2.5.1.1 Enterprise Requirement*

One of the differences that this research presents compare to other works in engineering domain is that the usual limitations on requirements are lifted completely. The term 'enterprise requirement' in this research includes but not limited to engineering requirements, functional requirements and business requirements. Instead, all kinds of requirements can be included under the category of enterprise requirements. The rationale behind this is that in order to facilitate a holistic and comprehensive assessment of technology during the technology assimilation, multiple viewpoints must be involved during the enterprise and project analysis and consequently, different types of requirements will be brought in to consideration. Such requirements are then grouped together to reduce the level of complicatedness. However, this requires an extra method to process and analyse all the enterprise requirements that originally on different levels or from different domains. As discussed later, this research partially adopts AHP to make this practical and sensible.

#### *2.5.1.2 Technology Feature*

In this research, the features of a technology are focused instead of the detail specifications. As the key beneficiaries of this proposed approach of the technology assimilation are the decision-makers, the detailed specifications of a technology can be complicated and preventing a holistic view of the technology. The technology features, however, when defined properly, can reflect the essences of a technology and help to maintain a high-level analysis of technology during assessment. The three technological viewpoints (NTV, STV and HTV) defined in Section 2.1.1 are guidelines to defined technology features belonged to Natural, Social and Human aspect of a technology. Examples of these practices can be found in Chapter 6 where two sets of case studies that showcase how to populate TAF are presented. The technology features, in the scope of this research, are directly associated with the enterprise requirement. A technology feature can help to fulfil an enterprise requirement while another technology feature jeopardise one. Such associations are the key to relational transformation adopted from Relational Oriented Systems Engineering (ROSE) which is explained in later chapters. Moreover, interrelationships can be identified and defined among different technology features. Such interrelationships are translated into the criterion of complexity of technology in TAF and later enabling TRMA. Overall, the probability of the proposed holistic approach for ameliorating the effect of ‘Valley of Death’ is enabled by focusing on technology features.

### 2.5.2 Vee model of Technology Assimilation

After reviewing the literature, the complexity of technology assimilation can be divided into two categories in general. The first one is brought by the knowledge growth that leads to more complex technologies and hence more complex research and development (R&D) processes (86,90,91). The second category of complexity of technology assimilation has emerged with the increasingly complex enterprise structures and product lines (81,92–94). Technology assimilation is no longer isolated from other business concerns such as marketing, instead, multiple influence factors from other department have been identified (95). Moreover, the boundaries for companies R&D activities have been broadened because of the increased global competition, rapid technological change, and the need for sharing heavy technology investments (82,85,96–99). Hence, as an important part of R&D, the technology assimilation process involves interactions with other entities in the business environment such as competitors, distributors, customers, suppliers.

More specifically, as explained previously, the focus of this research is automotive OEMs due to the nature of this industry. This industry produces complex products that need to be responsive to the market as well as to multiple stakeholders. Therefore, for successful technology assimilation in this industry, multiple viewpoints and judgments need to be considered (31–35). Moreover, in automotive OEMs, technologies are also assimilated across multiple platforms and programme to offer new services and provide new capabilities on vehicles or to offer business advantages such as increasing profit (100–103).

A general process of technology assimilation in automotive OEMs is assumed in this research that serves to identify the steps of technology assimilation. This general process is shown in Figure 2.4. This is the result of learning from the standard Vee model of systems engineering and different fields of researches to identify the boundary and environment of technology assimilation from a holistic viewpoint (104–107).

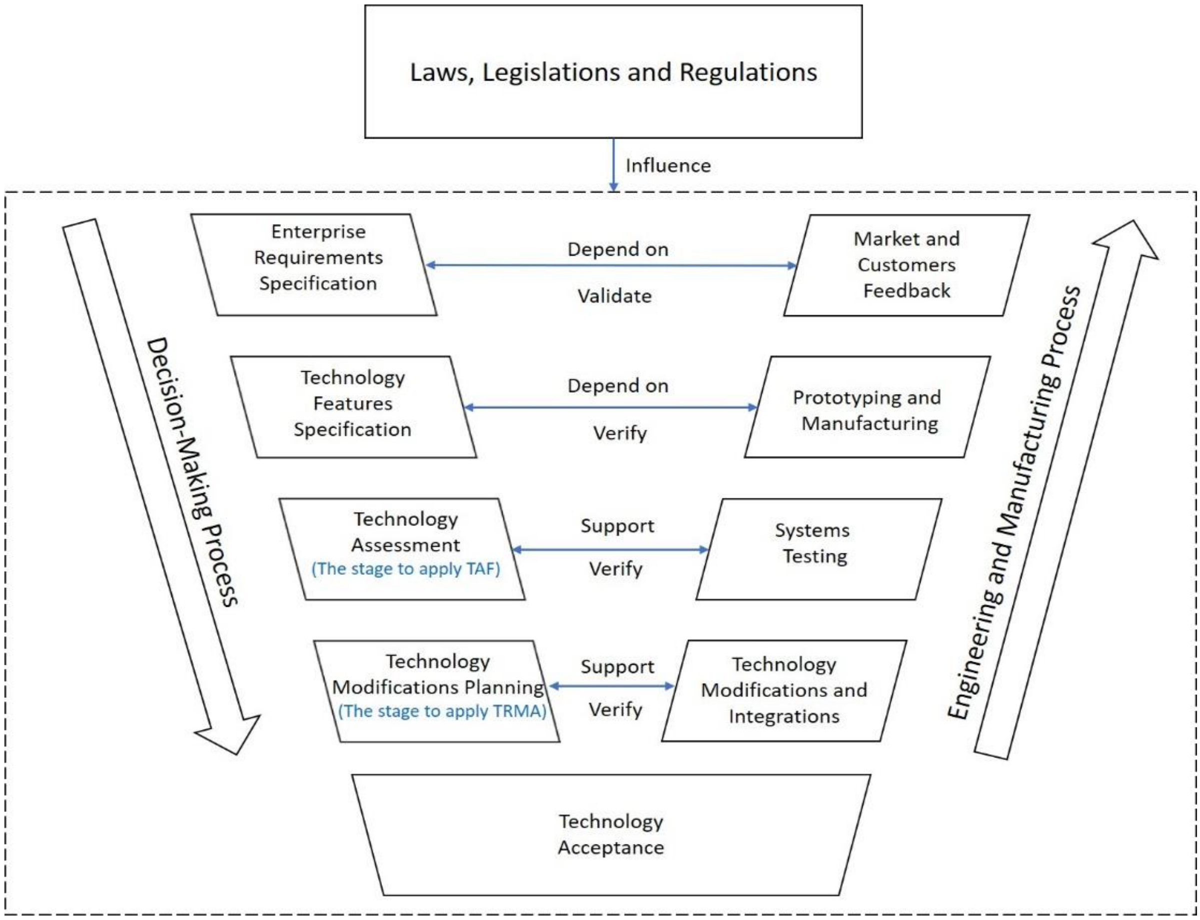


**Figure 2.4 Vee model of Technology Assimilation**

The left arm of the Vee model is the decision-making process and the right arm of the Vee model is the technology assimilation process. The first stage of the decision-making process is setting the enterprise requirement specification, which will determine standards and any performance criteria. The enterprise requirements are therefore impacted by issues related to cost, innovation pressure, customer demand and market forces, as well as regulation and legislation. The second stage is the technology feature specification which depends on analysis of the prototypes or the products that are equipped with the technology. Before making a decision to proceed with a particular technology and moving on to technology assimilation, the technology needs to be rigorously assessed and then technology modification needs to be planned. These two stages, where TAF and TRMA are applied, are associated with system test and technology modification and integration respectively. The bottom stage shown in the Vee model is termed technology acceptance where a decision is made to proceed and the technology is accepted.

Based on this Vee model, the process of technology assessment should be conducted based on an enterprise requirement specification and technology feature specification with the support of system testing results, these activities then support the decision-making process as well as technology assimilation planning.

In summary, technology assessment is a complex process that requires multiple viewpoints to deal with multiple factors that each of these viewpoints can impact upon technology assimilation.  Traditional methods of technology assessment do not take into account the different aspects of a complex environment, where there are multiple constraints and requirements that influence assimilating technology effectively and explicitly into a platform or programme.

## 2.6 Technology Assessment and Decision Making

At this point, one of the purposes of this literature review is to examine the current technology assessment methods and standards in order to identify insufficiencies and inefficiencies. This research seeks to fill the gaps and develop a framework that extends the existing technology assimilation methods to include consideration of the other technologies associated with Social and Human Science so that the framework contains a holistic view of technology assimilation.

As mentioned previously, over the last four decades, technology assessment, which is an essential precursor to technology assimilation, has become a focus for research in many industries (26–30,108,109). Tools and methods to support technology assessments have been developed such as the most popular technology readiness levels (TRLs) categorization (24,25,63,65,66,110) and those derived from TRLs. Although TRLs and other tools derived from TRLs such as integration readiness levels (IRLs) (25,65,66) and manufacturing readiness levels (MRLs) (65,111) are popular and helpful in practice, the literature has argued that these approaches are not sufficient in a complex business environment (112). This is because such single factor technology assessment tools do not tackle the challenge of providing various stakeholders with multiple viewpoints and holistic viewpoint of analysis (113).

In the scope of traditional engineering, the assessment of technology is either too reliant on numerical, quantitative data, which is compiled through costly physical testing and prototyping (114); or is over-reliant on the experiences and expertise of practitioners and experts, which are difficult to codify and test (26,89,114). However, recent research on technology assessment acknowledges the importance of objective analysis and subjective analysis (26,100), and so the development of methods that can accommodate and combine both, is one of the challenges in the research area of technology assessment (28,29,109). This research believes that the ideal technology assessment methods should be to able reduce the reliance on physical testing and prototyping, and also provide methods that structure the subjective aspects of human judgment (27,30,115).

As mentioned previously, one of the focuses of this literature review is on reviewing the literature about the assessment of laboratory-level technologies that contains the technologies from invention and innovation. Therefore, the literature review of technology assessment begins with technology readiness levels (TRLs) that are a well-used method to evaluate the maturity of laboratory-level technologies, which was initiated by NASA to serve as an important role in technology readiness assessment (TRA).

### 2.6.1 Technology Readiness Levels

Use of Technology Readiness Levels (TRLs) is arguably the most popular way for assessing technology in terms of the readiness of technology assimilation in the industry (25,63,65,112,116–121). This research has no intention to criticize this method, which has been proven useful and effective over years of applications. However, this part of the literature review is conducted with intent to find the limitations of this method and explain why it is insufficient to a certain degree. TRLs are defined as *'a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology'* (122).

TRLs, which was proposed by NASA for conducting Technology Readiness Assessment (TRA), is a practice that has gained general acceptance across industry and research domains . TRLs serve as a helpful knowledge-based standard and shorthand for assessing technology maturity with the support of human judgements (112).

The TRL methodology was initiated by Stan Sadin at NASA Headquarters in 1974 (110). The Original NASA TRL definitions were published in 1989. The original TRLs had 7 levels, which were (123):

*'Level 1 – Basic Principles Observed and Reported.*

*Level 2 – Potential Application Validated.*

*Level 3 – Proof-of-Concept Demonstrated, Analytically and/or Experimentally.*

*Level 4 – Component and/or Breadboard Laboratory Validated.*

*Level 5 – Component and/or Breadboard Validated in Simulated or Real space Environment.*

*Level 6 – System Adequacy Validated in Simulated Environment.*

*Level 7 – System Adequacy Validated in Space.'*

The origin of the TRLs concept is rooted within the scope of the NASA space programme, and this first metric-based technology assessment method has proven useful to NASA through these applications. However, this purpose-specific version of TRLs is not adequate for other use. Therefore, this version has been developed by NASA as well as other organisations into more detailed content while its application scope has been broadened. For example, the TRLs, which are used by U.S. Department of Defence, are similar but have differences with the NASA TRLs (110,118). Over the years, different versions of TRLs have developed into a more general version and also expanded into nine levels instead of seven levels. Moreover, the cross-domain applications of TRLs have been demonstrated over the years. The most visibly evidence of this is the adoption of TRLs by EU and its implementation in the most recent EU framework, H2020, where TRLs is proposed to apply to from nanotechnology to informatics and communication technology(124). One of the description of current TRLs are shown in Figure 2.5 (112,122,125) with a reference to an adapted version of TRLs from European Association of Research Technology Organisations (EARTO) (124,126) In the Figure 2.5, the NASA TRLs are illustrated in blue on the right hand side whereas the adapted version of TRLs from EARTO is highlighted in red on the left hand side.

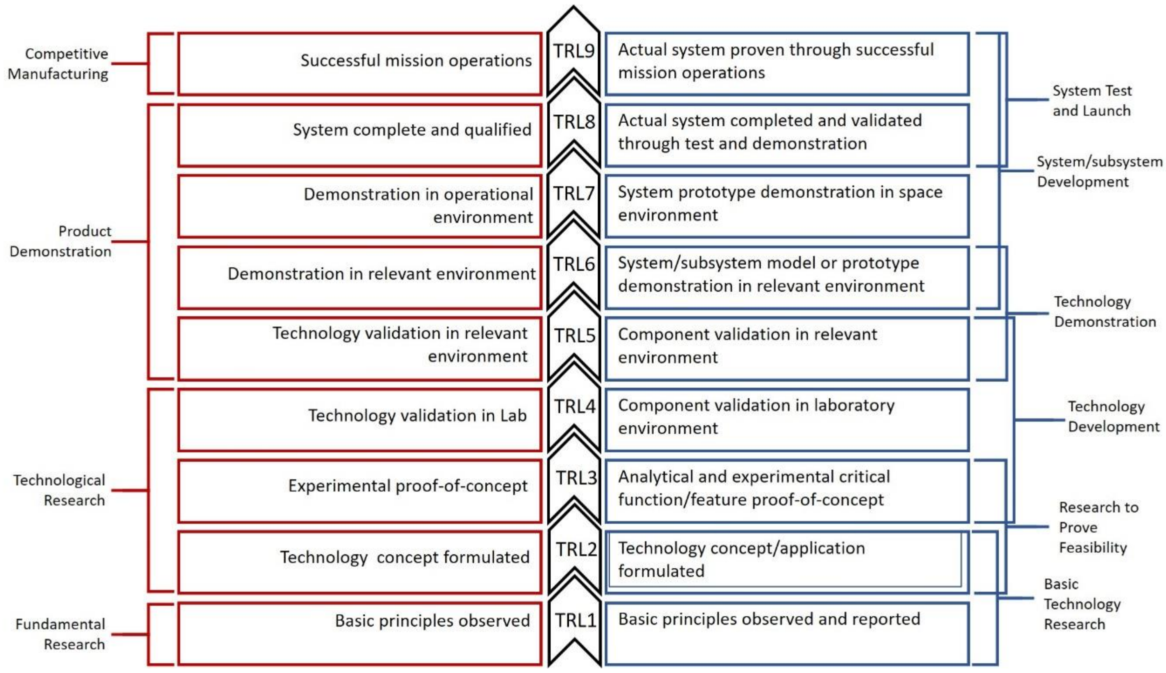


**Figure 2.5 Illustrations of TRLs** (112,122,124–126)

Since TRLs are popular in many countries and organisations, the interpretations of TRLs vary in many ways and change through time. A good example of this is shown in Figure 2.5 In order to understand the actual meaning of each level of TRLs, this literature review combines and interprets the explanations over 15 years of TRLs research (110,122). The following contents are the interpretations of such work combined.

TRL 1 is the lowest level of maturity of any given technology. The scientific research starts to be translated into applied research and development and named ‘basic principles observed and reported’. The cost and resource needed to achieve this level of maturity is ‘very low and unique’ in a relative term, and is typically borne by scientific research programs (110,122).

TRL 2 is the level that practical applications of basic physical principles’ characteristics can be identified once basic physical principles are observed after

TRL 1. At TRL 2, the technology is still speculative due to lack of experimental proof and detailed analysis to support the conjecture. The TRL 2 is named as ‘technology concept and/or application formulated’. The cost to achieve this level of maturation is also ‘very low and unique’ in a relative term. Hence, the investment cost is still borne by scientific research programs (110,122).

According to literature, TRL 1 and 2 are mainly assigned to technology that the elements of the scientific research such as basic principles or technology concept are developing but are not addressed in much detail in the process. The typical cases of these two levels are analytical or theoretical predictions with little supporting test data. Hence there is a major risk to assimilate technology at this stage due to the feasibility of system application being unknown (127,128).

TRL 3 is the step in which active research and development (R&D) is initiated. Both analytical studies that aim to set the technology into an appropriate context and laboratory-based studies that aim to physically validate the analytical predictions in previous levels must be included in this level. After the formulation of technology applications/concepts at TRL 2, the validation that serves to achieve ‘proof-of-concept’ should be constituted from the studies and the experiments. TRL 3 is called ‘*analytical and experimental critical function and/or characteristic proof-of-concept’*. The cost to push a technology to this level of maturity is ‘low and unique’ in a relative term, and is dependent of the specific technology (110,122).

Generally speaking, a technology can be assigned as TRL 3 when the concept is considered to be proven and evidence based on analytical and experimental process to identify critical functions and/or characteristics is presented (127,128). For a physical technology or hardware-like technology, the testing of breadboard or generic hardware should have been accomplished before assigning TRL3 to this technology. At this level, the features and functionalities of the technology should be defined. In the scope of TRLs, a technology that reaches TRL 3 has the value to be further developed and even transited for system application (127,128). However, there are still major risks to assimilate technology at this level of maturity since the results of deployment of the technology are not proven.

TRL 4 follows the successful 'proof-of-concept' work when the basic technological elements must be integrated to prove that the elements will work together to achieve concept-enabling levels of performance at the component and/or breadboard level. The concepts formulated earlier in previous levels must be supported from this validation and also the requirements of potential system applications. This validation can be 'low-fidelity'. TRL 4 is called *'component and/or breadboard validation in laboratory environment'* and the cost to achieve this level is 'low-to-moderate and unique' in a relative term. The cost is also technology specific, but probably requires more investment into factors that are beyond the technology development. (110,122)

This level applies the moment when the component validation of hardware of new technology is conducted in the relevant test environment. Based on the test data, the initial analytical models can be defined. Moreover, TLR 4 is normally the level where people predict the cost of the whole development programme or assimilation of the technology. The legacies of this level are models for design and performance predictions. The test data may prove that this technology is able to transit to system application even though the integration issues are not well defined (127,128).

TRL 5 is called '*component and/or breadboard validation in relevant environment'*. The fidelity of the validation of component and/or breadboard has to increase significantly from TRL 4. The validation of the integration of the elements must be associated with reasonably realistic supporting elements so that the total applications can be tested in a simulation or somewhat realistic environment. The cost of this level is 'moderate unique' in a relative term which means that the investment cost will be technology dependent, but likely to be affected by several factors resulting a greater cost than that of TRL 4 (110,122).

TRL 5 is an upgrade of TRL 4 for the requirement of 'component validation of hardware of new technology is conducted in the relevant test environment' since this level requires that 'the testing must be of hardware of appropriate scale and functionally equivalent to flight articles'. At this level, the models should be analytical models of the technology integrated into the systems including the test correlations. The integration issue is defined so that the potential for transition into system application can be judged as good (127,128).

TRL 6 is called 'system/sub-system model or prototype demonstration in a relevant environment (ground or space)'. TRL 6 is a major step towards achieving the fidelity of the technology demonstration. A representation model or prototype system (going well beyond ad hoc) would be tested in a relevant environment (cannot be replaced by different environment). At this level, several-to-many new technologies might be integrated into the demonstration (prototype). The cost is technology and demonstration specific. It will be a fraction of TRL 7 if tested on ground but nearly the same if testing in space is required (110,122).

TRL 7 is called '*system prototype demonstration in a space environment'*. Its requirement for an actual system prototype demonstration in a space environment makes TRL7 a significant step beyond TRL6. The prototype entering TRL7 should be near or at the scale of the planned operational system, and the demonstration must take place in space or in the designated environment. Normally, after reaching this level, a technology provides confidence to both systems engineering and development management. However, TRL7 is an optional level which means not all technologies in all systems will have to reach this level. The tests and demonstrations needed for assigning this level to a technology are only necessary if this technology and/or subsystem application is mission critical and has relatively high risk. The cost of TRL7 is technology- and demonstration-specific, but a significant fraction of the cost of TRL8 (110,122).

TRL 8 is called 'Actual system completed and 'flight qualified' through test and demonstration (ground or space)'.. All technologies that will be applied or deployed in actual systems in the future need to go through TRL8. Basically, the TRL8 is the end of true 'system development' for almost technology elements. The unique cost of TRL8 is mission specific and typically the highest (110,122)。

TRL 9 is called 'Actual system 'flight proven' through successful mission operations'. As with TRL 8, all technologies that are aimed to apply and deploy to actual systems in the future need to go through this level. It is the end of the last fix-bug aspects of the true system development. The integration of new technologies into an existing system might be included in this level. The planned product improvement of on-going or reusable systems is not included in this level (110,122).

#### *2.6.1.1 Critical review of TRLs*

TRLs is a very helpful knowledge-based standard and shorthand for assessing technology maturity that has been applied not only in many military/aerospace project but also in other industry sectors (24,25,63,66,112,116,119–121,125,128–130). However, it has some major drawbacks when used in civilian enterprises, which have been found through the literature review of TRLs.

The most obvious drawback is that TRLs require expert opinions and advice without providing a structured method to collect such subjective data (112). This makes TRLs unable to minimise the influence of human judgement for decision-making. Normally it takes a longer time and more resources to proceed with human involvement than to proceed without human involvement. The longer time and larger resource required makes the project and product slower to meet development requirements and therefore reduce the success rate of technology assimilation. Without an objective framework to guide processes involving human judgement, the application of this approach makes the technology assessment results contentious and subjective.

As TRLs were first developed by NASA, which is an aerospace enterprise, then widely accepted within DOD which is a military-related enterprise (110,122,131), the focus of TRLs development was to serve as a knowledge-based standard and shorthand for evaluating technology maturity in military/aerospace programme (123). Through the literature review, however, one of the finding is that the terminologies in TRLs have been reinterpreted to broaden the usage and definitions.

The current TRLs have specifically defined the maturity of a technology into levels and identified the associated costs and risks. The level specification allows a critical assessment as to whether a technology is ready for employment and to what extent in terms of the risk. However, when TRLs are applied in civilian enterprises, especially technology-oriented enterprises, such as automotive OEMs, rather than government funding organisations or defence organisations, the current TRLs do not include the concerns of market and support other viewpoints from stakeholders other than cost (130). For example, based on the one of the most common enterprise perspectives in automotive industry, technology is the fundamental element to achieve better business and gain competitive advantage. However, the maturity assessments provided by TRLs do not necessarily support the prediction of the business prospects of technology after assimilation or deployment (112). Moreover, TRLs do not include the assessment of the influence of a technology on the enterprise structure and production layouts.

As mentioned, TRLs assessments do provide the general cost predictions of technology development and deployment with regard to different levels. As reviewed in the previous section, the general cost predictions of each level of technology maturity are different. Therefore, combining with the predicted costs and the respective maturities of technology represented by different levels, a rough prediction of risk of technology can be concluded based on the readiness level assigned. However, this research argues that this is not enough to support the decision-making in automotive OEMs.

Another insufficiency of TRLs is that no comparative analysis in terms of which technology is relative better can be supported by applying this approach. A technology that reaches TRL 7 is not necessarily better than a technology at TRL 4 in terms of the concerns such as suitability and profitability. Therefore, TRLs do not support pre-selection phase in technology assimilation when multiple candidate technologies exist. This research believes the core insufficiency of TRLs are one cannot solely use TRLs to compare any set of given technologies in terms of their capabilities, complexities of assimilation and contributions that can be made to the mission/project/product.

After reviewing the literature, one of the major problems of TRLs in practice is that the prototypes of certain technologies and their test environments are required so that a higher level of maturity can be assigned to such technologies that provides the confidence for enterprise to proceed with the assimilation or deployment process. However, not all technologies are able to be prototyped and not all the essential test environments are able to be built for all kinds of enterprises. Also, the time and resource needed to support TRLs assessment can be considerable, which prolongs the overall timeframe of technology assimilation and potentially causes resource waste on technologies that may not eventually be assimilated. This contradicts with the ever-growing concept of rapid development in the current manufacturing environment. This research believes that this is one of the reasons why TRLs, when applied alone, are sometimes insufficient in the environment of automotive OEMs where a balance among cost, time to market and performance is being constantly pursued.

#### *2.6.1.2 Summary of Technology Readiness Levels*

Despite the fact that TRLs are popular in space and defence industry with numerous successful application cases of technology maturity assessment, some major insufficiencies of TRLs are concluded in literature which are list here after.

1. TRLs do not provide a complete representation of the difficulty of integration or assimilation of the subject technology or sub systems into an operational system.

2. TRLs include no guidance into the uncertainties and complexities that may be expected in moving through the maturation of TRLs, and

3. TRLs do not support comparative analysis between different technologies.

Based on these fundamental conjectures, this researcher concludes that TRLs are useful for technology assessment but not comprehensively. Therefore, the technology readiness level assigned to a technology should be acknowledged as a feature or aspect of technology rather than only thing that matters for technology assessment.

### 2.6.2 Research and Development Degree of Difficulty

In order to complement the existing Technology Readiness Levels (TRLs) metric, Research & development degree of difficulty, as a measure of the difficulties which are expected to be encountered in the process of maturity of a particular technology, is introduced (120,132).

As reviewed previously, TRLs are systematic metric/measurement systems that support assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology. The "Research and Development Degree of Difficulty" (R&D$^3$ or DD) is proposed as an additional measure of TRLs(120).

This measurement provides different values that link to the probabilities of failure of the process of maturity of a technology that are bounded by zero and one. Bigger value and higher level refer to more difficult and higher risk of the process of maturity, and vice versa. For example, when the difficulty value is one, there is a 100% anticipated failure to the process of maturity of a technology. DD can also be interpreted as the possibility of technology failure. The detail levels of R&D$^3$ is shown in Figure 2.6

| Degree of Difficulty | Risk Level | Difficulty Value |
|---|---|---|
| Level 0 | No Risk and Guaranteed Success | 0.0 |
| Level 1 | Very Low Risk | 0.1 |
| Level 2 | Moderate | 0.3 |
| Level 3 | High | 0.5 |
| Level 4 | Very High | 0.7 |
| Level 5 | Extremely High | 0.9 |
| Level 6 | Guaranteed Failure | 1.0 |

**Figure 2.6 R&D$^3$**(120)

The R&D$^3$ scale is an approach that meets the management need of developing a clear understanding of the remaining “development hurdles” and the projected uncertainty in the likelihood of development success for novel technologies.

After review the literature related to this measurement, the interpretations of different level of R&D$^3$ are explain hereafter (120,132). However, only level 1 to 5 shown in Figure 2.6 are explained since level 0 means no risk and level 6 means guaranteed failure.

R&D$^3$ level 1: The degree of difficulty in achieving the research and development objectives for particular technology is anticipated to be very low. Such objectives include system concept, performance, reliability and cost goals. ‘Only a single, short-duration technological approach’ is needed to be assured of a high probability of success in achieving technical objectives in later systems applications.

Example: Design a new engine at a thrust of 45000 lbf when there is an existing engine exists at a thrust of 38000 lbf for the same propellant and with similar other performance/cost goals.

R&D$^3$ level 2: The degree of difficulty in achieving the research and development objectives for particular technology is anticipated to be moderate. A single technological approach is sufficient in normal situation but it is better to prepare an alternate approach at the early stage of this research and development in order to make sure of a high probability of success in achieving the technical objectives in later systems applications.

Example: Design a new engine which has some degree of emission control, where an existing engine is able to expend same level of propellant to reach similar other performance goals.

R&D$^3$ level 3: The degree of difficulty in achieving the research and development objectives for particular technology is anticipated to be high. Two technological approaches and an alternative approach as well are needed. These technological approaches should be conducted at the early stage of the research and development to ensure a high probability of success in achieving technical objectives in later systems applications.

Example: Design a new engine which has high degree of emission control, where an existing engine consume different propellant but still with similar other performance goals.

R&D$^3$ level 4: The degree of difficulty in achieving the research and development objectives for particular technology is anticipated to be very high. It is necessary to pursue multiple technological approaches and it should be done at an early stage of the research and development cycle so that an alternate system concept can be pursued if necessary in order to increase the probability of success in achieving technical objectives on later systems application.

Example: Design a new engine which has very high degree of emission control, where an existing engine consumes different propellant without similar other performance goals, and after-treatment is not acceptable on the new design of engine.

R&D$^3$ level 5: The degree of difficulty in achieving the research and development objectives for the particular technology is anticipated to be so high that a fundamental breakthrough in basic concepts and theory in physics or chemistry or some other domains is needed, and basic research in key domains is necessary to move onto feasible system concepts.

R&D$^3$ gives an addition measurement to the assessment of certain technology in development alongside TRLs. However, this research argues that R&D$^3$, just like TRLs, does not provide structured method to collect that human judgement which makes the measurement less reliable and accuracy.

Nonetheless, together with TRLs, R&D$^3$ provides users a better understanding of the technology before assimilation. Also, the existence of R&D$^3$ facilitates that by developing complementary measurements rooted in TRLs, technology assessment by applying TRLs can be more objective.

### 2.6.3 System Readiness Levels and Integration Readiness Levels

In this section, two readiness levels related to technology are reviewed which are System Readiness Levels (SRLs) and Integration Readiness Levels (IRLs). Similar to R&D[3], this research believes that they are also developed based on the concept of TRLs and hence as complementary measurements to technology assessment by using TRLs.

#### *2.6.3.1 Integration Readiness Levels*

The need for development of IRLs comes from the need of supplement TRLs when a new technology is introduced into a system or program that the configuration item does not leverage (130). Over the years of applications of TRLs, the cost and schedule risk related to configuration and subsequently integration of new technology are often underestimated at the start of the technology assimilation (133). Therefore, IRLs are developed as a metric to support the assessment of cost and schedule risk of technology integration based on integration characteristics of technology.

The original IRLs are shown in figure 2.7

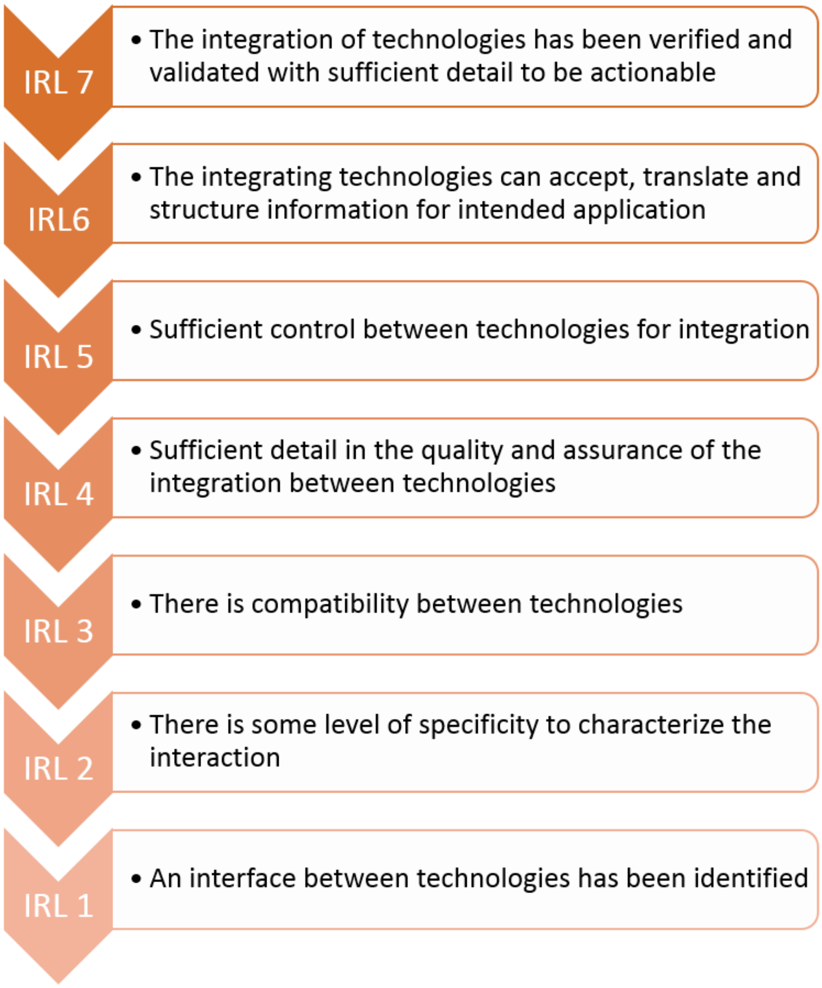


**Figure 2.7 IRLs**(130)

The IRLs is developed as a systematic measurement of the interfacing of compatible interactions for various technologies and the consistent comparison of the maturity between integration points (TRLs). IRLs also can be used to assess the risk of integration. The need for an integration measurement increases as a system's complexity increases. The world is in need of a reliable method and ontology for integration that allows TRLs to collectively combine for developing these complex systems.

Even though IRLs provide a means to translate integration characteristics of technology into risk level for technology integration, the human judgements based on the experience of experts are still required to arrive at meaningful conclusion to support the assessment of cost and schedule estimates for the integration efforts (119,130,133,134).

However, the ILRs' limitations are similar to those of the TRLs in that the technologies it can measure are from the Natural Technological Viewpoint rather than the holistic view which means that it is not clear how to measure technologies such as management technologies or new working practices (133,134). Therefore, IRLs application also rely heavily on subjective input to facilitate the decision-making process. However, similar to TRLs, no structured method for collecting such subjectivities are provided by IRLs (133,134). This is argued as a major insufficiency of all TRLs related or derived methods in this research.

#### *2.6.3.2 System Readiness Levels*

The system readiness levels (SRLs) is one of the methods to supplement TRLs that become popular in recent years. SRLs metric is developed as a scalar function of the constituent TRLs and the IRLs (134,135). SRLs have been gaining popularity among experts as they believe SRLs provide valid and useful insights into the complex system that new technology is assimilated into (134).

The original proposed SRLs are shown in figure 2.8


**Figure 2.8 SRLs** (65)

Based on literature, some of the limitations and insufficiencies have been identified. First, similar to TRLs and IRLs, SRLs do not provide the verification of the assigned levels in terms of whether they are meaningful or correct as they are also heavily rely on human judgements (134,135). Second, there is little literature that rigorously validates the actual improvement of risk management and assessment that consequently support the decision-making process later in the technology assimilation process (134,135). Third, some of the literature argues that the results provided by SRLs are misleading due to the invalid arithmetic operations on ordinal data from TRLs and IRLs (134). Overall, this research believes that such readiness levels on technology and integration are useful whereas readiness of systems, especially complex systems, as a multidimensional concept, is too complex to be characterised in to levels that assigned with values (134,136). Last but not the least, other viewpoints involved in technology assessment are not included in SRLs consideration for monitoring and proactively managing the later process of technology assimilation (134).

Overall, this research believes that TRLs, IRLs and SRLs, as technology assessment methods, suffer from lackingrationality and traceability of results as they heavily rely on tacit knowledge of experts.

### 2.6.4 Multi-Criteria Decision Analysis

MCDA is a sub-discipline of operations research that explicitly evaluates multiple criteria in decision making (113,137). MCDA is mostly used for explicitly structuring complex problems, with the intention that consideration of multiple criteria will lead to more informed and better decisions (113,115). Over the years, many MCDA methods have been developed (108,113,138–140), driven by demand for different approaches to weighting the criteria (113). In the context of complex products, multiple criteria can often be in conflict with each other. For example, the cost of a product is usually one of the main criteria taken into account, with some aspect of quality normally being another critical measure. From a theoretical perspective, these two criteria could be considered to conflict with each other quite often. When managing technology assessment in a complex product environment, decision making needs to make judgments to deal with enterprise requirements that may conflict with each other due to increasingly complex social, economic, technological, and environmental factors that are present. To help manage this process, this research adopts the philosophy and methodology of MCDA in this research.

In automotive OEMs, as mentioned previously, there are multiple viewpoints involved in the technology assessment as well as technology assimilation. These viewpoints bring different requirements of technology assimilation as well as different criteria of technology assessment. To tackle this challenge, our method provides decision-makers with results based on multiple criteria to enhance the comprehension of the risks, challenges and benefits of technology assessment. Moreover, in this research, the Analytic Hierarchy Process (AHP, see below), as a methodology that belongs to the domain of MCDA, is adopted specifically for processing the above mentioned different requirements.

### 2.6.5 Analytic Hierarchy Process

The AHP is a multi-criteria decision making method (141,142). Over 30 years, due to wide application and ease of use, AHP has been studied extensively (143). The essence of AHP is the use of pair-wise comparisons. This is different to the methods previously used by psychologists that directly allocated weights to criteria. AHP has been widely applied in many disciplines such as manufacturing systems and operation evaluation since introduction (143). AHP shines when helping decision makers to solve complex problems with multiple subjective criteria that may conflict with each other (30,113,143). There are several key concepts of AHP which are explained hereafter.

#### *2.6.5.1 Problem Modelling*

Arguably, the first step of all decision-making processes is to structure the problem. In AHP, a hierarchical structure of the criteria is made to provide better focus on specific criteria and sub-criteria for allocation of the weights. Different structuring of the problem will lead to different weights allocation and different final rankings (141,143).

#### *2.6.5.2 Judgment Scales*

The fact that AHP allows for evaluation of quantitative and qualitative criteria, as well as modelling various alternatives on the same preference scale is one of the strengths of AHP. The use of verbal responses is intuitively appealing for decision makers. However, the verbal comparisons have to be converted into numerical comparisons to derive priorities. In the first instance, verbal statements are converted into integers from one to nine as shown in Table 2.2 (141).

**Table 2.2 Numerical Scale**

| Intensity of importance | Definition |
|---|---|
| **1** | Equal importance |
| 2 | Weak |
| **3** | Moderate importance |
| 4 | Moderate plus |
| **5** | Strong importance |
| 6 | Strong plus |
| **7** | Very strong or demonstrated importance |
| 8 | Very, very strong |
| **9** | Extreme importance |

Theoretically, the numbers and the verbal gradation are not restricted. Therefore, several other numerical scales have been proposed over the years of studies of AHP, the linear scale with the integers from one to nine set out here in Table 2,2 is the approach most often used (143).

#### *2.6.5.3 Pairwise Comparisons*

AHP uses ratio scales that require no units in the comparison which is contrary to methods using interval scales. The judgments made for pairwise comparisons are relative values or quotients such as a/b if two quantities a and b share the same units (143). Instead of providing a numerical judgment, a decision maker can only make relative verbal comparisons which is more familiar in daily life (141,143). The pairwise comparisons are recorded in a positive reciprocal matrix (143) shown in Equation 2.

Equation 2 Positive Reciprocal Matrix

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & \cdots & a_{ij} & \cdots \\ \vdots & a_{ji} = 1/a_{ij} & \cdots & \cdots \\ a_{n1} & \cdots & \cdots & 1 \end{bmatrix}$$

where $a_{ij}$ is the value assigned to the pairwise comparison.

The condition of perfectly consistent positive reciprocal matrix is shown in Equation 3.

Equation 3 Condition of Perfectly Consistent Positive Reciprocal Matrix

$$a_{ij} = a_{ik} \cdot a_{kj}$$

for all values assigned to the pairwise comparisons.

However, this is rarely the case due to the fact that the real world is inconsistent by nature.

#### *2.6.5.4 Priorities Derivation*

In AHP, the priorities vector of the criteria is proven to be the principal eigenvector $p$ of the positive reciprocal matrix by using perturbation theory (143) shown in Equation 4.

Equation 4 Calculation of the Principal Eigenvector of a Positive Reciprocal Matrix

$$A \cdot p = \lambda \cdot p$$

where $A$ is the positive reciprocal matrix

$p$ is the priorities vector

$\lambda$ is the maximal eigenvalue of the positive reciprocal matrix

#### *2.6.5.5 Consistency Check*

Although inconsistency is allowed in the scope of AHP, such inconsistency is necessary to be checked to assure a minimal inconsistency for deriving meaningful results. Therefore, a consistency index (CI) is included in AHP based on the eigenvalue method (143). The calculation of CI is shown in Equation 5.

Equation 5 Calculation of Consistency Index

$$CI = {}^{\lambda - n}/_{n - 1}$$

where $n$ is the dimension of the positive reciprocal matrix

$\lambda$ is the maximal eigenvalue of the positive reciprocal matrix.

To check the consistency ratio, Consistency Ratio (CR) and Random Indices (RI) are introduced (143) and the calculation of CR is shown in Equation 6.

Equation 6 Calculation of Consistency Ratio

$$CR = {CI}/{RI}$$

where RI is the random index that is the average CI of 500 randomly filled matrices shown in Table 2.3.

**Table 2.3 Random Indices of Original AHP**

| $n$ | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|
| RI | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

AHP recognises the judgments recorded in the positive reciprocal matrix are consistent if CR is less than 10% (143). However, in AHP, as CR increases, the inconsistency of the matrix increase which is anti-intuitive. Therefore, the CR is referred to as inconsistence ratio in this thesis from this point beyond.

In this research, the aspects of AHP that are useful for capturing and validating human judgments in terms of the comparative importance of enterprise requirements are adopted. AHP is also applied for ranking these enterprise requirements. The weights calculated by AHP are key inputs of the Technology Contribution Matrix (TCM) (explained in a later chapter as an essential component of the Technology Assessment Framework).

## 2.7 Valley of Death Theory and Technology Assimilation Failures

### 2.7.1 Definition of 'Valley of Death' and Its Effect

The 'Valley of Death' is a metaphor that refers to an intermediate stage where expertise and resources are relatively lacking for development . This concept of 'Valley of Death' implies that there are relatively more resources for research on the one side and on the other side there are relative more resources for commercialisation (39). Based on the report from Science and Technology Committee in House of Commons in 2013, the 'Valley of Death' prevents the successful commercialization of scientific outcomes from laboratory environment (63).

Moreover, 'Valley of Death' existed in the availability of capital from "basic research" to "commercial operation" in the phase of development & scale up (144). Also, four scenarios in manufacturing where 'Valley of Death' exists have been identified which are technology transfer/assimilation, product launch, new product development and start-up business (145). Apart from such perspectives that define 'Valley of Death' in general, the 'Valley of Death' has also been defined in terms of cash flow or cumulative profit and loss (37,146,147).

However, in this research, the focus is on technology assimilation, and as mentioned previously, the 'Valley of Death' exists in this process. By understanding there are different interpretations of this metaphor, this research, in order to simplify the problem, focuses on the effect of the 'Valley of Death', which is relatively more straightforward. The effect of the 'Valley of Death' in the environment of the automotive OEMs is understood as the outcomes that the majority of new technologies fail to survive through the assimilation process for various reasons (1,36,37,63,144,148–150).

The understanding of the ‘Valley of Death’ in technology assimilation is illustrated in Figure 2.9.

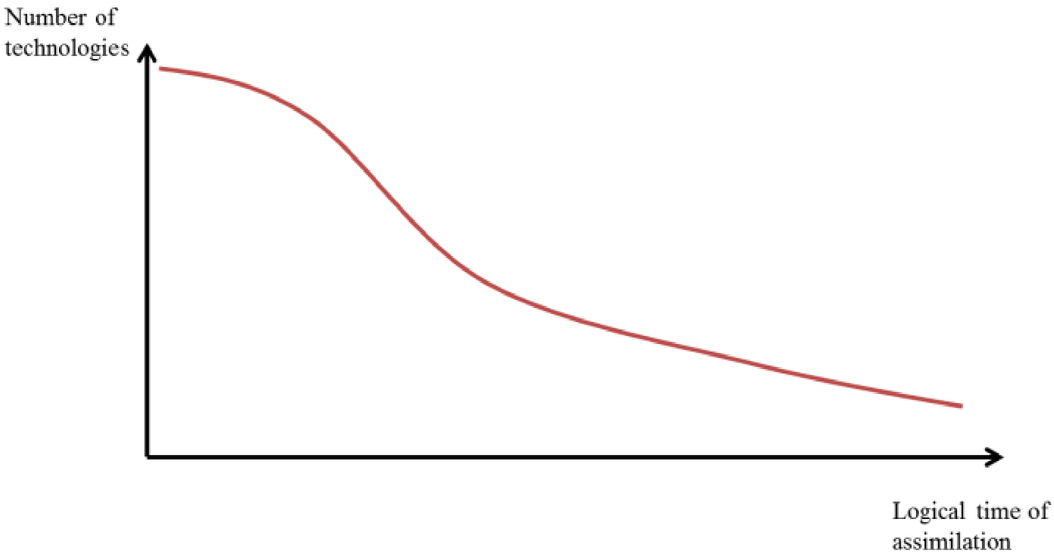


**Figure 2.9 The Effect of ‘Valley of Death’ in Technology Assimilation**

As shown in Figure 2.9, the number of technologies in the process of assimilation decreases through logical time of assimilation. At the end, only small portion of the technologies could survive the whole assimilation process where as the majority of technology assimilation projects fail due to various reasons. Such various reasons are not defined due to the fact that different technology assimilation projects are, in most cases, on the basis of fundamentally different sets of requirements and different natures of the enterprise. Therefore, this research chooses to only focus on the effect and the consequential outcomes of the ‘Valley of Death’

### 2.7.2 Solutions to 'Valley of Death'

There have been remarkable efforts to understand and solve the problems caused by the 'Valley of Death'. One of the more popular ways is to identify the 'Valley of Death' from the perspective of TRLs. In this perspective, 'Valley of Death' normally reflects the difficulty of getting a new technology through TRLs 4 to 7. During this process, the investment and resource requirements are high while the certainty of success of technology development remains low. The effect of 'Valley of Death' can be more serious for safety-critical applications (144,151).

Technology assimilation is a complex process with a high probability of failure, and there are many publications that explain why an awareness of the effect of 'Valley of Death' is crucial for companies (144,147,149).

Over the years, there have been many attempts to solve the problem of 'Valley of Death' from different perspectives. One of the most fundamental and important understanding that this research acknowledges is that in order to control and minimize the effect of the 'Valley of Death', multiple contributing factors such as social, political, and cultural transitions as well as material resource limitations should be included for consideration (36,37,39,63,144,145,148). In other words, a holistic viewpoint that incorporates different viewpoints should be applied to the solution of the 'Valley of Death'.

Also, some believe that the establishing a partnership with government and introducing some degrees of intervention from the government are required to bridge the 'Valley of Death' in industries such as space, defense and other industries that produce safety-critical products and applications. They also believe that companies and countries that do not have such partnerships can be at a severe competitive disadvantage (63,149). It is also essential that the Government ensuring investors to have access to information that would encourage their interest in technology based investments (63).

As mentioned previously, 'Valley of Death' can be defined based on TRLs. From this perspective, some believe that in order to solve the problem of 'Valley of Death', a manufacturing readiness assessment that parallels with TRLs should be introduced that assess the manufacturing process is matured so the product can be manufactured economically and in volume with consistent quality. Based on this idea, according to House of Commons Science and Technology Committee, a set of Manufacturing Capability Readiness Levels (MCRLs), which are a nine-point scale, has been developed. MCRL 1 to MCRL 4 represent the 'proof of concept' and assessment of the manufacturing technology. MCRL 5 and 6 are the critical "pre-production" phase, where expensive full-scale equipment and processes must be implemented ahead of product launch, or factory investment. MCRL 7, 8 and 9 indicate the implementation of the process on the shop floor and confirmation of volume production with assured quality (63,152–154).

Based on MCRLs, the 'Valley of Death' shows up during MCRL 4 to 6, where investment is high but there is no certainty that the product will be launched or that the proposed process will be successful. In this perspective, the TRLs and MCRLs have been applied together for a better understanding of development assessment. The assessment results from TRLs and MCRLs should be parallel. Otherwise, letting the MCRL of a manufacturing process (or set of processes) get too far ahead means wasted investment if the technology is not eventually proven, and letting the TRL of a technology get too far ahead before the MCRL of the corresponding manufacturing process catches up means delayed entry to the market, or worse, the launch of a product with low quality and unduly high cost (153,154).

There are also other efforts made in trying to bridge the 'Valley of Death'. For example, based on Barr, Baker, and Markham's 14 years of experiences in developing Commercialization of Technology (COT) in higher education and practicing it in corporations, their means of bridging the 'Valley of Death' is to train student with skills in COT (38).

### 2.7.3 Summary of 'Valley of Death' and its effect

The 'Valley of Death' is a metaphor that is often employed to refer to the phenomenon that exists in every technology assimilation process (38). The overall effect of the 'Valley of Death' highly depends on the types of technologies (63). This effect will be experienced as variations in both the difficulty and time taken to cross the 'Valley of Death'. The technology assimilated by civilian enterprises such as automotive OEMs is mostly influenced by the investment, market expectations and the market reaction on this matter (155).

Also, there are significant differences in the way that the 'Valley of Death' affects technology assimilation in civilian enterprises such as in the automotive industry and the way that it affects technology assimilation in military/aerospace enterprise. For military/aerospace enterprises, the focus of new product development is on the quality and safety of product rather than the profit and market. More importantly, for military/aerospace project, the investment is usually much bigger than civilian product development such as new vehicle development. (38,131)

Because of the fact that the 'Valley of Death' is almost inevitably a barrier during technology assimilation and requires many resources to cross, it needs front-end prediction and complexity management. When dealing with such a process requires front-end management and complexity management, it is reasonable to believe that the Systems Engineering could be useful.

## 2.8 Applied Methodologies in this Research

In this section of the literature review, the applied methodologies in this research are reviewed and discussed. This section covers the introductions and the details of such methodologies whereas Chapter 4 focuses on explaining how these methodologies are applied in this research.

### 2.8.1 Relational-Oriented Systems Engineering

Relational-Oriented Systems Engineering (ROSE) is a general systems methodology that employs model specification and relational transformation principles for system specification, analysis and design purposes (156). ROSE incorporates and furthers the studies of relational structure for systems engineering as well as relational homomorphism. The functional and hierarchical viewpoint of legacy systems engineering which depend on definition and decomposition is generalized by the ROSE methodology (157).

One of the key concepts of ROSE is the relational transformation which is defined as an association between the elements or parameters of two models of a system that induces a further mapping between the relationships in the models (156). For example, there are two relational models **M** and **N** where **M** = ($M$, $R_a$) and **N** = ($N$, $S_b$). These two models have elements with $M$ and $N$ respectively. $R_a$ and $S_b$ are the relations on $M$ and $N$ respectively. If there is Q as the mathematical relation between $M$ and $N$, this induces a relation on $N$ by transformation of the relation R on $M$. To be more specific, notation $y_i Q x_k$ indicates that a relation Q relates an element $y_i$ of $M$

and an element $x_k$ of $N$. Therefore, as a binary relation between $M$ and $N$, Q contains the order pair ($y_i$ , $x_k$) (157). The calculation of binary relationships transformation is shown in Equation 7 (157).

Equation 7 Calculation of Binary Relationships Transformation

$$\left(y_i, y_j\right) \in R \; with \; (y_i, x_k), \left(y_j, x_l\right) \in Q$$

$$implies \; (x_k, x_l) \in RQ$$

In summary, ROSE provides a multi-valued bidirectional relational transformation that is algebraically computable. This coherent mathematical foundation facilitates the analysis of the relations based on systems engineering (156,157). Therefore, this research attempts to combine ROSE with technology assessment to formalize and make the whole process more objective to a certain degree.

### 2.8.2 Requirements Engineering Methodology

As mentioned previously in Section 2.4, the quality of technology is a highly relative term which is not only decided by the technical quality of technology but also by the nature of the project or platform. This research argues that the requirements related to the technology assimilation highly affect the assessment of technology. There might be different assessment results for a technology when based on different sets of requirements. Therefore, the definition and the process of defining the requirements are vital to the process of technology assessment and hence to the success of technology assimilation. Based on this argument, this research reviews the literature in the field in Requirements Engineering.

Over three decades, researchers and practitioners have realised the importance of the requirements contributing to the overall success of product development (158,159). In terms of technology assimilation, the requirements challenge the success of technology assimilation if not being understood and processed appropriately (160).

One of the widely employed and straightforward categorization of the requirements processes in the literature defines the processes in to three facets namely discovery, specification and validation and verification (V&V) (159)(161). In the discovery stage of requirement process, the requirements are discovered based on the consultation with stakeholders and other sources (162). As mentioned previously, such efforts require the collaboration of different viewpoints and backgrounds. In a later section, the importance of a platform that facilitates a holistic viewpoint that enables such collaboration is discussed. The requirements specification in Requirements Engineering is both a noun and a verb based on literature. When using requirements specification as a noun, the outcome of this stage is a specification in the form of document in which the articulated requirements that representing an agreement on requirements among stakeholders are presented (159,163,164). As a verb, the requirements specification stage is the process that acquires, abstracts and documents the requirements (165)(143,145). Finally, the V&V of requirements ensures the requirements are both appropriate for the project and address the stakeholders' expectations with high quality and no inconsistencies or defects (159)(166). In the following subsections, all these stages are explained in detail with the considerations of their applications in technology assimilation process.

#### *2.8.2.1 Discovery Stage of Requirements Engineering*

For technology assimilation, similar to new product development, the first task is to determine what should be addressed by the technology in terms of organisational and customer needs. However, proper acquisition of such requirements knowledge requires certain techniques as such knowledge is often hidden deep inside the mind and experience of stakeholders. Traditional approaches of discovering the requirements include the most widely used one-on-one interviews with stakeholders, focus group discussions and direct observations of business projects. Also, in the field of Requirements Engineering, some more intensive discovery techniques such as protocol analysis as well as the use of ethnography have been proposed to render explicit tacit knowledge in terms of requirements. Last but not the least, prototyping, as mentioned previously, is also a widely deployed approach to establish a common understanding of the requirements.

#### *2.8.2.2 Specification Stage of Requirements Engineering*

The discovered requirements from discovery stage of Requirements Engineering are needed to be converted into some representational schemes or models for better understanding among the stakeholders and for better knowledge management. The specification stage of requirements is focus on achieving this goal. Arguably, the most popular approach to do this is modelling as requirements models establish baseline of understanding of complex technology assimilation of stakeholders. Moreover, such requirements models facilitate better communication between distinct stakeholder groups with different professions and knowledge background. Requirements models also enable the identification of hidden requirements, determination of inconsistencies of requirements and confirmation of requirements accuracy. Requirements models are also useful to simplify and organise the requirements through abstraction and decomposition.

However, within Requirements Engineering literature, an argument rises that the preferences of some other stakeholders are not valued enough. For example, Hsia et al argue that most stakeholders prefer natural language more than formal specification even though such natural language or verbal representations often cause ambiguity, incompleteness and inaccuracy (167). Therefore, a balance between formal/mathematical correctness and verbal/natural representations needs to be achieved.

Moreover, although requirements of technology assimilation are commonly articulated at multiple levels of detail such as enterprise, functional and non-functional levels, literature has argued that most of the focuses are on modelling function requirements at system level. However, other levels of requirements are of vital importance. Therefore, this research believes that the modelling of requirements should apply holistic viewpoints that facilitate analysis on all level of requirements. This argument is supported by the recent efforts to integrated enterprise level and non-functional requirements in the Requirements Engineering field.

#### *2.8.2.3 Validation and Verification Stage of Requirements Engineering*

The requirements Validation and Verification (V&V) stage of Requirements Engineering reveals whether the requirements processed from previous stages are effective and able to support later technology assessment and assimilation efforts or not. As the name of this stage indicates, there are two different concepts namely validation and verification. In the scope of the Requirement Engineering, where the focus is the requirement itself, this process is necessary for ensuring the requirements are correctly identified and defined as well as consistent throughout.

Even though V&V is typically positioned at the end of requirements process, V&V should begin almost simultaneously with previous two stages in practice. For example, as mentioned previous, the prototyping is also used to identify whether the requirements are the correct reflection on what in the minds of stakeholders.

In terms of technology assimilation, V&V is also of vital importance. As argued previously, the assessment results of technologies rely highly on the requirement of the technology assimilation. Therefore, without a validated set of requirements of technology assimilation, the results of technology assessment are unreliable.

#### *2.8.2.4 The Changing Nature of Requirements*

Over the decades, the researches in the field of Requirements Engineering have noticed the so called ‘requirements mess’ that is an ever-increasing pernicious challenge and motivation. The lack of user input, incomplete requirements and changing specifications have been associated to the flaws in design requirement. As a similar situation, this research believes that this also exists in the technology assimilation. Many novel challenges for applying Requirements Engineering to technology assimilation have emerged due to the reasons explained below.

According to Jarke et al, the first challenge is the fact that the economics of Requirements Engineering has changed over decades (159). More rigorous return-on-investment (ROI) analysis is required for large systems. Second, the application of Requirements Engineering requires a balance between new business and technological challenges and opportunities and existing complex environment including technological, organizational, social and political factors. Thirdly, the ever-increasing complexities of new technologies results in more complex relationships between technologies and the environment. Last but not the least, new factors such as time to market have become critical to the success of technology assimilation.

Moreover, the scope of the defined stakeholders of technology assimilation has been expanded that causes more dynamic environment of technology assimilation. All of this has resulted in the changing nature of requirements of technology assimilation. Therefore, this author believes that the application of Requirements Engineering in the field of technology assimilation should enable flexibility and expandability.

Overall, Requirements Engineering is believed to be one of the major guiding principles of the development of Technology Assessment Framework. There are several criteria, which can be summarized from this part of literature review, that the proposed approach of this thesis needs to meet. Such criteria are listed hereafter.

1. The requirements of technology assimilation collected by the proposed approach should include not only functional requirements but also enterprise requirements and non-functional requirements.
2. The requirements should be stored in the proposed approach.
3. A balance between mathematic formality and verbal representation of the specification of the requirements should be achieved in the proposed approach.
4. The requirements should be articulated into understandable form in order to be agreed by wide range of stakeholders.
5. A V&V process or technique should be suggested or provided by the proposed approach.
6. The requirements model should be expandable due to the changing nature of requirements.

### 2.8.3 Qualitative Research Methods

Qualitative methods are collections of different approaches used in many academic disciplines especially in Social Science, market research and research of service (168–170). Qualitative research is involved in studies of almost every imaginable phenomenon and the researchers are often required to go ‘in the field’ to obtain first-hand experience and knowledge.

As the title of this thesis suggests, this research aims to develop a holistic approach for ameliorating the ‘Valley of Death’ effect in technology assimilation. This requires the establishment of the understanding of the environment where technology assimilation takes place. Moreover, the trans-disciplinary nature of this research requires proper method for data collection and information gathering. In addition, Given (171) and Yin (172,173) both suggest that qualitative methods enable better understanding of the ‘how’ and ‘why’ aspects of problems. This research incorporated qualitative methods to enable a better understanding of the problems that technology assimilation project managers face through the ‘Valley of Death’.

Different qualitative research methods are applied in different stages of this research to facilitate different phases of information gathering. During the beginning stage of this research, several qualitative research methods such as unstructured interview, review of records and observations were applied when engaging with Jaguar Land Rover Limited. The information gathered in this phase is presented in Appendix 5. The utilization of such methods accelerated the identification of the research problems and supported the findings from literature review of this research. During the design and development stages of the TAF and TRMA, the qualitative feedback from Jaguar Land Rover Limited provided rich insight into the challenge of technology assimilation. Moreover, this research applied a case study approach as the major qualitative research method for the preliminary verification and validation stage. These case studies are presented in Chapter 6 and the information gathered in this phase is presented in Appendix 3 and 4.

In terms of the case studies in this research, the question that needs to be answered is *how well the proposed holistic approach is for ameliorating the 'Valley of Death' effect in technology assimilation works in the environment of automotive OEMs*. Yin also suggests that multiple sources of evidence can contribute to a case study and this seemed an appropriate method for the real-world situation. The sources of information in the case studies includes but not limited to literature, observations, questionnaires and unstructured interviews.

However, some concerns have been identified by researchers with regards to case study approach (172,173). For example, the greatest concern is the relative lack of rigor of case study approaches as some researchers do not follow the systematic procedures and report the evidence from case study In a biased manner. (173). In order to address this concern, as mentioned previously, this research reports all the proceedings and collected data, which were approved and validated by Jaguar Land Rover Limited, in Appendix 3, 4 and 5.

The detailed explanations of the methodology of this research that includes the applications of above-mentioned qualitative research methods are presented in Section 3.4 of Chapter 3.

## 2.9 Technology Assessment in Real World Situation

In this section, the findings from four Midterm Reviews (MTRs) of PSi held by Jaguar Land Rover Limited that the author was invited to are presented as the reflection of the technology assessment in real world situation. This section is to complement the findings from previous literature review and hence the research problem could be more accurately defined.

The Programme for Simulation Innovation (PSi) is a joint five-year research programme funded by Jaguar Land Rover Limited and EPSRC. This research programme includes nine themes, where each theme addresses various new technologies that may be desirable to be assimilated into practices and processes of this mentioned automotive OEM. The author was invited to observe four MTRs. These MTRs are listed below in Table 2.4 and the MTRs minutes of Theme 2, 1,and 9 are presented in Appendix 5 in  a chronological order.

**Table 2.4 MTRs Details**

| | Date | Theme name |
|---|---|---|
| Theme 2 | 01/10/2015 | Multi-physics and multi-functional simulation methods |
| Theme 1 | 04/11/2015 | Analysis of the vehicle as a complex system |
| Theme 3 | 07/04/2016 | Driving Simulation |
| Theme 9 | 12/04/2016 | Customer Life Cycle Prediction |

As shown in Table 2.4, the research topics of these four themes are different suggesting that the research approach and the outcomes should be different. However, based on the observations of the author, all four MTR meetings follow the same routine and process. The process of the MTR meetings is concluded and explained hereafter.

1. **Welcome and scene setting:** The Principal Investigator (PI) for each theme welcomes the attendees. This is followed by the managers of Jaguar Land Rover Limited who are responsible for the PSi programme stating the goals of MTR and the expected outcomes. Expected outcomes included:

1.1 Jaguar Land Rover Limited is interested in the potential research outcomes from each theme, particularly by the end of the PSi programme.

1.2 Jaguar Land Rover Limited is interested to hear the implementation plans for anticipated research outcomes

1.3 Jaguar Land Rover Limited expects knowledge transfer plans, including a plan to keep the researchers with talents and skills to make further contributions to Jaguar Land Rover Limited.

2. **Reports on Research**: The PIs and the leading researchers present their research outcomes up to the date and progress from a traditional technical viewpoint. Some comments on how the projects are progressing against the time plan are made. The attendees from Jaguar Land Rover Limited normally focus on asking questions from traditional technical viewpoint in this step. Also, some of the problems and challenges in the research were discussed, as well as progress and achievements. Jaguar Land Rover Limited is also interested to find out if the PhD students could contribute to Jaguar Land Rover Limited beyond the research they are engaged in at the time. The potentials for being recruited to Jaguar Land Rover Limited after the research are made clear.

3. **Wrap Up**: At the end of each MTR, the senior manager from Jaguar Land Rover Limited acknowledges the efforts made by each Theme. Based on the observation, Jaguar Land Rover Limited is satisfied with progress at all four of the MTR meetings.

### 2.9.1 Observations from the Midterm Review Meetings

In this section, some of the major observations are presented.

1. Some PIs do not seem to understand what Jaguar Land Rover Limited wants from the MTRs. The company focus more on the technology assimilation and the plan instead of the technical progress. This problem is observed from the focus on the technical issues in the presentations, with only a small proportion of time given to discussing the technology/knowledge transfer plan in general. However, the latter MTR meetings put more efforts on the technology assimilation. The author assumes that Jaguar Land Rover Limited notices this problem and send out clarified agenda before latter MTR meetings.
2. As the MTR meetings progresses, the PSi research teams learn from previous held MTR meetings about the sort of issues that Jaguar Land Rover Limited is interested in. For example, in the MTR meetings for Theme 2, the PI does not mention the risks associated with technology assimilation. However, in the Theme 1 MTR meeting, the PI and co-PI are prepared to answer the questions asked by senior manager of Jaguar Land Rover Limited about risk and the future plans for technology assimilation.
3. The processes of the MTR meeting were not completely synchronised with the process that Jaguar Land Rover Limited applies in its technology assimilation. In addition, no previous cases of technology assimilation outside PSi were mentioned and referenced during the MTR meeting. All of these cause the discussions related to technology assimilation during the MTR meetings not following the same criteria.

4. The attendees of all four MTR meetings from Jaguar Land Rover Limited are mainly managers. This limits the viewpoints involved in the MTR.
5. After the MTR meetings, the proceedings are all documented and circulated within the all PSi themes. However, such proceedings could have been generated with reference to the rigorous governance structure namely Technology Creation and Delivery System (TCDS) in Jaguar Land Rover Limited for better knowledge management or other structured methods.

### 2.9.2 Observed Gaps from MTR Meetings

In this section, the lessons learnt from the MTR meetings are presented. This would help to better define the research problem and hence better define the aim and objectives of this research. All of the reported findings in this section are also reported to Jaguar Land Rover Limited.

1. A wider range of participants that covers different knowledge and profession backgrounds is helpful for the technology assessment as multiple viewpoints are included to achieve a more comprehensive assessment of technologies.
2. A structured method of technology assessment is required to support to achieve better technology assessments
3. A more structured, instead of document-based, method of archiving the knowledge gathered through MTR meetings would be helpful for both Jaguar Land Rover Limited and University.
4. Plans and approaches for ameliorating the effect of ‘Valley of Death’ should be helpful as the focuses of all the research groups in PSi are on delivering the research outcomes (new technologies) at TRL 3 whereas Jaguar Land Rover Limited predominantly assimilate technologies that reach TRL 6.

## 2.10 Summary of Literature Review

The literature review of this thesis not only provides the understanding of technology assimilation and relating concepts but also reviews the applied methodologies in the later development of proposed approach. Moreover, the gaps have been identified in terms of the current approaches and tools with regard to technology assessment and assimilation.

The definitions of technology have been reviewed and expanded that provide a platform to propose the technological viewpoints based on different branches of science in one of the most popular science classifications. Such technological viewpoints are recognised as the foundation of this research.

Before moving onto the literature review of technology assimilation, a review on different but similar and confusing concepts related to technology assimilation has been conducted. This part of the literature not only help to achieve disambiguation but also informs the scope of the concept of technology assimilation in this research.

Then, general scenarios of technology assimilation have been suggested based on literature and real-world experience. This helps to further narrow down the scope of this research

In addition, this literature review helps to make the argument of the relative nature of quality of technology that one of the fundamental ideas of the development of TAF.

In order to better understand the process of technology assimilation as well as the relationships between technology assimilation and its environment, literature review has been conducted to assume a Vee model of technology assimilation that follows the Vee model in the Systems Engineering.

The approaches and tools of technology assessments and decision-making have also been reviewed to study their strengths and weaknesses. This provides an understanding on what should be avoided and what should be adopted during the design and development of proposed approach of this research. The technology assessment is a crucial process that increases the success rate and lowers the total risk of technology assimilation. The approaches and methods of technology assessment that this research has studied are insufficient and inadequate to a certain extent. This proves the necessity of this research as a new approach of technology assessment is proposed

Moreover, the concept of 'Valley of Death' has been studied to identify how the proposed approach in this research could help with the problems. The 'Valley of Death' also exists in the technology assimilation process. This phenomenon is unavoidable, but the effect of this phenomenon can be minimised by proper methods and management.  The goal of ameliorating the 'Valley of Death' is to lower the negative impact and thereby smoothing the overall process of technology assimilation and reducing the waste of resource. Literature has argued that front-end prediction and complexity management are crucial to fulfil this goal. Systems Engineering and approaches are believed to be able to help to solve this problem by using holistic viewpoint.

Last but not the least, the applied methodologies in this research are reviewed. This covers different methodologies from different disciplines that reflects the trans-disciplinary nature of this research.

Overall speaking, this literature review helps 1) to identify the research problem and shape the aim and objective of this research and 2) to understand different methodologies from different disciplines that could potential benefit the development of the proposed approach to ameliorate the effect of ‘Valley of Death’ to technology assimilation.

Most importantly, after reviewing the literature, some desirable features of ideal technology assessment and assimilation methods and tools that guides the development of the proposed approach of this research are identified. Such features are listed and explained below.

1. The involvement of subjectivity in technology assessment is important. However, this involvement should be contained and limited.
2. The approach of technology assessment should provide structured methods of collecting the subjective data.
3. The approach of technology assessment should facilitate holistic and multiple viewpoints from different stakeholders.
4. The approach of technology assessment should enable comparative assessment between candidate technologies. Comparative results are believed more reasonable and with more rationalities.
5. The results provided by technology assessment approach should be traceable.
6. The approach of technology assessment should provide not only results for current state of technology but also predictive result for technology in future state.

According to the literature review in previous sections, a conclusion of identified gaps in the literature is presented in this section.

The understanding of the technology itself has limitations. This has led to the solutions of many technical problems are limited from the beginning.

In most literature, the technology assessment process and technology assessment tools were initially designed for application in the military equipment industry. Therefore, in the field of civilian applications, they have the inherent shortcomings.

Most literature related to ‘the Valley of Death’ is based on the management or business views and trying to find solution of ‘Valley of Death’ on management level. There is rarely literature discuss this topic on the engineering level or the combination of management level and engineering level

The gaps of the literature lead this research to find a solution which can ameliorate the problem of ‘Valley of Death’ in technology assimilation that facilitates multiple viewpoints involved in technology assimilation and also benefits real world automotive OEMs.

# 3 Aim, Objectives and Methodology

## 3.1 Research Problem Statement

In this chapter, the problem of technology assimilation in automotive OEMs is presented based on the literature review and lessons learnt from MTR meetings in Chapter 2. The core research problem of this PhD research is the 'Valley of Death' in technology assimilation. However, according to the literature review and engagements with industry, many lower level problems that lead to this core research problem have been identified. Moreover, such lower level problems are categorized into two groups namely technology assimilation related problems and enterprise related problems. An illustration of the research problems is presented in Figure 3.1.

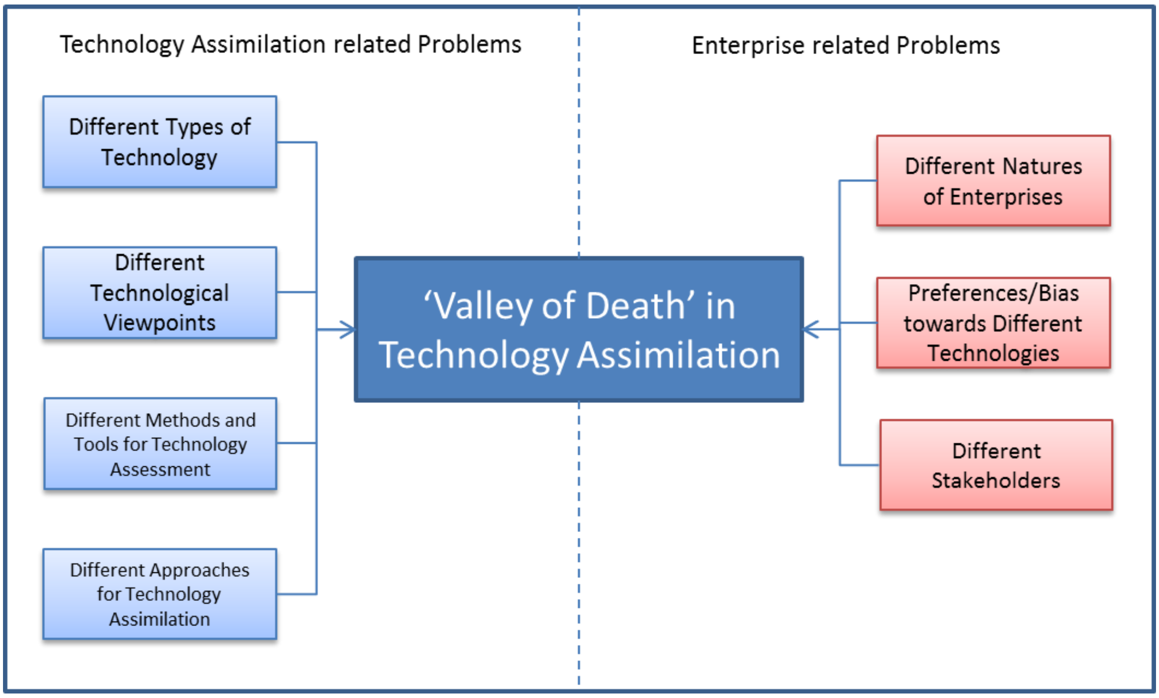


**Figure 3.1 Illustration of the Research Problems**

As shown in Figure 3.1, on the technology assimilation related problems side, there are four lower level problems namely different types of technology, different technological viewpoints, different methods and tools for technology assessment and different approaches for technology assimilation that are identified. On the other side, three lower level problems that induce the problem of 'Valley of Death' in technology assimilation are identified namely different natures of enterprise, different attitudes (preferences or bias) towards technologies and different stakeholders involved in technology assimilation.

However, all the lower level problems that induce the problem of 'Valley of Death' in technology assimilation are not to solve by the proposed holistic approach in this thesis. Instead, such problems are included into consideration of the development of the proposed approach and are covered by the proposed approach.

## 3.2 Aim of this Research

This research aims to develop a holistic approach to technology assimilation for ameliorating the effect of ‘Valley of Death’ by approaching this problem in three ways. First, by developing a method to reduce the number of technologies that are considered for assimilation by eliminating at an early stage any relatively weak technologies and include only those more likely to succeed. Second, by developing a method to support the enterprise in deciding the general direction of technology improvement and so increasing the probability of successful assimilation. Third, by exploiting this approach to better support knowledge management across the enterprise.

### 3.2.1 Detailed Explanation of the Aim

To address the first part of the research aim, a Technology Assessment Framework (TAF) will be developed with the capability to provide a holistic comparison of technologies with regard to their potential contributions to a project and to provide insight into the degrees of complexity that will need to be addressed moving forward to the assimilation process. TAF should be able to identify the dominant aspect of a technology based on Natural, Social and Human Technological Viewpoints. This is mainly to serve the fact that different enterprises prefer different technologies with different dominant aspects. TAF aims to serve a wide range of stakeholders, whom have different profession and knowledge background, involved in the technology assimilation process.

In the second stage of this research, a Technology Refinement and Modification Algorithm (TRMA) will be developed. The purpose of this algorithm is to identify and suggest directions of improvement for the refinement and modification of a technology in ways that will still meet requirements. By combining TAF and TRMA, the outcomes of technology assimilation should be improved the by reducing the number of technologies considered for assimilation and also through understanding how to improve the survival rate of each technology as it evolves during the process of assimilation.

The final stage of this research is to exploit this approach to enhance knowledge management across the enterprise and to encourage the development of new problem- solving capability and decision-making for long-term benefit. This will require the approach developed in this research to be able to facilitate better knowledge gathering, sharing and archiving.

## 3.3 Objectives

The objectives of this research that help to achieve the aim are list below.

1. Review the general process of technology assimilation and different methods and tools involved in current technology assessment and assimilation to identify their strengths and weaknesses.
2. Define and model the general process of technology assimilation.
3. Review the knowledge management from the literature and define the relationship between knowledge management and technology assimilation.
4. Define the problem of technology assimilation from literature and practitioner feedback.
5. Define different technological viewpoints involved in technology assessments and assimilation and build the Hexahedron Model of Technology (HMT) that serves as the foundation of the Technology Assessment Framework (TAF).
6. Develop TAF and a method of populating it.
7. Develop a Technology Refinement and Modification Framework (TRMA) on the basis of TAF.
8. Apply TAF and TRMA to two case studies of technology assimilations in partnership with Jaguar Land Rover Limited to preliminarily verify and validate the effectiveness and feasibility of this approach.
9. Analyse the advantages of supporting knowledge management by the approach propose in this research.

## 3.4 Methodology

In this chapter, the overall methodology of this research is introduced and explained. The structure of this research is shown in Figure 3.2 and followed by the explanations of each steps. Different methodologies being applied and adopted in this research, which are introduced in literature review chapter, are also explained in terms of how this research applies and adopts them.

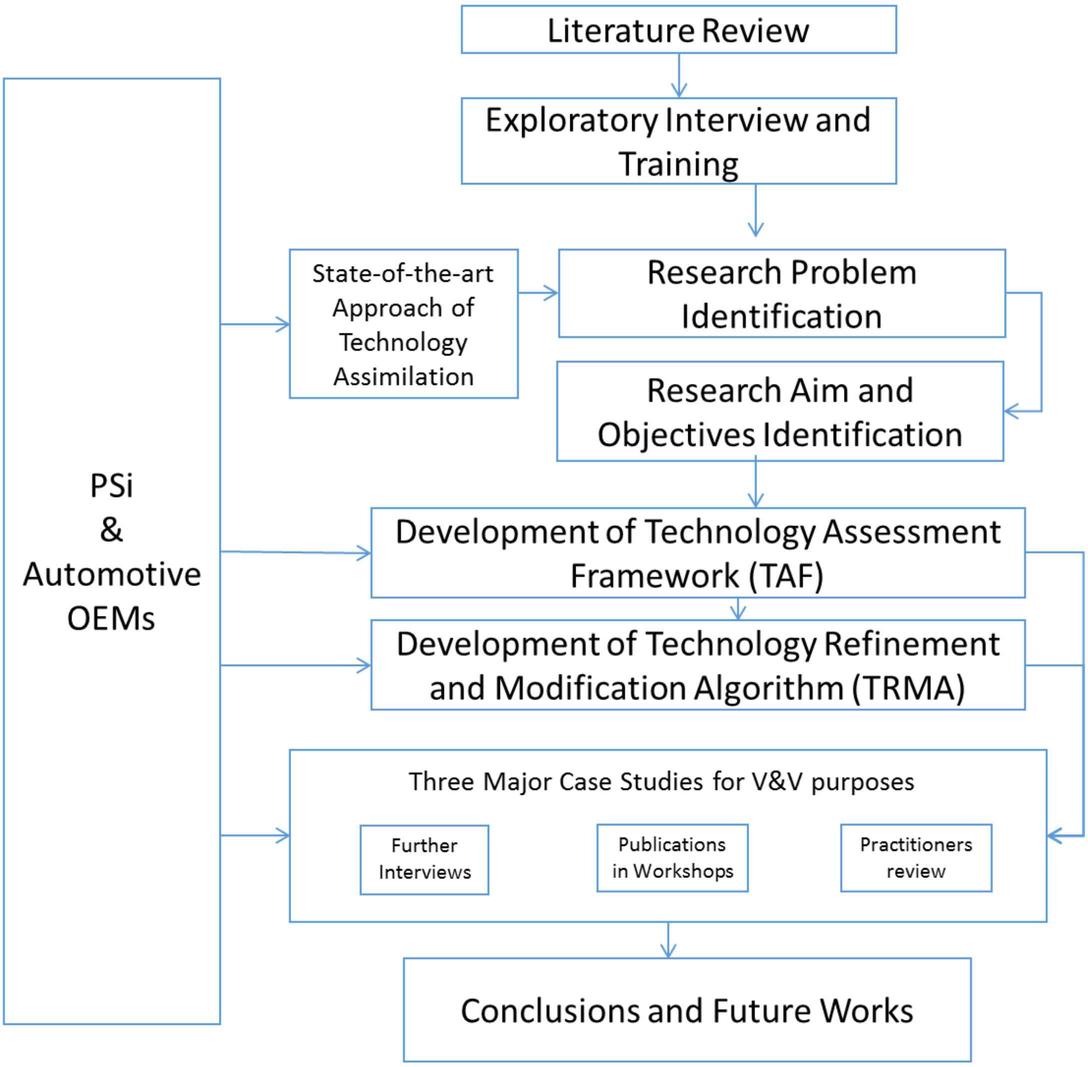


**Figure 3.2 Overall Structure of this Research**

This research is part of the Theme 1 of the Programme for Simulation Innovation (PSi) that is a joint five-year research programme funded by Jaguar Land Rover

Limited and Physical Sciences Research Council (EPSRC) (174). Therefore, this programme becomes the major data and information source of this research. As shown in Figure 3.2, almost all steps of this research have links with PSi and corresponding automotive OEMs.

The first step of this research is the literature review. This helps to establish the fundamental understandings of the technology assimilation and corresponding concepts from academic viewpoints. Also, through exploratory interviews with stakeholders in PSi and automotive OEMs, this research gathers the general understanding of the state-of-the-art approaches of technology assimilation in automotive OEMs. The author of this thesis was invited to several mid-term reviews held by Jaguar Land Rover Limited where different technologies under development were assessed. These experiences from such mid-term reviews are essential to this research and the findings and the meeting minutes are reported in a later chapter and included in Appendix 5 respectively.  All of these then help this research to identify the problems and gaps of technology assimilations in automotive OEMs from both academic and practical viewpoints. After the problem identification step, the aim and objectives of this research are set up. Up to this point, the pre-development phase of this research is done.

As shown in Figure 3.2, the next step of this research is the development of the Technology Assessment Framework (TAF). During the development process, the Systems Engineering (Architecture and Design) Methodologies, Information Design Methodologies and Requirements Engineering Methodologies are applied with the considerations of MATLAB programming environment compatibility. The outcome of this stage namely Technology Assessment Framework is also enabled by the

Relational Transformation from the Relational-Oriented Systems Engineering (ROSE).

The next step of this research is the development of the Technology Refinement and Modification Algorithm (TRMA). This algorithm is developed based on the TAF and with reference to the Perturbation Theory which is introduced and explained separately in Chapter 5.

After the developments of both TAF and TRMA, this research conducts two case studies with regards to different technologies (innovations) in automotive OEMs. Both case studies are conducted mainly for the V&V purpose of TAF and TRMA. This step involves further interviews with stakeholders in PSi and automotive OEMs and peer-reviewed publications.

Finally, with the conclusion of this research, future works is also suggested.

# 4 Technology Assessment Framework

In this chapter, the topics cover from the introduction and explanation of the Hexahedron Model of Technology (HMT), the conceptual design of the Technology Assessment Framework (TAF), the systems design of TAF based on a systems engineering approach, and the specifications of the TAF as well as the method of populating it.

## 4.1 The Hexahedron Model of Technology

As mentioned previously, the TAF is developed based on the Hexahedron Model of Technology (HMT), which is shown in Figure 4.1 where a transformation from 2-dimentional model to 3-dimentional model is illustrated for better understanding.

In Chapter 2, the technological viewpoints are defined and then elaborated to propose this model. In the scope of this research, a technology being assessed prior to assimilation is considered as a hexahedron that has six facets. These facets represent six different aspects of a technology corresponding to different technological viewpoints of analysis and understanding. HMT supports the argument that the technology should be assessed through comprehensive and holistic viewpoints (175). Another advantage of this hexahedron model is that the approach brings together different viewpoints and demonstrates the expectations that different stakeholders have for technology assimilation.  This in turn provides a platform for better discussion and analysis of a technology. Without a method to bring together different viewpoints and showing conflicts, technologies can be assimilated into products and enterprises with undue haste (175).  If different views are not discussed comprehensively, this can prevent people in the enterprise from gaining an accurate understanding of a certain technology in terms of the compatibility, likely performance and possible risks for an enterprise. Therefore, HMT supports the community in reaching a better understanding of new technology leading a more open discussion and realistic starting point for technology assessment and assimilation.

The six facets of HMT are introduced and explained from Section 4.1.1 to Section 4.1.6.

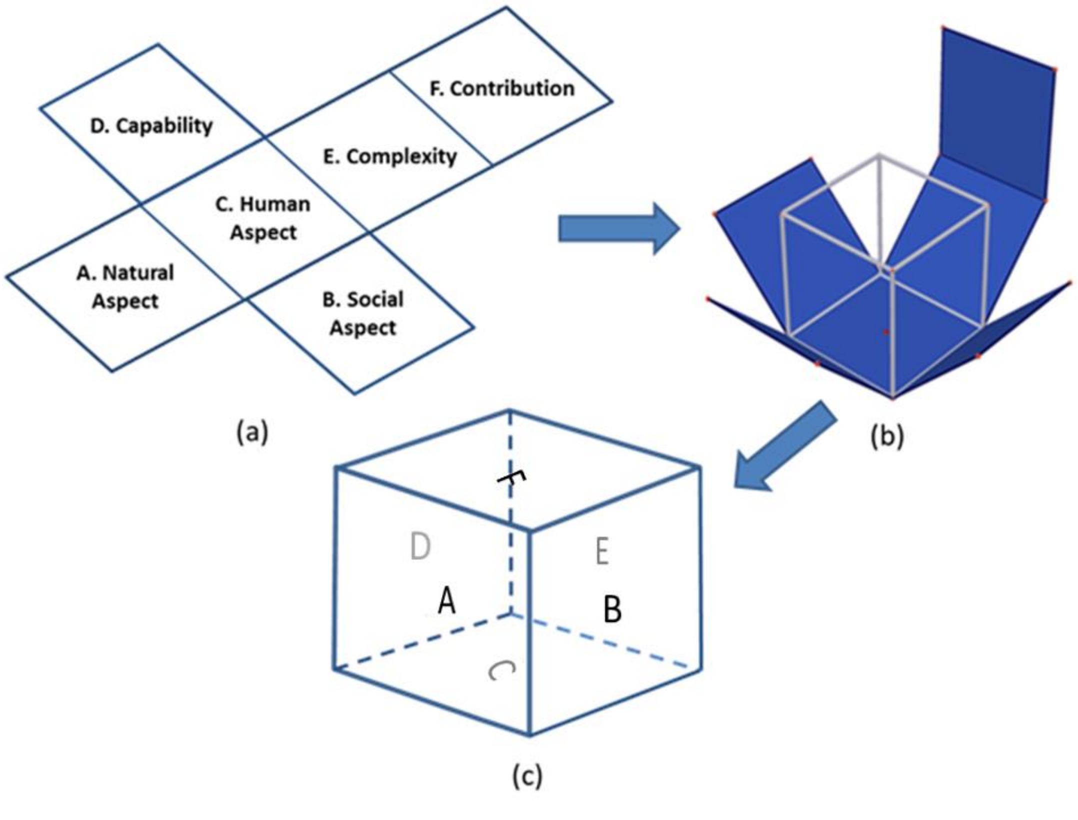


**Figure 4.1 Hexahedron Model of Technology**

### 4.1.1 Natural Aspect of Technology

The first facet of a technology is named 'Natural aspect' in HMT, as this facet incorporates objective and quantitative analysis comprised of methods rooted in Natural Science (175) and revealed by the Natural Science Associated Technological Viewpoint (NTV) or Natural Technological Viewpoint. As explained in Section 2.1.1, NTV incorporates traditional methods of technology assessment that focus on measurable quality and performance functions of a technology in a straightforward manner. This natural aspect of technology directly corresponds with specific technological requirements, such as the improvement of a particular system element.

### 4.1.2 Social Aspect of Technology

The second facet of HMT is name 'Social aspect' of technology. This aspect is revealed by the Social Science Associated Technological Viewpoints (STV) that explained in a previous chapter. This facet represents the aspects of technology that affects the enterprise on organisational level and vice versa. For example, technology features that require cross-department collaboration and communication in order to assimilate the technology are categorized in Social aspect of technology in HMT. This aspect of technology is not rare as literature argues that a new technology requires co-operation and communication between different departments of an enterprise to be fully deployed (175,176). This aspect reflects the fact that bringing the management of the corporation and other stakeholders 'on board' in order to fully unleash the potential of a technology is sometimes more important than looking at the engineering problem directly. Often, through better organizational management and communication, the cost of technology assimilation can be significantly reduced, the quality of the assimilated technology can be improved and the time to market can be reduced. This aspect of technology also covers issues of governances, regulations, and policies that related to the technology. For example, green technology (177) has a Social aspect that is related to policies because of the promotion by government.

### 4.1.3 Human Aspect of Technology

The third facet of HMT is named 'Human aspect' of technology as it is revealed by the Human Science Associated Technology Viewpoint (HTV). The Human aspect of technology has an influence on the end user and stakeholders of technology assimilation physically and mentally, and this aspect of technology has potential interactions with end users when using the technology and stakeholder during technology assimilation. More importantly, the Human aspect largely decides the user perception of the technology (178). For example, 'user friendly', as a feature belongs to Human aspect of technology, could promote the prospect of a technology. Before introducing the next three facets of HMT, Figure 4.2 illustrates the relationships between a technology, the three aspects of technology, and the technology features upon which this research is based.

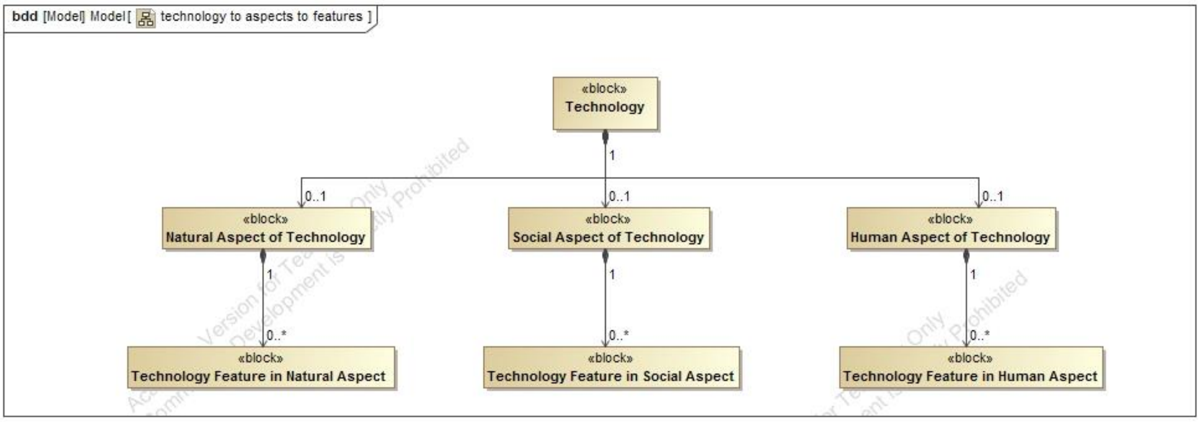


**Figure 4.2 Relationships among Technology, Aspects and Features**

In the perspective of this research, three aspect of technology namely the Natural aspect, Social aspect and Human aspect that can be identified from a technology. Each aspect includes different technology features. However, some technologies may not have all the aspects defined as no feature from a particular aspect may be defined due to various reasons.

### 4.1.4 Capability of Technology

The fourth facet of HTM is the capability of technology and technology assimilation. As explained in Section 2.1.3 of Chapter 2, the capabilities provided by a technology after its assimilation is another important aspect that an enterprise needs to consider. The capability of a technology is understood as an all-or-nothing proposition in this model where a technology provides a certain capability only if the corresponding enterprise requirement can be completely fulfilled. The detailed review of this concept was presented in Section 2.1.3 of Chapter 2.

### 4.1.5 Complexity of Technology

As mentioned previously, there are many definitions of complexity in different domains, and one universal definition of complexity does not exist (56). In this research, complexity is defined from a subjective point of view based on elaboration of different definitions of complexity (54,56). The definition of complexity is *“the degree by which the interrelationships and (or) interactions of a system’s components cause difficulties for the observer to gain a holistic understanding of the system”* which is detailed explained and discussed in Section 2.1.2 of Chapter 2. That is, technology complexity is understood to be highly dependent on the perception and the understanding of the enterprise that wants to assimilate the technology as well as the interrelationships among the technology feature owners.

The fact that one highly complex technology may not be as complex for one other enterprise supports this definition. This viewpoint offers insight into the potential risks a particular technology might present during and after an assimilation process, as opposed to the potential ‘reward’ offered through technology assimilation. The detailed review of this concept was presented in Section 2.1.2 of Chapter 2

### 4.1.6 Contribution of Technology

The final facet of HTM is the contribution of technology. The contribution of technology is also associated with the enterprise requirements of the assimilation project. However, unlike capability of technology that explained previously, this facet of HMT reflects the reward of technology assimilation from a holistic viewpoint in contrast to complexity of technology, which reflect the risk of technology assimilation. This facet of HMT indicates how good a technology contributes to the overall enterprise requirements of technology assimilation. The detailed explanations and discussions can be found in Section 4.4 of Chapter 4.

Overall, HMT is proposed to help analysing technology from a comprehensive and holistic viewpoint. In addition, as explained in Section 4.3 and 4.4 of Chapter 4, all these six facets are criteria applied within the technology assessment in TAF.

## 4.2 Conceptual Design Process of Technology Assessment Framework

In the Chapter 2 and 3, the gaps in current technology assimilation approaches were identified and the different technological viewpoints were introduced. In this section, the conceptual design of the TAF is discussed. This research applies systems engineering approach to the design the Technology Assessment Framework at the conceptual level.

The purpose of this part of the research is, as previously discussed, to expand the limitations of current technology assessment approaches and therefore the TAF should be able to facilitate the consideration of different viewpoints during the technology assessment process.

In the following sections, the steps and details of how the TAF has been conceptually designed and developed are discussed. In Section 4.2.1, the requirements of TAF development are defined and presented, and the environment of TAF is defined and discussed in Section 4.2.2.

### 4.2.1 Requirements Specifications

In this section, the requirements of the Technology Assessment Framework (TAF) are set out based on the studies of literature and engagement with Jaguar Land Rover Limited. More specifically, the identified insufficiencies of current technology assessment approaches from literature review are converted to the requirements of TAF. Also, the inputs of practitioners are valued highly in the identification of requirements. The identification of stakeholder and environment analysis are conducted based on the elaboration of both literature review that are presented in Chapter 2 and engagement with Jaguar Land Rover Limited (PSi midterm review meetings) that are described in Section 2.9 of Chapter 2.

#### *4.2.1.1 Stakeholder identification*

As explained previously, current methods and tools such as TRLs were either developed in the aerospace and defence domains, where there are different stakeholders and expectations, or developed under different perspectives than those of this research. Moreover, as declared in the aim of this research, the TAF is designed to serve a wider range of stakeholders. Therefore, it is not valid to assume that the same stakeholders for this research work. Thus, based on the principles of Systems Design in the field of Systems Engineering, to develop this Technology Assessment Framework, the initial task is to identify the stakeholders and their expected influences on TAF.

For the development of TAF, many stakeholders have been identified such as engineers, managers, chief engineers, technology provider, technical director, finance director, H&R executives and programmer. These stakeholders are categorised based on the natures of their professions and the relationships with TAF.

Moreover, the MTR meetings also provided important insights of this matter which is presented in Section 2.9 of Chapter 2. These stakeholders and their relationships are illustrated in a Class Diagram shown in figure 4.3 and explained hereafter.

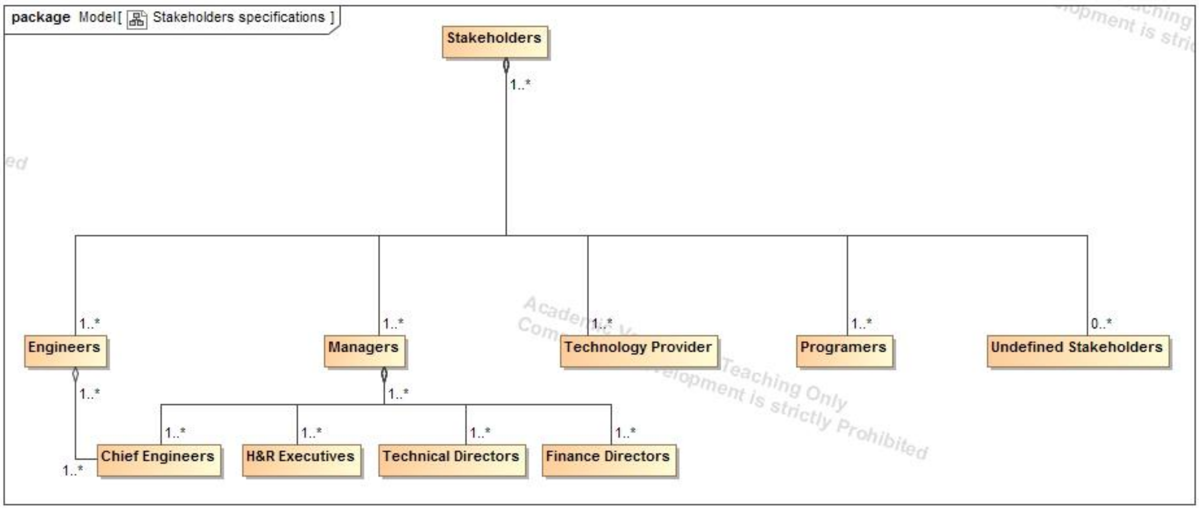


**Figure 4.3 Class diagram of stakeholders of TAF**

1. Engineer: in this research, the engineers as a term is understood as the people who do engineering work in automotive industry. This means they should have direct interaction with both technology and TAF. The engineer's opinions on certain technologies are most likely useful and should be considered as important inputs of TAF. They also have first-hand testing data of technologies under assessments. This class of stakeholders also includes Chief Engineers who have the authority to make decision on technology assimilation. Therefore, the stakeholders represented by this class are recognised as one of the major groups of stakeholders of TAF.

   1.1 Chief engineer: there are some differences between engineer and chief engineer. First, chief engineer is normally taking responsibility for a certain technology assimilation project. The technology assessment result contributes highly to their decision making. Second, the chief engineer needs to look at the project from a higher level and multiple technological viewpoints. They are the appropriate people to decide what technology analysis result goes into TAF in order to make most efficiency and effectiveness out of TAF.

2. Manager: in automotive industry, based on observation, there are different individuals who have authority over the technology assimilation and are responsible for the management of the technology assimilation. In this research, the focus between management and engineering is the main factor to distinguish manager from chief engineer. While the chief engineer is more focussed on engineering, the manager focuses more on management. As mentioned previously, technology provides new service or product to an automotive company which means the success of a technology assimilation project can give an automotive company a competitive edge. The result of TAF is definitely a manager's concern. How accurate and how much support that TAF can give in terms of technology assessment are key of TAF development in a manager's perspective.
3. Technology provider: technology provider is interpreted as a general designation of people or organisation that provide technology to the automotive industry. The technology provider can include external research facilities, universities, individual inventor, other company or internal R&D department. In general, the technology providers rely on the technology assessment result to let people in automotive industry believe that the technology they provide is the right technology. Moreover, they can modify the technology based on the assessment result to make certain technology be more valuable to an automotive company.

4. Programmer: Due to the fact that TAF is not merely a document-based framework and should provide automatic calculation function, TAF should be programmable. Hence, the programmer is the last stakeholder identified in this research related to TAF. Based on observation, MATLAB is ubiquitous in engineering departments in the automotive industry. Therefore, TAF should be programmed in MATLAB so that all other stakeholders can integrate TAF into their working practice without much effort. Moreover, this makes TAF easy to upgrade and maintain after integration.

#### 4.2.1.2 Identified Requirements of TAF Development

In this section, the requirements of TAF from stakeholders are identified. As mentioned previously in Section 4.2, the requirements are defined with reference to the inefficiencies and insufficiencies of current tools and methods applied in technology assessment identified in literature review chapter and based on the inputs from practitioners.

The requirements are then categorised into three groups namely performance, function and lifecycle. Requirements on performance of TAF are non-functional requirements in the scope of Systems Design in Systems Engineering. Such requirements set the goal of how well TAF should perform. Requirements on the functions of TAF are the functional requirements in systems engineering terms. Finally yet importantly, lifecycle requirements are also non-functional requirements which focus on the lifecycle of TAF including maintenances, integration issues and upgradability.

The stakeholder requirements are listed and explained with the support of a SysML requirement diagram that is shown in Figure 4.4.

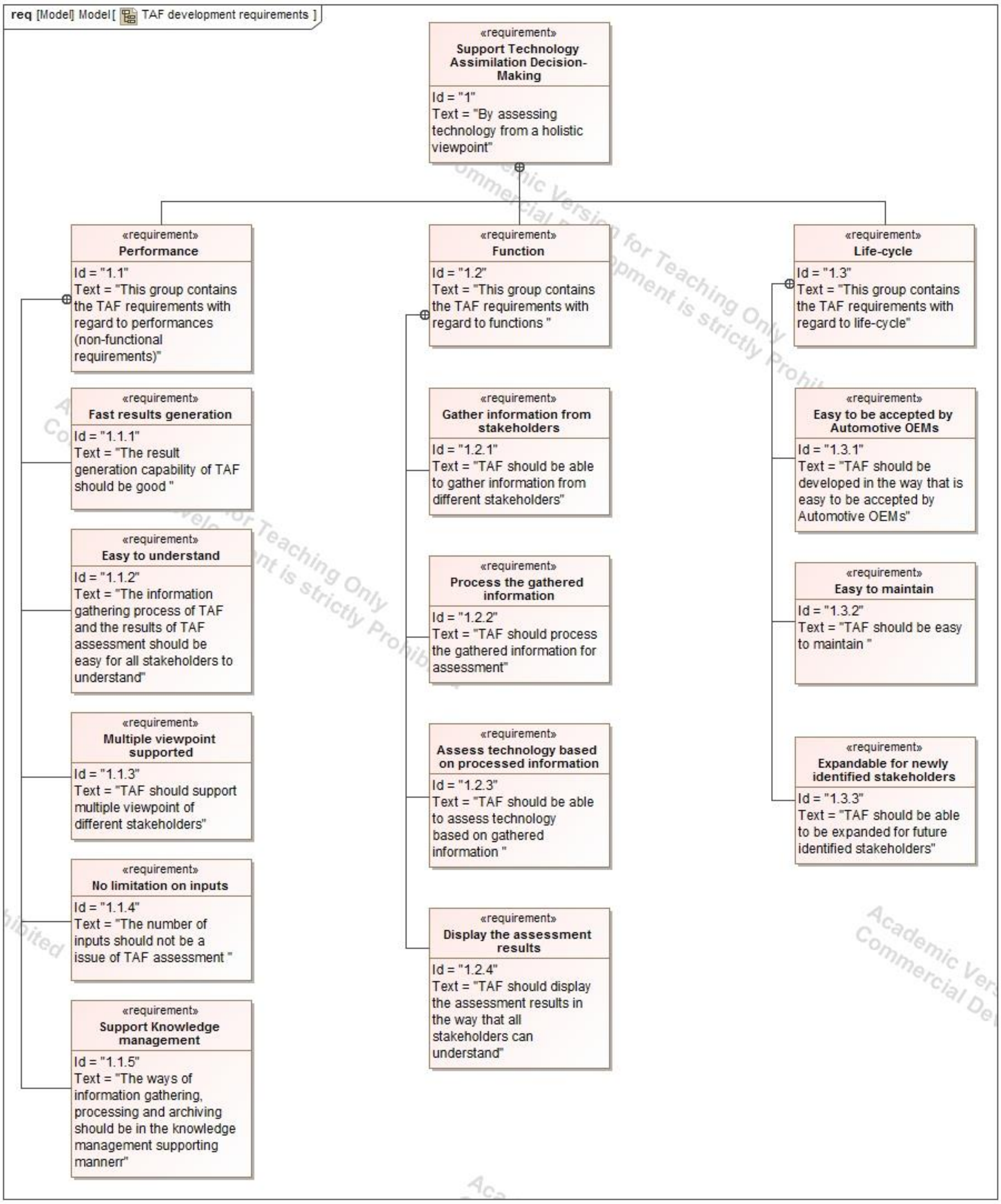


**Figure 4.4 Requirements diagram of TAF development**

1.1.1 Fast result generation: Within New Product Development, the speed to market is a key concern. This also applies to technology assessment. Therefore, the whole process of TAF assessment should not be lengthy. Especially, TAF should generate results fast after the gathering information from stakeholder.

1.1.2 Easy to understand: This requirement of TAF development includes two levels of meaning. First, the process of whole TAF assessment should be easy to understand including the information gathering process. Therefore, all stakeholders who may have different professional and knowledge backgrounds, should be able to participate without difficulties. Second, the results generated by TAF should be easy to understand as well. This means when people in automotive OEMs look at the results, they can understand which technology is relatively better without further analysis.

1.1.3 Multiple viewpoints supported: The TAF should support the multiple technological viewpoints mentioned previously in this thesis and be able to assess technology based on six aspects of technology specified in HMT. This should encourage the participation of different stakeholders to input their understandings and opinions with regard to the technologies under assessment, and provide assessment results based on a holistic viewpoint.

1.1.4 No limitation on inputs: This requirement also has two levels of meaning. First, the number of inputs should not be limited. Many methods and algorithms are deeply affected by the numbers of inputs in general such as Genetic Algorithm (GA). This means that the number of the input should not hinder the results generation speed of TAF. Second, the input type should not be limited to one format. This requires TAF having a translation mechanism or method to convert different types of inputs of stakeholders so that the stakeholders are further encouraged to input their thoughts and opinions.

1.1.5 Support knowledge management: This requirement is self-explanatory. The information gathering, processing and archiving of TAF assessment should be done in the way that support better knowledge management.

1.2.1 Gather information from stakeholders: TAF should be able to collect information from stakeholders and gather collected information together. This requires TAF provide information collection method as well as information storing capability. Moreover, due to the different backgrounds of stakeholders, TAF should be able to collect different types of information as well.

1.2.2 Process the gathered information: TAF should be able to process the gathered information for further calculations. More importantly, TAF should provide traceability to such information processing in order to increase the credibility of TAF assessment results.

1.2.3 Assess technology based on information gathered: This is the core requirement of TAF. TAF should be able to assess technology based on the information gathered and processed to provide comprehensive and apprehensible results.

1.2.4 Display the assessment results: TAF should be able to display the assessment results to stakeholders in the form that is suitable to wide-range of stakeholder that have different professional and knowledge backgrounds.

1.3.1 Easy to be accepted by industry: This requirement has three levels of meaning. First, the environment of software development of TAF should fit the preferences of industry. For example, MATLAB, as one of the most popular software in automotive OEMs, would be preferable for the software implementation of TAF development. Second, the results of TAF assessments should be accepted by industry as well. This particularly requires TAF using the same terminologies as the target industry using. Third, TAF should be easy to apply to technology assessment project in general, and the software of TAF should be easy to use.

1.3.2 Easy to maintain: TAF software/codes should be easy to maintain through the lifecycle. This also emphases the necessity of developing TAF software in a familiar software development environment of automotive OEMs so that the software engineers would maintain TAF software without significant difficulty.

1.3.3 Expandable for newly identified stakeholders: Due to the wide-range of stakeholders of technology assessment and assimilation processes in general. TAF should be able to be expanded to cope with newly identified stakeholders and their viewpoints and inputs in future. This requires TAF having a flexible structure. The expandability of HMT, which is the basis of TAF, suits this requirement.

### 4.2.2 Environment Analysis

In this section, the environment of TAF is discussed and analysed. This research utilizes Systems Engineering methods to develop the TAF that emphasize the importance of front-end analysis. Therefore, the environment of TAF is analysed in advance of the systems design. This allows a better understanding of the scope of TAF. As shown in Figure 4.5, a UML sequence diagram captures the interactions among user, technology and TAF during technology assessment.

If TAF is being considered as a system, then the stakeholders and technology that is being assessed are within the environment of TAF. The stakeholders directly interact with TAF while technology does not. The technology that is being assessed is only analysed by stakeholders. From this high- level environment analysis, the fact that TAF does not rely on individual technologies can be identified. This is one of the most important features of TAF since TAF should be able to assess all kinds of technology while providing guidance for stakeholders to analyse technology based on a holistic viewpoint so that the analysis of technology can be conducted comprehensively.

However, this also means that the results of stakeholders' technology analysis affect the assessment results. In this research, as previously stated in Chapter 2, such subjectivities are unavoidable. Hence, TAF embraces the subjectivities involved in technology assessment process and provides structured guidance for information gathering to reduce the negative effects of such subjectivities. This is further explained in Section 4.4 of Chapter 4.

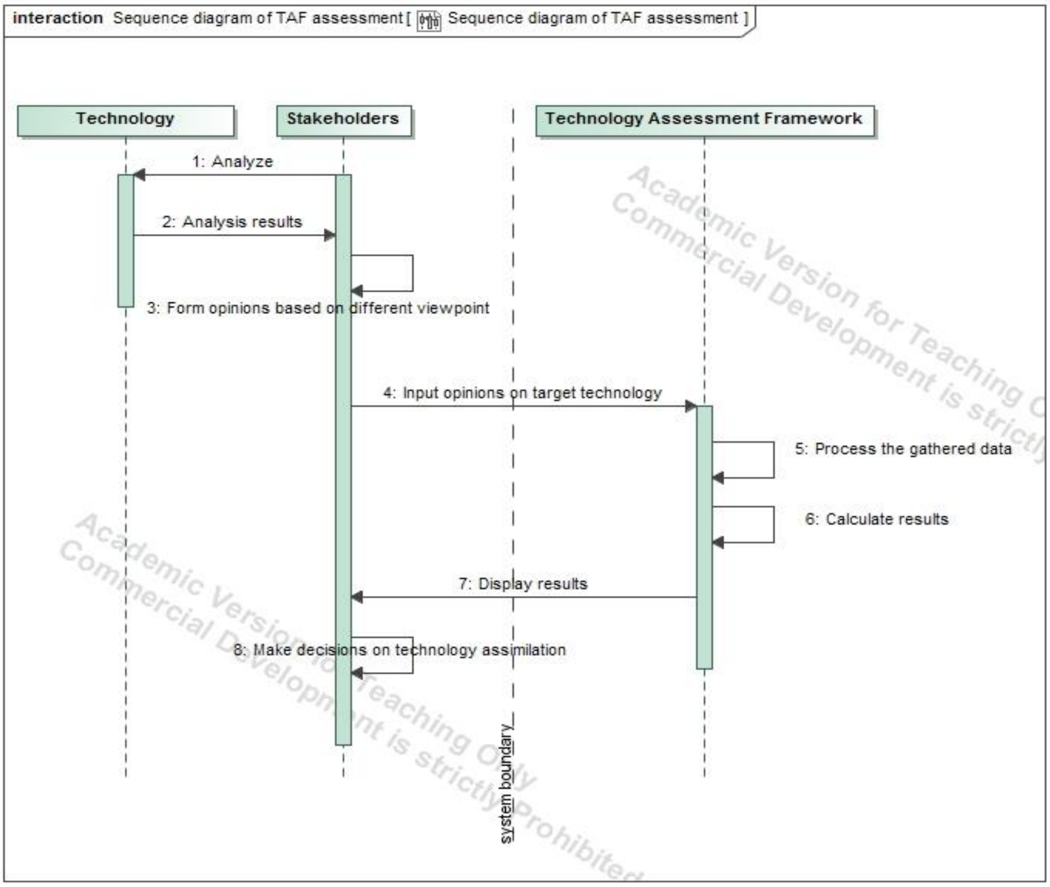


**Figure 4.5 Sequence diagram of TAF assessment**

Figure 4.5 is a sequence diagram that captures the high-level interactions of the stakeholders using TAF to assess a technology. As stated earlier, the stakeholders need to analyse the technology and obtain the results before actually using TAF to assess that technology. After their analysis, the stakeholders input the analysis results into TAF. TAF then processes the inputs based on its algorithm and calculates the assessment results. The stakeholders can use the displayed results to support decision making on technology assimilation afterwards.

## 4.3 Systems Design of Technology Assessment Framework

In this section, the system designs of TAF and its process are presented. All of these systems designs are provided based on the previous high-level conceptual design of TAF development presented in Section 4.2 of Chapter 4.

### 4.3.1 Use Case Specifications

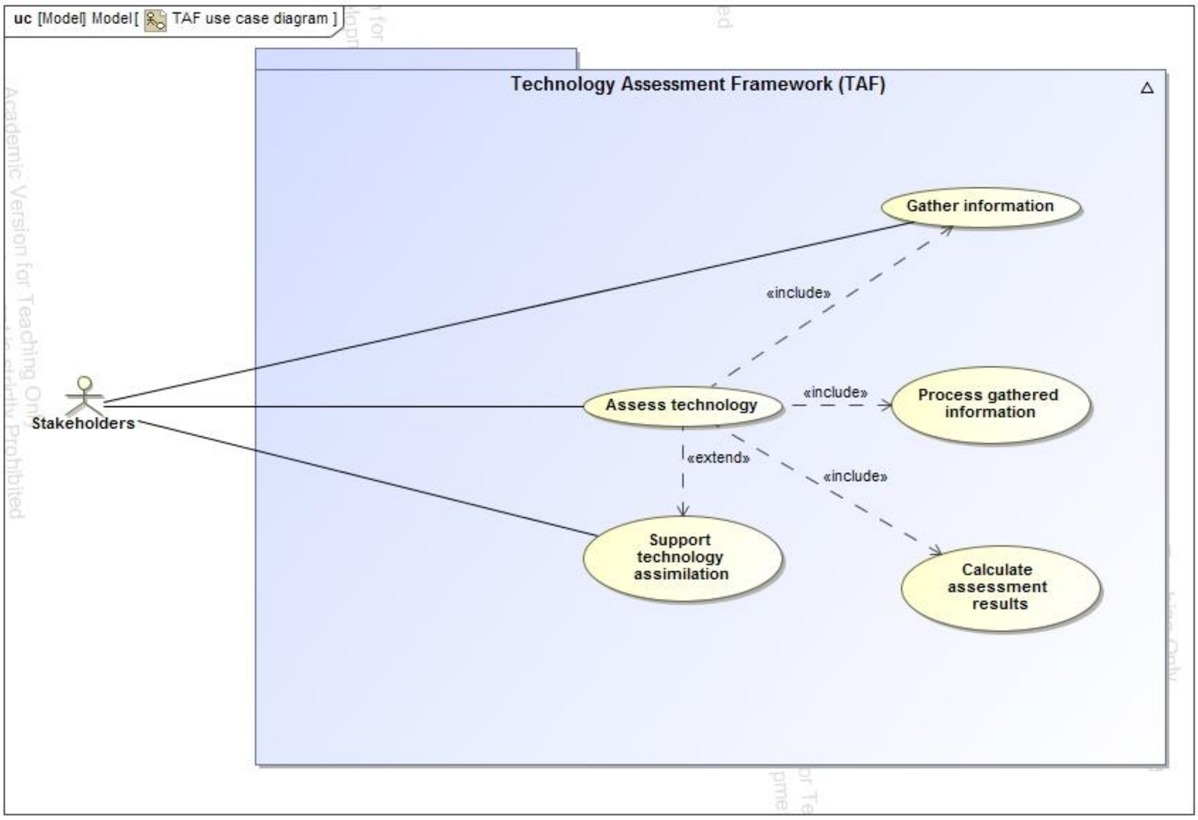


**Figure 4.6 Use Case Diagram of TAF**

This first step of systems design of TAF is to define its use case specifications. As shown in Figure 4.6, the use case diagram captures the use cases of TAF. As mentioned previously, multiple stakeholders of TAF exist in the process of technology assessment. Therefore, the main users of TAF are defined as the stakeholders of technology assessment. The stakeholders are identified in Section 4.2 of Chapter 4. The highest-level functions provided by TAF are to assess technologies and to support the technology assimilation process. As shown in this use case diagram, there are three major use cases representing functions of TAF are defined to achieve the two main functions. Such major use cases also echo with the functional requirements defined in Section 4.2.1 of Chapter 4. The use cases are explained hereafter.

1. Gather information: TAF gathers information from the stakeholders with regard to the technology and enterprise analysis results.
2. Process the gathered information: TAF processes and arranges the gathered information based on TAF's implemented approaches and algorithms for later calculations.
3. Calculate assessment results: TAF calculates the assessment results of technologies based on the information gathered and processed in previous two use cases.

This use case diagram shows the high-level design of TAF functionalities and in the following section, the design of components of TAF are shown and explained.

### 4.3.2 Components Design of Technology Assessment Framework

The Technology Assessment Framework is aggregated by three major matrices namely Enterprise Requirement Matrix (ERM), Technology Contribution Matrix (TCM) and Technology Feature Matrix (TFM). These matrices are explained and discussed in Section 4.4. In this section, instead, the focus is to introduce the high-level components design of TAF as part of the results of systems engineering design process.

As shown in Figure 4.7, the high-level components design is captured in a SysML Block Definition Diagram. The highest-level components of TAF, as mentioned, are ERM, TCM and TFM. On the next level, the enterprise requirement entries and grouped technology features based on technological viewpoints are elements of ERM and TFM respectively. Also, the enterprise requirements entries and grouped technology features are also elements of TCM. Up to this level of specification, the basic structure of TAF is formed.

The next level of specification contains pairwise comparisons, individual contribution made by technology features to enterprise requirement and identified interrelationships among technology features as elements of ERM, TCM and TFM respectively. The further explanations of such elements are included in later sections.

The lowest level elements defined in this high-level specification are calculated weights of enterprise requirements in ERM and different types of interrelationships among technology features in TFM.

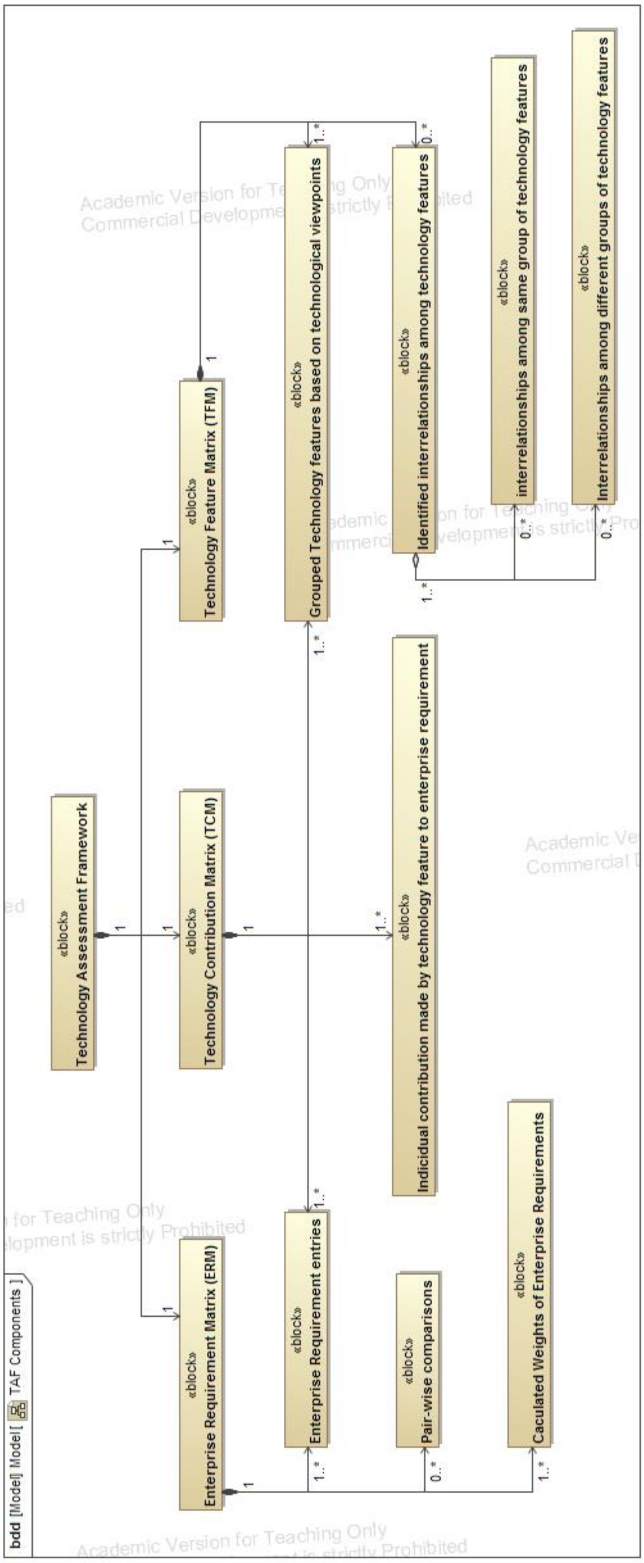


**Figure 4.7 Block Definition Diagram of TAF**

### 4.3.3 Conceptual Design of Technology Assessment Framework

In this section, following the design of TAF components in previous section, the conceptual design of TAF is shown in Figure 4.8 and explained afterwards.

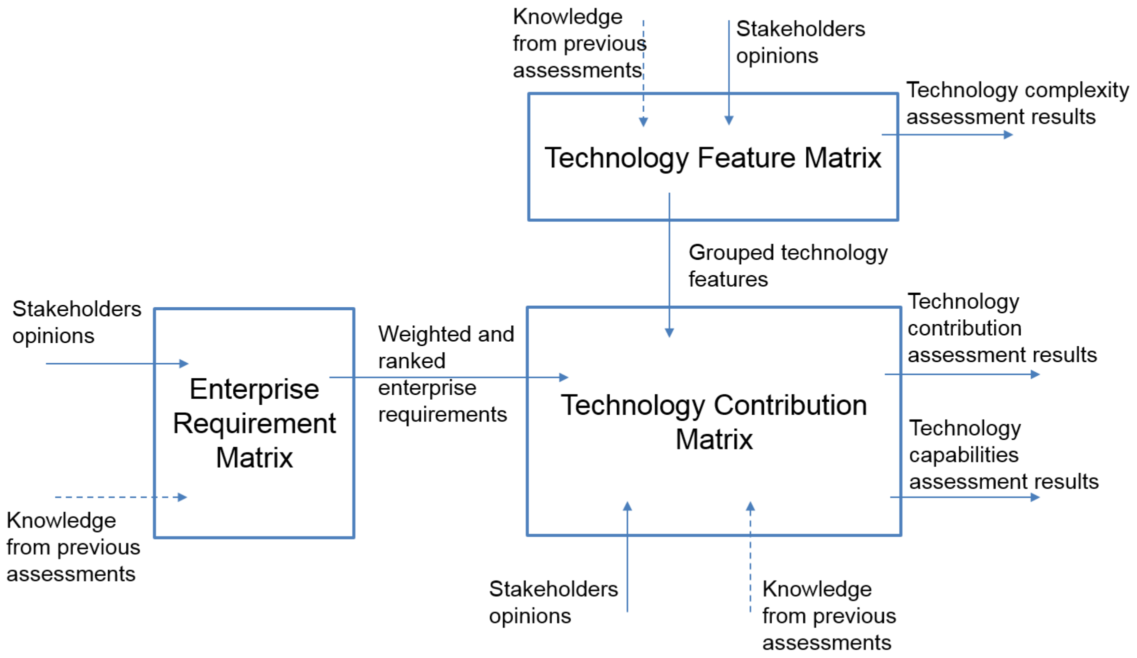


**Figure 4.8 Conceptual design of TAF**

As shown in Figure 4.8, the inputs and outputs are specified for the conceptual design of TAF. The inputs and outputs of each matrix are explained hereafter.

With regard to the Enterprise Requirement Matrix (ERM), there are two inputs and one output. As shown in Figure 4.8, the stakeholders' opinions are illustrated as a solid arrow as these would always be the input of ERM whereas the knowledge from previous assessments may not always available as it is illustrated as dashed arrow. This applies to all other matrices as can be seen in Figure 4.8. However, the details of such inputs depend on specific matrix in TAF meaning that different type of stakeholders' opinion and knowledge are required for input by different matrices. As mentioned previously, TAF should support the knowledge management in automotive OEMs and provide better knowledge management capability to automotive OEMs. TAF archives the stakeholders' inputs to enhance the reusability of such knowledge. In an ideal situation, the longer TAF has been applied in automotive OEMs, the easier the whole process of TAF assessment would be as more and more archived knowledge can be reused to replace the stakeholders' inputs.

The conceptual design of TAF shown in Figure 4.8 also specifies the outputs of each matrix on high level. The outputs of ERM are ranked enterprise requirements and their weights that go into Technology Contribution Matrix (TCM). The outputs of Technology Feature Matrix (TFM) are grouped technology features based on different technological viewpoints defined in previous chapters that also go into TCM and the complexity assessment results of technology for the stakeholders. The outputs of TCM are the contribution and capability assessment results of technology for stakeholders. Overall, TAF assessment requires either different kinds of stakeholders' opinions or previous archived knowledge to provide the complexity, contribution and capability (3C) assessment results for stakeholders. This conceptual design of TAF specifies the 3C assessment results as the highest-level outputs. However, during the TAF assessment process, there are also other assessment results that can be provided by TAF which are introduced and explained in a Section 4.4 of Chapter 4.

## 4.4 Specifications of Technology Assessment Framework

As explained in the previous chapter, assessing a technology requires comparison and analysis of different weightings and combinations of these different viewpoint contributions. This research proposes a novel approach to this process in the form of the Technology Assessment Framework (TAF) which complies with the objective 6 introduced in Section 3.3. In calculating the various algorithms for results in TAF, this research adopts the relational transformation approach set out in ROSE (156,157). In this section, the architecture of TAF and the methods of populating it are presented and explained.

As stated previously, TAF is comprised of the major matrices, namely Enterprise Requirements Matrix (ERM), Technology Contribution Matrix (TCM) and Technology Features Matrix (TFM). The architecture of the components and elements of the matrices is illustrated in Figure 4.9.

There are discussions in detail, following the figure; and then the three matrices are specified in detail in later sub-sections

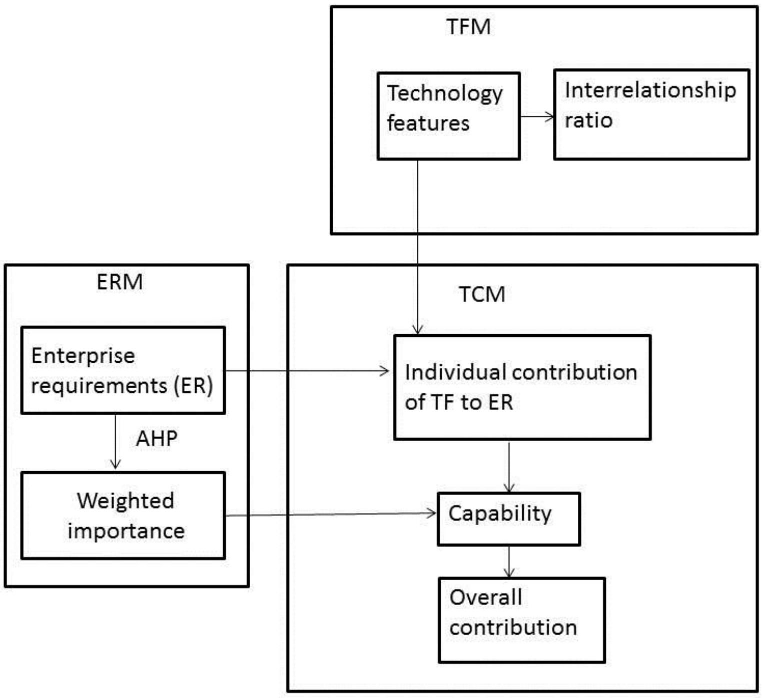


**Figure 4.9 Architecture of TAF**

### 4.4.1 Components and Elements of the Matrices

As shown in the block diagram in Figure 4.9, the components and elements of this framework that are explained hereafter.

1. Enterprise Requirements (ERs): As previously explained in Section 2.5.1, the enterprise requirements are the results of enterprise and project analysis, which are provided by experts in terms of the technology assimilation and enterprise requirements. In this research and also in the scope of TAF, ERs cover all kinds of requirements related to technology assimilation including but not limited to engineering requirements, functional requirements and business requirements. By covering all kinds of requirements, TAF encourages different stakeholders with different knowledge and professional backgrounds to participate the process of enterprise and project analysis related to technology assimilation. In addition, TAF facilitates different viewpoints of technology assimilation from different departments in automotive OEMs. By applying the concepts of AHP, which is reviewed in Section 2.6.5 of Chapter 2, with the pair-wise comparisons of importance of ERs made by stakeholders, ERM produces the weights of each ER. The ERM produces the weights of each ER which can then be ranked according to their weights
2. Weighted Importance of Enterprise Requirements: The TAF has partially implemented the Analytic Hierarchy Process (AHP). This calculates the principle eigenvectors of the Enterprise Requirements Matrix (ERM) that contain the pair-wise comparison of the relative importance of enterprise requirements. The elements of the normalized principal eigenvectors are the

weighted importance of the respective ER that become the basis of the ranking of the enterprise requirements.

3. Technology Features (TFs): In the scope of this research, the technology features that contribute to Enterprise Requirements (ER) are entries of the Technology Features Matrix (TFM). Based on the HMT, which is explained in Section 4.1 of this chapter, TFs can be categorized into three aspects of technology namely Natural, Social and Human aspect. Also, the interrelationships among TFs, which are further processed to calculate the interrelationship ratio, are identified by stakeholders based on their tacit knowledge and experiences.
4. Predicted Capability of Technology: The capability of technology is one of the aspects of technology based on HMT and one of the criteria of TAF assessment. The detailed methods for predicting the capability of a technology are presented and discussed in Section 4.4.3 of this chapter.
5. Total Contribution of Technology: Similar to the capability of technology, the total contribution of technology is also an aspect of technology based on HMT and one of the criteria of TAF assessment. This aspect of technology reflects the overall ‘rewards’ of technology assimilation. The details of the methods to predict total contribution of technology is presented and explained in in Section 4.4.3 of this chapter.
6. Individual Contribution of TF to ER: The individual contributions of each TF to each ER are the elements of TCM. These individual contributions are specified by stakeholders based on their tacit knowledge and experiences. In order to encourage the participation of stakeholders to the specifications of such elements and also to simplify the process of doing so, the stakeholders

can only provide their judgments in verbal representations such as major contribution and minor contribution. An interpretation and translation of such verbal representations is provided in TAF which is introduced and explained in Section 4.4.3 of this chapter.

7. Interrelationship Ratio: This is one of the major outputs of TAF that is designed to reflect the complexity of the technology. In addition, such calculated interrelationship ratios could potentially indicate the 'risk' of technology assimilation with the support of proper interpretations.

All of three matrixes that form TAF are explained in separated sections in detail.

### 4.4.2 Enterprise Requirements Matrix

This section presents the Enterprise Requirements Matrix (ERM) in detail. The specifications of ERM are results of the elaboration on the corresponding conceptual component shown in Figure 4.8 of Section 4.3.3. The MATLAB code of TAF that associate with ERM is presented in Appendix 1A.

As introduced in previous section, ERM contains the enterprise requirements that the technologies need to fulfil. Such enterprise requirements are not limited to any particular type of requirement such as engineering requirements and business requirement. Instead, enterprise requirements include all possible requirements related to the technology assimilation. The output of ERM is the ranked enterprise requirements as well as the normalized corresponding weighted importance.

In order to reduce the subjectivity involved in the ranking and weighting of the enterprise requirements, TAF partially adopts the AHP methodology to rank and weight the enterprise requirements.

Because of the high level of subjectivity involved in the requirement ranking process, the scale of numbers for the intensity of importance are simplified to 1,3,5,7,9 which represent equally important, moderately more important, strongly more important, very strongly more important and extreme importance respectively. This is slightly different to the original AHP that was introduced and reviewed in Chapter 2.

The elements of ERM are the pairwise comparisons made by stakeholders in the form of above-mentioned intensity of importance. Such elements of ERM form a reciprocal matrix that is the main body of ERM. The corresponding elements of the normalised principal eigenvector of this reciprocal matrix are the weights of the enterprise requirements. The ranking of the enterprise requirements is made based on the weights of enterprise requirements.

The method of the validation of the ranking is also provided by AHP and adopted by TAF because human judgments are often inconsistent. However, the inconsistency ratio is not recognised as a threshold of TAF assessment. Even though the original AHP only considers the matrix to be consistent if the inconsistency ratio is less than 10%, TAF accepts an ERM even if a higher inconsistency ratio exists. For importance pairwise comparisons, one can make the judgment of B>A, A>C, and B<C when the pairwise comparison of B, C either has a higher priority than A, or is based on a different perspective for the pairwise comparisons B, A and A, C. For a N by N matrix, one needs to make a total of (N-1) *N/2 pairwise comparisons. In the case studies of Chapter 6, one can easily notice the relatively large number of pairwise comparisons based on different priorities or different perspectives, which are required to be made. To have an inconsistency ratio that is less than 10%, many revisions of the ERM are required and this will significantly prolong the process of whole TAF assessment. One of the considerations behind the deprioritising of the IR is that, for the highly subjective nature of technology assessment, a 9.9% IR and a 10.1% IR do not have a significant difference. Having stated this, the IR is still an output of ERM in TAF. However, the implementation of TAF in MATLAB will not stop the user from proceeding the assessment if a higher IR is produced. Instead, the user should be aware of the high IR and considering revise the ERM if applicable. Otherwise, a better set of questions should be asked in order to extract more consistent tacit knowledge of the pair-wise importance among the enterprise requirements from the practitioners. Also,

The examples of populating ERM are shown in the case studies of Chapter 6.

### 4.4.3 Technology Contribution Matrix

This section explains the Technology Contribution Matrix (TCM). The specifications of TCM are results of the elaboration on the corresponding conceptual component shown in Figure 4.8 of Section 4.3.3. The MATLAB code of TAF associated with TCM is presented in Appendix 1B.

TCM is designed to contain the captured relationships between enterprise requirements and technology features. To be more specific, the captured relationships represent the contributions of each technology feature to the fulfilment of each enterprise requirement. Such contributions are represented as a percentage where 0% means no contribution and 100% means complete fulfilment. A negative percentage means that a technology feature has a negative impact to the fulfilment of an enterprise requirement. In this case, such technology features jeopardise the fulfilment of these enterprise requirements.

An interpretation of how such percentages representations are translated from verbal representations and vice versa is also introduced as a guide in TAF. This interpretation is applied to all percentages throughout this research not only in TAF but also in TRMA that is introduced in Chapter 5. The interpretation of the percentage representations is shown in Figure 4.10.

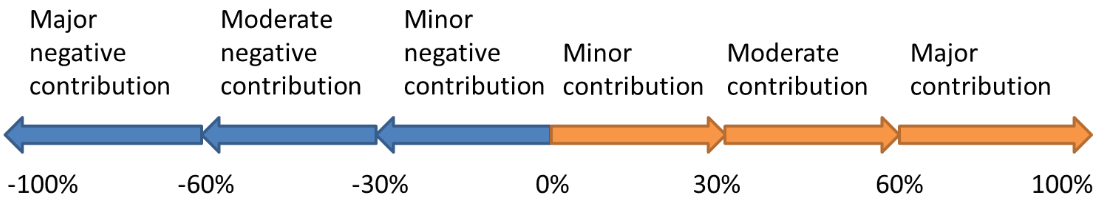


**Figure 4.10 Interpretation of the Percentage Representation**

One primary function of TCM is to convert the individual captured contributions of technology features to enterprise requirements to overall predicted fulfilment of each enterprise requirement through calculations of capabilities of technology. This conversion requires a certain set of rules that are introduced hereafter

The seven rules of TAF assessing the fulfilment of individual enterprise requirement are explained in seven examples cases. Table 4.1 to Table 4.7 contain the examples of the rules one to seven respectively. In these cases, ER1 to ER7 are seven enterprise requirements and a, b and c are three technology features of a technology. It should be noted that these cases are purely for demonstration purposes.

1. If one or more individual contributions of any technology feature to an enterprise is marked as 100% and other contributions are all positive, the overall fulfilment is predicted as 100% as fulfilled.

**Table 4.1 Rule One of TCM**

| TF / ER | a | b | c | Capability |
|---|---|---|---|---|
| ER1 | 20% | 100% | 10% | =100% |

2. If all captured contributions of the technology feature to an enterprise requirement are positive but none reaches 100%, TAF shall calculate the approximate percentage of overall fulfilment brought by the technology as the

average of the minimum and maximum of the combination of individual contributions possible. In Table 4.2, the minimum of the combination of the contribution is 70% when the contribution made by technology feature a to ER2 (20%) and the contribution made by technology feature c to ER2 (10%) are all covered by the contribution made by b to ER2 (70%). The maximum of the combination of the contribution is 100% when none of the contributions made by technology feature a, b and c overlaps with each other. Therefore, TAF predicts the approximate capability as 85% which is the average of 70% and 100%.

**Table 4.2 Rule Two of TCM**

| TF / ER | a | b | c | Capability |
|---|---|---|---|---|
| ER2 | 20% | 70% | 10% | ≈85% |

3. Similar to rule one, if one or more individual contributions of any technology feature to an enterprise is marked as -100% and other individual contributions are all negative, the capability of this technology is marked as -100% which means the technology jeopardises the fulfilment of this enterprise requirement.

**Table 4.3 Rule Three of TCM**

| TF / ER | a | b | c | Capability |
|---|---|---|---|---|
| ER3 | -20% | -100% | -10% | = -100% |

4. Similar to rule two, if all individual contributions of the technology feature are negative but none reaches - 100%, TAF shall calculate the approximate percentage as the average of the minimal and maximal of the combination of the individual contributions possible.

**Table 4.4 Rule Four of TCM**

| ER \ TF | a | b | c | Capability |
|---|---|---|---|---|
| ER4 | -20% | -70% | -10% | ≈-85% |

5. If the individual contribution percentages include 100% and -100% at the same time, TAF recognises the contribution marked as -100% has higher priority and shall mark the capability as -100%. This is because the assessment of TAF is predictive and forward-looking, therefore, the potential disadvantages of the technology shall be emphasized.

**Table 4.5 Rule Five of TCM**

| ER \ TF | a | b | c | Capability |
|---|---|---|---|---|
| ER5 | -100% | 70% | 100% | = -100% |

6. If the individual contributions of technology features include both positive and negative percentages while none reaches 100% or -100%, TAF shall first calculate the average contribution of positive items following Rule 2 (which is 75% in this example) and calculate average negative contribution of negative items following Rule 4 (which is -20% in this example). The sum of the positive and negative results is the predicted percentage of the contribution of the technology to the fulfilment of the enterprise requirement (which is 55% in this example).

**Table 4.6 Rule Six of TCM**

| ER \ TF | a | b | c | Capability |
|---|---|---|---|---|
| ER6 | -20% | 70% | 10% | ≈55% |

7. If all of the individual contributions of technology features are marked as 0%, the overall fulfilment shall be marked as 0% which is self-explanatory.

**Table 4.7 Rule Seven of TCM**

| TF / ER | a | b | c | Capability |
|---|---|---|---|---|
| ER7 | 0% | 0% | 0% | = 0% |

After predicting individual fulfilment percentages of individual enterprise requirements, TAF calculates the overall contribution of the technology to the fulfilment of the overall enterprise requirements as the sum of the products of weighted importance of individual enterprise requirements from ERM and corresponding capability percentages. In terms of the overall capability brought by the technology, TAF outputs the ratio of number of fully fulfilled enterprise requirements over overall number of enterprise requirements as an indication of the capability of this technology.

TAF also enables the calculation of the contributions made by the Natural aspect, Social aspect and Human aspect of technology separately. When calculating the contribution made by technology features based on the Natural aspect, for example, TAF ignores the technology features based on Social and Human aspects and their contributions to enterprise requirements to form a transitional TCM. This transitional TCM is used to calculate the predicted contribution that the technology features based on the Natural aspect can make. TAF calculates the contributions made by technology features based on the Social and Human aspects similarly. Such calculations are designed to determine the dominant aspect of technology out of

Natural, Social and Human aspect in terms of the fulfilment of the enterpriser requirements.

Overall, the outputs of TCM are 1) predicted overall contribution of the technology to the fulfilment of the overall enterprise requirements, 2) predicted capability ratio and 3) determination of the dominant aspect of technology. The examples of populating TCM are demonstrated in case studies of Chapter 6.

### 4.4.4 Technology Features Matrix

This section explains the Technology Feature Matrix (TFM). The specifications of TFM are results of the elaboration on the corresponding conceptual component shown in Figure 4.8 of Section 4.3.3. The MATLAB code of TAF associated with TFM is presented in Appendix 1C.

In TAF, the final matrix is the TFM that contains the captured interrelationships among the technology features. The entries of the TFM are the technology features that are grouped based on the Natural, Social and Human aspect of the technology explained in the Section 4.1 of HMT.

In terms of the elements of this matrix, only the directions of the interrelationships are required to be input if they exist due to the fact that the assessment the TAF is predictive and forward-looking. Therefore, the strengths of such interrelationships are not considered to avoid over prediction and over confidence.

The rules of TFM are explained as follows in decreasing priority order.

1. Only the upper diagonal matrix contains the information. The lower diagonal matrix should be left blank.
2. Only the interrelationships between any two technology features that at least contribute to a same enterprise requirement once shall be input to TFM. For example, if technology features ‘a’ and ‘b’ do not contribution to a particular enterprise requirement at the same time, the interrelationships between a and b, no matter whether they exist or not, shall not be marked in TFM.
3. If interrelationships do not exist between two technology features, the corresponding element of TFM should be left blank or put as ‘0’.

4. If a positive interrelationship is found, the corresponding element in TFM should be marked as ‘1’. Similarly, if a negative interrelationship is found, the corresponding element in TFM should be marked as ‘-1’. As explained previously, only the directions of the interrelationships are required.

After generating the TFM, TAF calculates the ratio of the number of all marked elements in the upper diagonal matrix over the overall number of elements in the upper diagonal matrix. This ratio serves as the indicator of the complexity of the technology. Moreover, TAF also calculates the ratio of number of marked elements that represent the interrelationship between technology features that are grouped into different aspects of technology (N/S/H) over the overall number of marked elements as the ratio of the complexity that need to be dealt by cross domain/department efforts from the enterprise. This ratio serves to indicate the cross-department complexity.

# 5 Technology Refinement and Modification Algorithm

The refinements and modifications of technologies during the technology assimilation process are vital to automotive OEMs for the further enhancement of the probability of successful assimilation. In the previous chapter, the Technology Assessment Framework (TAF) is proposed for technology assessment and supporting the decision-making involved in the technology assessment process. In this chapter, the Technology Refinement and Modification Algorithm (TRMA) is introduced that serves to support the forward-looking planning of the technology refinement and modification after the acceptance of the technology. TRMA is designed to process the gathered information in TAF in order to provide suggestions to the decision-maker on how to improve the technology for better technology assimilation results. Therefore, TRMA could potentially extend the support of decision making from TAF to later stages of technology assimilation and eventually ameliorate the effect of 'Valley of Death' in technology assimilation.

In the scope of traditional engineering, the refinement and modification of technology is either too reliant on costly physical testing and prototyping which provide numerical and quantitative data; or is over-reliant on the experiences and expertise of practitioners and experts that are difficult to codify and verify. However, in this research so far, especially in the development of TAF, the contributions of both the objectivity and subjectivity of technology assessment is acknowledged, and so developed the TAF and the methods that can accommodate and combine both. Therefore, one of the main arguments of this part of research is that the equal importance of objectivity and subjectivity should also apply to technology refinement and modification during the technology assimilation. The design aim of TRMA proposed in this chapter is to reduce the reliance on physical testing and prototyping, and also provide useful information to decision-makers in terms of the technology refinement and modification.

The major contribution of this chapter is an algorithm to evaluate technology refinement and modification in a forward-looking manner that can effectively and explicitly integrate different viewpoints to suggest and demonstrate to engineering and business professionals how to improve a technology by changing technology features and how the requirements for this specific technology may be better met within a platform or programme after the refinement and modification on the basis of information captured and produced by TAF. To achieve this, the process by which automotive Original Equipment Manufacturers (OEMs) undertake technology refinement and modification after accepting new technologies into their complex products are studied. Moreover, in order to reduce the complexity of the problem of forward-looking planning of technology refinement and modification, as one of the novel aspects of this research, Perturbation theory (179) from modern physics is reviewed and adapted to the development of TRMA.

## 5.1 Background of Technology Refinement and Modification

In this section, the background of technology refinement and modification is introduced. In addition, this section proposes the feature-based refinement and modification that is the foundation of TRMA. As mentioned previously, Perturbation Theory is adapted to the development of TRMA and this theory is also introduced and explained in this section.

### 5.1.1 Problem Identification

As mentioned previously, technology is acknowledged as a main drive of automotive OEMs in this research. A new technology can provide new capabilities on the product and therefore provide competitive advantage. However, as argued previously, this could only be true when the technology is successfully assimilated. The ‘Valley of Death’ causes uncountable loss of resource to automotive OEMs therefore many studies have been conducted to attempt to find a solution. The motivation of this part of research is to increase the survival chance of technologies that enter the ‘Valley of Death’. This part of the research aims to develop methods to support automotive OEMs to decide the general directions of technology improvement in a forward-looking manner as right directions of improvement of technology increases the successful chance of technology assimilation and reduces the cost of technology assimilation.

### 5.1.2 Feature-Based Technology Refinement and Modification

This research believes that one of the novelties of both TAF and TRMA is how they use technology features to identify and distinguish technology. By specifying the technology features of a technology, one could analyse this technology as a black box without detail analysis that requires costly and time-consuming physical tests and prototyping. As explained previously in Chapter 5, TAF contains the specified interrelationships among technology features as well as the transformations between technology features and enterprise requirements. By operating on such quantified human judgements, TAF provides assessment results and supports the decision-making in technology assessment.  Moreover, as TAF being a relational-oriented framework, by changing the above-mentioned technology features, specified interrelationships and transformations between technology features and enterprise requirements, the results provided by TAF change with them. Therefore, optimal refinement and modification solutions could be calculated based on the information provided by TAF. This idea is the foundation of the development of TRMA.

As discussed in previous chapter, each of the technology features has the potential to fulfil or jeopardize different enterprise requirements. In addition, technology features can be enhanced or reduced. For example, by increasing the technology feature of ‘engine size’ of a vehicle, potentially, the requirement of ‘performance of the vehicle’ would be fulfilled better. However, at the same time, this may jeopardize the fulfilment of, for example, the requirement for ‘coping with emission regulations and legislations. Such trade-offs are essential when planning the technology refinement and modification. By focusing on technology features instead of more detailed technology configurations, one can plan the modification and refinement at a higher level and before the costly tests and prototyping.

However, due to the interrelationships among technology features, changing one technology feature may cause other technology features to change with it. The prediction of the results of changing is vital to this feature-based refinement and modification. Therefore, this research adopts the idea of Perturbation Theory from modern physics to simplify the problem. The Perturbation Theory is introduced and explained in next section.

### 5.1.3 Perturbation Theory

In the previous chapter, as one of the criteria of TAF assessment, the approximate complexity of a technology is closely related to the interrelationships among the technology features. In order to tackle the problem of predicting the results after changing technology features, TRMA adopts the Perturbation Theory.

Perturbation theory finds approximate solutions to the problems by starting from the exact solutions of related but simpler problems. One of the most important features of this method is that the problem is broken into ‘solvable’ and ‘perturbation’ parts. This theory is ideal to apply to a problem where the problem cannot be exactly solved but can be approximated by adding perturbations to exactly solvable part of the problem which fits the abovementioned problem.

Perturbation theory leads to an expression for the desired solution in the form of a formal power series in some "small" parameters which are known as a perturbation series. Such perturbation series quantify the deviation from the exactly solvable problem. The solution of the exactly solvable problem is the leading term in this power series whereas further terms describe the deviations in the solution. Formally, the approximation to the full solution $A$ can be shown as a series in the small parameter (here called $\varepsilon$), like the following:

$$\mathrm{A} = A_0 + \varepsilon^1 A_1 + \varepsilon^2 A_2 \cdots$$

Where $A_0$ is solution of exactly solvable part of the problem which is the leading terms and $A_1, A_1 \cdots$ are the higher-order terms which may be found iteratively by some systematic procedure. Due to $\varepsilon$, higher-order terms in the series become successively smaller.

Therefore, by truncating the series, the approximate "perturbation solution" is normally obtained by keeping only the first two terms, the initial solution and the "first-order" perturbation correction, like the following:

$$\mathrm{A} \approx A_0 + \varepsilon A_1$$

Perturbation theory sets the mathematic foundation of TRMA potentially. However, the ‘small’ parameter involved in TRMA are not necessarily related to each other like $\varepsilon^1$ and $\varepsilon^2$ in equation (1). The ‘small’ parameters of higher-order terms can be defined independently based on human judgements. TRMA adopts the idea of perturbation theory but provide more flexibility to the users. The example of this difference is provided in the next section.

## 5.2 Design of Technology Refinement and Modification Algorithm

In this section, the conceptual design and the mathematical model of TRMA are introduced and explained.

As introduced in previous chapter, there are three matrices namely Enterprise Requirement Matrix (ERM), Technology Contribution Matrix (TCM) and Technology Feature Matrix (TFM) in Technology Assessment Framework (TAF). Figure 5.1 shows a simplified logic flow of TAF.

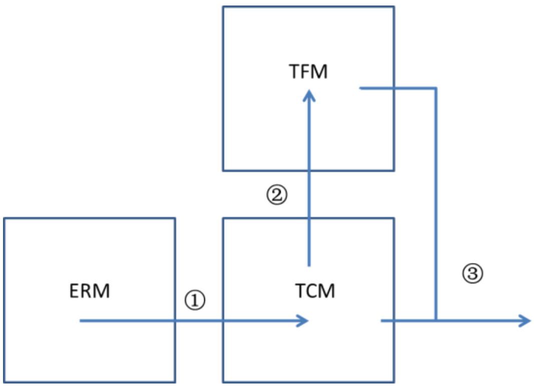


**Figure 5.1 Simplified Logic Flow of TAF**

As shown in figure 5.1, the whole TAF assessment start with ERM and the output of ERM becomes one of the inputs of TCM. After this, the TCM guides the user to populate TFM. In the end, the output of TFM and TCM form the overall assessment result.

As mentioned previously, TRMA is based on TAF and uses the information captured by TAF. However, the logic flow of TRMA is different from the logic flow of TAF as shown in figure 5.2.

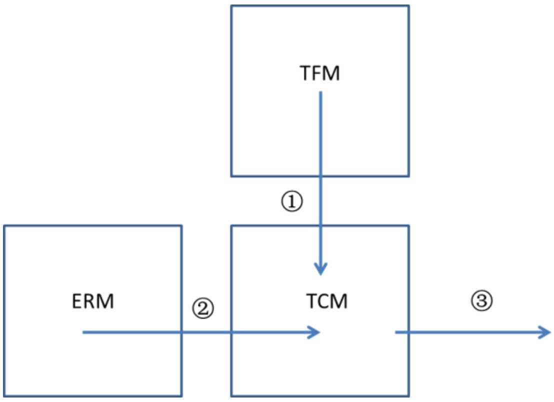


**Figure 5.2 Simplified Logic Flow of TRMA**

The first step of TRMA is to identify the interrelated technology features in the TFM. This involves the application of perturbation theory to break down the complex interrelationships into 'solvable' and 'perturbation' parts. Table 5.1 serves to help explain this application of perturbation theory.

**Table 5.1 A simple example of TFM**

| | TF1 | TF2 | TF3 | TF4 |
|---|---|---|---|---|
| TF1 | | 1 | | -1 |
| TF2 | | | 1 | -1 |
| TF3 | | | | 1 |
| TF4 | | | | |

Table 5.1 is a simple example of TFM where four technology features and five interrelationships among technology features are identified. Obviously, if the TF1 is changed, the other technology features will be changed passively due to the interrelationships. However, in TRMA, the degrees of such passive changes are recognised differently with regard to the types and orders of interrelationships. For example, the TF1 and TF2 are directly interrelated whereas TF1 and TF3 are interrelated indirectly through TF2 and TF4. Therefore, this research introduces an

application of modified perturbation theory to handle the direct and indirect interrelationships.

To be more specific, Figure 5.3 shows a tree diagram to illustrate the overall interrelationships.

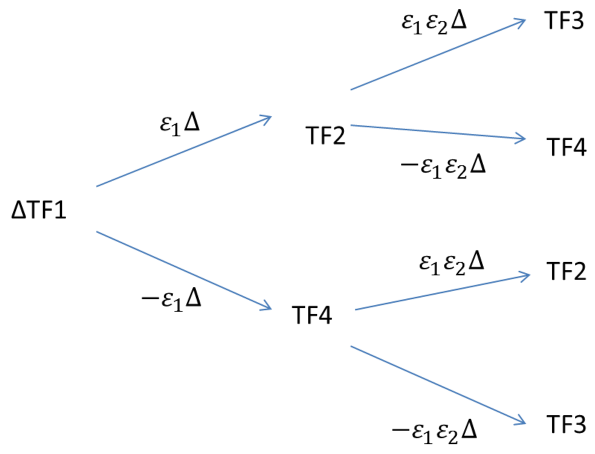


**Figure 5.3 Tree Diagram of the Interrelationships in the Example**

Due to the fact that the subsequent indirect interrelationship will have far less influence to the overall systems, they are ignored as irrelevant perturbation.

As can be seen in Figure 5.3, instead of $\varepsilon^1$ and $\varepsilon^2$ that are introduced in original perturbation theory, TRMA introduces $\varepsilon_1$ and $\varepsilon_1\varepsilon_2$ as the parameters to define the ‘perturbation’ part of the problem. This modification allows more freedom for users to define the perturbations as well as the subjectivity involved in technology assimilation and decision-making.

The results of overall changing following the change of TF1 are shown in Table 5.2 hereafter.

Table 5.2 Results of Overall Changing

| TF1 | TF2 | TF3 | TF4 |
|---|---|---|---|
| $\Delta$ | $(\varepsilon_1 + \varepsilon_1\varepsilon_2)\Delta$ | $0$ | $-(\varepsilon_1 + \varepsilon_1\varepsilon_2)\Delta$ |

Therefore, the prediction of the overall status of technology features can be made based on the approximated change of the technology features.

Before introducing the new set of technology feature after changing into the TAF, there is one key concept of TRMA that connect the change of TFM with TCM which is explain hereafter.

In this research, the individual contribution of a single technology feature made to single enterprise requirement is defined based on human judgement as explained in Chapter 5. In addition, the interpretation of percentage representations is inherited from TAF that is shown again in figure 5.4.

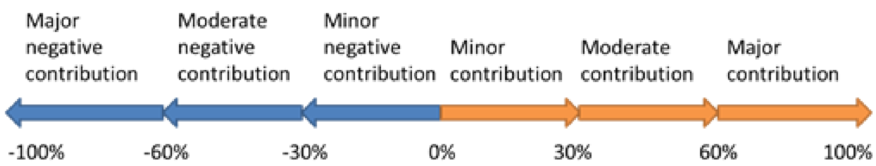


Figure 5.4 Interpretation of Percentage Representations

This interpretation is served to guide the user to translate the verbal judgment to percentage and vice versa. Based on this interpretation, Table 5.3 shows a simple TCM as an example to illustrate how the change of technology feature will influence the TCM.

**Table 5.3 Example of TCM**

| | TF1 | TF2 | TF3 | TF4 | Capability |
|---|---|---|---|---|---|
| ER1 | 50% | 0% | -70% | 30% | -5% |
| ER2 | 40% | 100% | 30% | -40% | 60% |
| ER3 | 70% | -20% | 0% | 0% | 50% |

In Table 5.3, the technology is predicted to fulfil -5%, 60% and 50% of ER1, ER2 and ER3 respectively by using the prediction method in TAF. As in Table 5.2, for the illustration purpose, $\Delta$ is set to 50% which means the TF1 is being enlarged by 50%, and $\varepsilon_1$ and $\varepsilon_2$ are set to 1 and 0.5 as first order perturbation coefficient and second order perturbation coefficient respectively.

After doing this, the results of changes of technology features shows in Table 5.4.

**Table 5.4 Changes of Technology Features in Example**

| TF1 | TF2 | TF3 | TF4 |
|---|---|---|---|
| $50\%$ | $75\%$ | $0$ | $-75\%$ |

The status of technology features after change are shown in Table 5.5

**Table 5.5 The Status of Technology Features after Change**

| TF1 | TF2 | TF3 | TF4 |
|---|---|---|---|
| $150\%$ | $175\%$ | $100\%$ | $25\%$ |

In the design of TRMA, one of the most important concepts is that the contributions made by one technology feature are assumed to be changed by the same ratio as the change of technology feature itself. For example, when TF1 is enlarged by 50%, the contribution of TF1 made to ER3 would be 105% instead of 70%, which is enlarged by 50% as well, before being capped to 100%. Similarly, when TF4 is reduced by 75%, the negative contribution of TF4 made to ER2 would be -10% instead -40% which is reduced by 75% as well. Therefore, by introducing the status of technology features after the changes that are shown in Table 5.5 into the example TCM shown in Table 5.3, the new TCM is shown in Table 5.6.

**Table 5.6 New TCM after Changes in Example**

| | TF1 | TF2 | TF3 | TF4 | Capability |
|---|---|---|---|---|---|
| ER1 | 75% | 0% | -70% | 7.5% | 8.75% |
| ER2 | 60% | 100% | 30% | -10% | 90% |
| ER3 | 100% | -35% | 0% | 0% | 65% |

As shown in Table 5.6, by enhancing TF1 by 50%, all capabilities provided by this technology are increased. When combining the individual capability with the corresponding normalised weight of enterprise requirement, the overall contribution of the technology after perturbation can be predicted. Table 5.7 is an example of results of ERM where the weights of enterprise requirements are calculated based on pairwise comparisons made under human judgment.

**Table 5.7 Example of ERM results**

| | |
|---|---|
| ER1 | 0.4 |
| ER2 | 0.2 |
| ER3 | 0.4 |

By summing the combination of the individual weight of an enterprise requirement and the corresponding capability provided by the technology, the original contribution predicted is 30% whereas the contribution predicted after enhancing TF1 by 50% is

47.5%. Therefore, for this simple example, TRMA suggests that a 17.5% increase of contribution of the technology can be expected if TF1 can be enhanced by 50%.

Currently, TRMA is designed to apply the change from -100% to 100% to all individual technology features one at a time to suggest the trends of the changes of overall contribution of technology after the change of each technology feature. -100% of the change is interpreted as completely erasing one technology feature and 100% is to double the degree of one technology feature. Apparently, -100% of the change is maximum value of reduction that is reasonable. However, technically, there should be no cap of maximum value of enlargement. Nevertheless, for symmetry results purposes, the current programming of TRMA in MATLAB limits the change range from -100% to 100%.

To fully explain the TRMA, the algorithm and process are presented in next section.

## 5.3 Technology Refinement and Modification Algorithm Workflow

In this section, the detail of Technology Refinement and Modification Algorithm (TRMA) is explained. The MATLAB code of TRMA is presented in Appendix 2.

The flow of TRMA is depicted in Figure 5.5. The first step of TRMA is to set the range of change of technology features. Normally, this research suggests setting the range of change to -100% to 100% for symmetry purpose. However, TRMA supports the user to change the enhancement ratio accordingly. Then, a change parameter is chosen within the range of change to proceed. Normally, TRMA select the change parameter from low to high. The next step of TRMA is to ask inputs from user for the first and second order perturbation coefficients. As shown in the example in the previous section, the user can set the first perturbation and second order coefficients based on tacit knowledge or experience of cases as well as quantitative test results. This finalises the preparation stage of TRMA.

After preparation, TRMA first identifies all interrelating pairs of technology features based on TFM in TAF as well as the directions of such interrelationships. All of this information is stored in a database for later use. The next step is to select one technology feature to change. Before applying the change parameter and perturbation coefficients set in preparation stage, the TRMA checks whether the selected technology feature is interrelating with any other technology feature based on the information stored in the database from the last step. If not, the TRMA applies only the change parameter set in preparation stage to corresponding column in TCM to form a new TCM. The data in this newly formed TCM is then processed by TAF to provide post-change status of this technology in terms of the overall contribution. However, if the interrelationships check identifies any interrelationship of this selected technology feature with other technology features, then the situation is more complicated and complex. This is when the adopted perturbation theory is applied to the problem.

If the selected technology feature is directly interrelating with one or more technology features, TRMA recognises them as first order interrelating technology features to the selected technology feature. All of these first order interrelating technology features are assigned with first order perturbation coefficient and the change parameter as well as the corresponding directions of interrelationships that are store in database. Then, the first order interrelating technology features of the selected technology features are checked for whether there is any further interrelating technology feature of them. If a first order interrelating technology feature has further interrelating technology features, then the further interrelating technology features are assigned with second order perturbation coefficients and change parameter as well as the corresponding directions of interrelationships, and recognised as second order interrelating technology features of the selected technology feature. In TRMA, a technology feature can be identified as the second order interrelating technology feature for the selected technology feature multiple times through interrelating with different first order interrelating technology feature. After this assigning process, all of the assigned parameters of individual technology feature other than the selected technology feature are combined to assign the corresponding change parameters of the individual technology features that are changed passively due to the change of selected technology feature. The change parameter and all of the corresponding change parameters are then applied to the corresponding column in the TCM of the TAF to form a new TCM. The data in the new TCM is then processed by TAF to produce new results of the technology after changing the selected technology feature in terms of the overall contribution. The new results are stored in the database.

As shown in Figure 5.5, TRMA loops to select new technology features as changing features until all technology features are selected. After finishing this, TRMA goes back to select a new changing parameter and follow the work flow all over again as loop until all changing parameters are selected from the range of changing set at the very beginning of TRMA workflow.

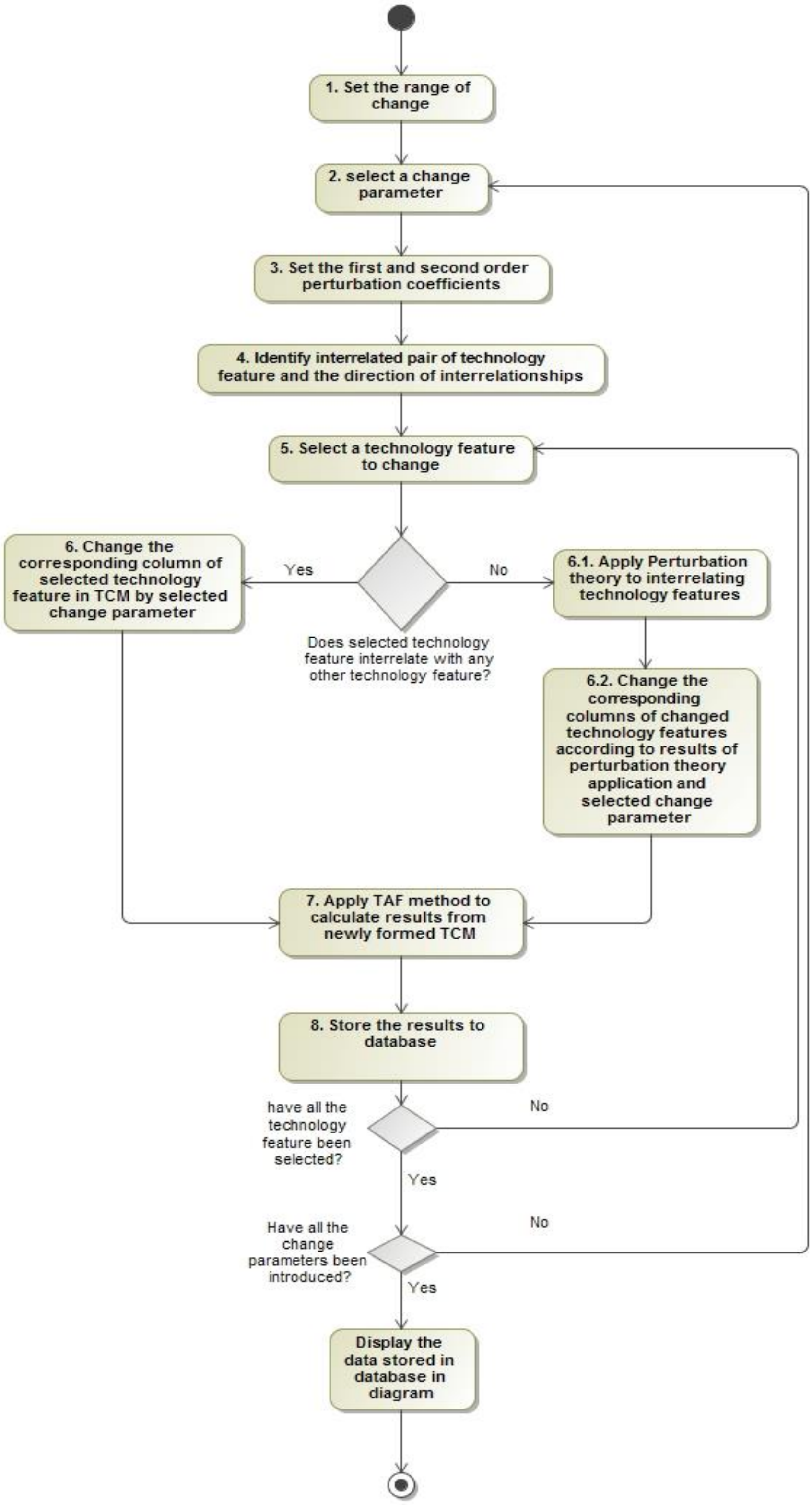


**Figure 5.5 Workflow of TRMA**

# 6 Case Studies of the Applications of Technology Assessment Framework and Technology Refinement and Modification Algorithm

In this chapter, two case studies are presented for demonstrating the overall process of proposed approach of ameliorating 'Valley of Death' which includes Technology Assessment Framework (TAF) and Technology Refinement and Modification Algorithm (TRMA). As mentioned previously, both TAF and TRMA have been programmed into MATLAB executable codes which are shown in Appendix 1 and 2. Moreover, both case studies demonstrate the method of populating TAF. These case studies also serve to preliminarily verify and validate the availability and feasibility of proposed approach of ameliorating 'Valley of Death' in technology assimilation.

The first case study is the comparative assessment between two electrical systems in modern vehicles namely Advanced Driver Assistance System (ADAS) and Autonomous Driving System (ADS) that could both potentially solve the requirements of electrical systems in automotive OEMs. The information used to conduct this case study comes from the author's understanding on the subjects, literature and industry inputs, and this case study is conducted based on a hypothetical situation. In this research, based on the expended definition of technology presented in Chapter 2, such systems are recognized as technologies. Therefore, proposed approach in this thesis should be able to apply to this assessment and the results of this case study proves this point. This case study is mainly for demonstrating the whole process of the proposed approach for ameliorating the 'Valley of Death' in technology assimilation.

The second case study includes the comparative assessment for two type of Gateway Module (GWM) architectures that involved in the design of a new distributed and service-oriented electronic architecture, referred to as Electronic Vehicle Architecture 3 (EVA3). This case study is no longer based on a hypothetical situation, instead, this case study was conducted in the collaboration with Jaguar Land Rover Limited meaning that all of the information comes from Jaguar Land Rover Limited, and the results of this case study was presented to Jaguar Land Rover Limited during the PSi Programme Steering Group Meeting, Loughborough 2017. As the final case study of this research, this case study serves as the ultimate demonstration of the proposed approach in this research. This case study is mainly for demonstrating the advantage of applying the proposed approach for ameliorating the ‘Valley of Death’ in a real-world situation.

## 6.1 Comparative Assessment Case Study of Electrical Systems on Vehicle

This case study concludes the process and results of comparative assessments of the Advanced Driver Assistance System (ADAS) and the Autonomous Driving System (ADS) by using the Technology Assessment Framework (TAF). Also, the one that has better assessment results is then being suggested refinement and modification directions by using Technology Refinement and Modification Algorithm.

This case study is based on material obtained from the literature and the author's analysis of the subject as well as industry inputs. However, the validities of such information have not been proven as this case study is aiming to be conducted based on a hypothetical situation. This research proceeds with such information due to the purpose of this case study is to demonstrate the process of technology assessment by using TAF and TRMA.

### 6.1.1 Background of Two Technologies

Advanced Driver Assistance Systems (ADAS) enables many features on modern vehicles that assist drivers on driving safely. Safety features provided by ADAS include collision avoidance, potential problem alertness and vehicle control take over in certain situations. Also, ADAS can provide adaptive features to vehicles including but not limited to automated lighting, adaptive cruise control and GPS-based traffic warnings (180,181).

The Advanced Driver Assistance Systems (ADAS) are one of many fastest-growing technologies in the scope of automotive electronics. Being a relatively mature technology, there are several industry-wide quality standards that have been adopted by the automotive industry, including but not limited to ISO 26262 (Road vehicles – Functional safety), IEEE 2020 (Image Sensor Quality) and Vehicle

Information Access API (communications protocol)(180,182). The next step of ADAS development includes the wireless network connective based on V2V (Vehicle to Vehicle) and V2X (Vehicle to Infrastructure) data (180,183).

While ADAS changes the way of driving and transportation on an incremental basis, the second technology for assessment in this case study namely Autonomous Driving System (ADS) has the potential to change road transportation fundamentally (184). The U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA) suggests a five-step continuum which conceptualizes the different levels of automation of vehicles (184). Based on this continuum, ADAS pushes the automation of vehicle from level 0 to level 2 and ADS achieves automation levels of 3 and 4. Even though some argue that ADS evolved from ADAS, but ADS is in many ways a revolutionary approach, using advanced technologies such as machine learning (185). Therefore, this case study recognizes ADAS and ADS as two distinct technologies and ignores the possible connections between these two.

As mentioned previously, this case study is conducted based on a hypothetical situation and adopts the perspectives of a hypothetical automotive enterprise. Due to the fact that this case study is for demonstrating TAF and TRMA and the populating methods, this hypothetical automotive enterprise does not imply any real enterprise of automotive OEMs. Moreover, this research believes that the majority of enterprises in any industry is in the market follower position which has limited resources (186,187). Therefore, this hypothetical automotive enterprise is a market follower meaning the perspectives of this enterprise is based on being in a market follower position. This enterprise has a set of enterprise requirements that both technologies (ADAS and ADS) have the potential to fulfil. Therefore, the TAF is being applied to this assessment task to identify which technology should be assimilated by this hypothetical automotive enterprise in order to achieve its overall goals.

### 6.1.2 Enterprise Requirements for Automobile Electronics Systems

Due to resource constraints, the number of enterprise requirements related to automobile electronics systems collected from the literature and practitioners are limited to nine. Each enterprise requirement listed and explained here after is given a serial number. However, the serial number of each enterprise requirement in this section does not represent the ranking of requirement.

ER1. Safety: The assimilated technology should be safe to use for all potential customers. Also, the assimilated technology should not hinder the overall safety level of the product. Potential customers include the disabled and elderly, as well as the fit and able-bodied.

ER2. User-friendly: The assimilated technology should be user-friendly. Therefore, the new functions that this technology provides must suit a wide potential customers group.

ER3. Affordability**:** The assimilated technology should be affordable to the enterprise. Not only should the technology itself be affordable in terms of purchase or development cost, but also the overall process of assimilation of the technology should be affordable.

ER4. Provide new feature: The assimilated technology should be able to provide new features to the product. Therefore, the price of the product can potentially be increased. Also, the potential market share of the product can be increased.

ER5. Development cycle: The development cycle of the assimilated technology should be as short as possible. Therefore, the overall time before the launch of the product can be shortened.

ER6. Integration: The assimilated technology should be to be integrated with the existing product or manufacturing process. The enterprise should be able to manage the difficulties and complexity of the integration process.

ER7. Law and legislation: The assimilated technology should be in line with current laws and legislations and preferably be supported by laws and legislations. Also, the assimilated technology should support the overall product to comply with the increasingly stringent emission legislation.

ER8. Low failure probability: The assimilated technology should not reduce the product reliability. Also, the assimilation failure probability of the technology should be as low as possible. In other words, the selected technology should have a higher probability to survive through the 'Valley of Death'.

ER9. Corporate image: Preferably, the assimilated technology should enhance the corporate image. The corporate image is arguably a broad concept so that this requirement does not specify.

As shown in Table 6.1, the pairwise comparisons are made by the author based the perspectives of the decision-maker from the hypothetical automotive enterprise in this case study.

The weights of enterprise requirements are associated elements of the normalised eigenvector of this matrix. The results are shown in Table 6.2 after ranking.

The inconsistency ratio of this matrix is 12.3% which is not ideal from the point of view of AHP. However, since 12.3% is not greatly excess of 10%, the human judgments involved in this ERM are deemed valid in this case study. For nine enterprise requirements, the author believes that this result is good enough and chooses to proceed.

**Table 6.1 ERM of Case Study One**

| | ER1 | ER2 | ER3 | ER4 | ER5 | ER6 | ER7 | ER8 | ER9 |
|---|---|---|---|---|---|---|---|---|---|
| ER1 | 1 | 3 | 1 | 1 | 1 | 1 | 1 | 1 | 3 |
| ER2 | 1/3 | 1 | 1 | 3 | 3 | 3 | 1/7 | 1/7 | 5 |
| ER3 | 1 | 1 | 1 | 3 | 1 | 1 | 1/7 | 1/5 | 3 |
| ER4 | 1 | 1/3 | 1/3 | 1 | 1/3 | 1/3 | 1/7 | 1/5 | 1 |
| ER5 | 1 | 1/3 | 1 | 3 | 1 | 1 | 1/7 | 1/5 | 1 |
| ER6 | 1 | 1/3 | 1 | 3 | 1 | 1 | 1/9 | 1 | 3 |
| ER7 | 1 | 7 | 7 | 7 | 7 | 9 | 1 | 3 | 7 |
| ER8 | 1 | 7 | 5 | 5 | 5 | 1 | 1/3 | 1 | 5 |
| ER9 | 1/3 | 1/5 | 1/3 | 1 | 1 | 1/3 | 1/7 | 1/5 | 1 |

**Table 6.2 Weights and Ranks of ERs in Case Study One**

| Ranked enterprise requirements | Weights |
|---|---|
| ER7 | 0.3446 |
| ER8 | 0.1940 |
| ER1 | 0.1182 |
| ER2 | 0.0865 |
| ER6 | 0.0734 |
| ER3 | 0.0651 |
| ER5 | 0.0538 |
| ER4 | 0.0349 |
| ER9 | 0.0296 |

### 6.1.3 Technology Features of ADAS

In this section, the respective features of ADAS are listed and explained.

a) *High Technology Readiness Level*: As a relatively mature technology, some ADAS has reached high technology readiness levels (TRLs) in general. For a technology with high TRLs, the performance is more likely to be valid and the development risks are reduced.

b) *Coupling*: In this case study, ADAS is recognised as a collection of different components that can function independently. As a system, ADAS has lower coupling than ADS.

c) *Different forms of ADAS available*: there are different forms of ADAS on the market that already as different types of end products.

d) *Reliance on ECUs*: The functions and quality of ADAS rely heavily on Electronic Control Unit (ECUs). ECUs process the data from sensors and give commands to vehicle systems.

e) *Reliance on sensors*: ADAS relies on sensors on the vehicle for data input. Based on different ADAS sub systems, the sensors are different including but not limited to camera, ultrasonic, RADAR and LIDAR.

f) *Multiple standards exist*: As mentioned in the background section of the case study, there are many standards that guide the design and manufacture of the ADAS. As a trend, the number and types of such standards are increasing.

g) *Cost*: Cost is a feature for almost every technology that is contributed to by many factors. For this case study, the cost of ADAS is recognised as relatively lower than that of ADS.

h) *Provide situational awareness*: As a main feature of ADAS, situation awareness is provided to the driver of a vehicle equipped with ADAS.

i) *Keep driver engaged*: ADAS requires the driver to remain engaged with the vehicle even though ADAS can help the driver to make some decisions when driving. Based on the five-step continuum suggested by NHTSA, this feature separates ADAS from ADS.

Nine technology features of ADAS have been identified above. The technology features from a) to e) reflect the Natural aspect of ADAS. Similarly, the technology features f) and g) reflect the Social aspect of ADAS and technology features h) and i) reflect the Human aspect of ADAS.

### 6.1.4 Technology Features of ADS

In this section, the respective features of ADS are listed and explained.

a) *Low Technology Readiness Levels*: ADS is a technology that is under development by the automotive industry, the technology readiness levels of ADS are still low. The industry needs to wait for some time longer before the ADS can be mass produced and validated, even though some prototypes of ADS have been tested.

*b) Able to fully take over the vehicle:* As a main feature of ADS, a vehicle can be fully controlled by the ADS when the driver wants to disengage.

*c) Reliance on environmental data*: As mentioned in the previous section, ADS is a technology that can be recognised as a step further than ADAS. Although this case study treats ADS and ADAS as two different technologies, ADS is still a more advanced technology concept at least. Therefore, other than ECU and sensor, ADS rely on environmental data heavily. Moreover, some road or city infrastructures need to be built before vehicles equipped with ADS can be on the road and be fully autonomous.

d) *Reliance on ECUs*: Similar to the requirement d) of ADAS

e) *Reliance on sensors*: Similar to the requirement e) of ADAS

f) *Cost*: The definition of this feature is similar to the requirement g) of ADAS. However, this case study recognises that the cost of ADS is higher than the cost of ADAS.

g) *Potential to fundamentally change road transportation*: ADS has the potential to fundamentally change transportation and the way people drive.

h) *Requirement for human-machine collaboration*: ADS should allow the human driver to disengage from driving as well as to reengage. Therefore, human-machine collaboration is required as a switching mechanism that affects the user experience heavily.

i) *Disengagement of driver*: The fact that driver can disengage from driving in a vehicle that is equipped with ADS can be a very attractive feature of this technology. This is a main feature provided by ADS in terms of the Human aspect of ADS.

Nine technology features of ADS have been identified. The technology features from a) to e) of ADS reflect the Natural aspect of ADS. Similarly, the technology features f) and g) reflect the Social aspect of ADS and technology features h) and i) reflect the Human aspect of ADS.

### 6.1.5 Technology Contribution Matrix of ADAS and ADS

After specifying the technology features for both technologies, the case study proceeds by applying TAF to the ADAS and ADS assessment.

Table 6.3 and Table 6.4 demonstrate the TCMs of ADAS and ADS assessment of technology capability based on the author’s understanding of the subjects.

**Table 6.3 TCM of ADAS**

| | N | | | | | S | | H | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1a | 1b | 1c | 1d | 1e | 1f | 1g | 1h | 1i | Capability |
| ER7 | | | 20% | | | 100% | | | | =100% |
| ER8 | 50% | 30% | 20% | -30% | -30% | 70% | 30% | | | ≈55% |
| ER1 | 20% | 40% | 40% | -20% | -20% | 50% | | 80% | | ≈100% |
| ER2 | 10% | | -10% | | | | | 50% | 70% | ≈90% |
| ER6 | 40% | -30% | 50% | | -20% | | | | | ≈30% |
| ER3 | 10% | | 80% | -10% | -20% | | 60% | | | ≈90% |
| ER5 | 60% | | 50% | -10% | | | | | | ≈75% |
| ER4 | | 100% | | | | | | 30% | | =100% |
| ER9 | | | | | | 20% | | 20% | | ≈30% |

**Table 6.4 TCM of ADS**

| | N | | | | | S | | H | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2a | 2b | 2c | 2d | 2e | 2f | 2g | 2h | 2i | Capability |
| ER7 | | 60% | -10% | | | | 70% | | | ≈90% |
| ER8 | -50% | | | -30% | -30% | -20% | | -10% | | ≈-95% |
| ER1 | | 100% | -20% | -20% | -20% | | | -30% | 100% | ≈90% |
| ER2 | | 100% | | | | 20% | 30% | 30% | 100% | =100% |
| ER6 | -40% | | | - | -20% | | | | | ≈-30% |
| ER3 | -30% | | | -20% | -10% | -70% | | | | ≈-100% |
| ER5 | -70% | | -20% | -10% | | | | -30% | | ≈-100% |
| ER4 | | 100% | | | | | 50% | 30% | 100% | =100% |
| ER9 | 20% | 100% | 10% | | | 20% | 70% | 20% | 50% | =100% |

Based on the capability results in Table 6.3 and 6.4 as well as the weights of individual enterprise requirement shown in Table 6.2, the potential contribution of ADAS and ADS to the fulfilment of the overall enterprise requirements can be calculated as the sum of the products of weighted importance of individual enterprise requirements and corresponding capability percentages. For first level contribution assessment, the potential overall contributions of ADAS and ADS to the fulfilment of the overall enterprise requirements are 81.2% and 24.2% respectively which are calculated based on the explanation in Section 4.4.3. This suggests that from contribution viewpoint, ADAS is a better option than ADS for this hypothetical automotive enterprise.

In terms of the contributions made by Natural, Social and Human aspects of two technologies, the respective contributions made by Natural, Social and Human aspect of ADAS are 31.1%, 61.3% and 19.3% whereas the respective contributions made by Natural, Social and Human aspect of ADS are 12.7%, 23.3% and 18.6%. In terms of second level contribution assessment, the ratios of the respective contributions over the overall contribution of ADAS are 38.3%, 75.5% and 23.8% whereas the ratios of the respective contributions over the overall contribution of ADS are 52.4%, 96.1% and 76.7%. This suggests that the dominance aspects of both ADAS and ADS are Social aspects. Based on the interpretation of Social aspect of technology in this research, TAF suggest that both ADAS and ADS require relatively more effort on organisation management and communication across departments. Also, due to the dominant position of Social aspects of ADAS and ADS, the law and legislation have relatively bigger impacts on the technology assimilation of both technologies that may further influence the end products.

Moreover, as shown in Table 6.3 and Table 6.4, both ADAS and ADS have the capabilities to fulfil three enterprise requirements completely. Based on the TAF assessment and prediction, ADAS and ADS both fulfil three out of nine (33.3%) capabilities required by the enterprise from capability viewpoints.

### 6.1.6 The Complexity Assessment of ADAS and ADS

Table 6.5 and Table 6.6 demonstrate the TFMs for ADAS and ADS respectively.

**Table 6.5 TFM of ADAS**

| | 2a | 2b | 2c | 2d | 2e | 2f | 2g | 2h | 2i |
|---|---|---|---|---|---|---|---|---|---|
| 2a | | | | | | -1 | 1 | | |
| 2b | | | | | | | | | 1 |
| 2c | | | | 1 | 1 | 1 | | | |
| 2d | | | | | 1 | 1 | | | |
| 2e | | | | | | 1 | | | |
| 2f | | | | | | | -1 | | |
| 2g | | | | | | | | | 1 |
| 2h | | | | | | | | | |
| 2i | | | | | | | | | |

**Table 6.6 TFM of ADS**

| | 1a | 1b | 1c | 1d | 1e | 1f | 1g | 1h | 1i |
|---|---|---|---|---|---|---|---|---|---|
| 1a | | | 1 | | | | -1 | | |
| 1b | | | | 1 | 1 | | -1 | | |
| 1c | | | | | | | -1 | | |
| 1d | | | | | 1 | | 1 | | |
| 1e | | | | | | | 1 | | |
| 1f | | | | | | | | | |
| 1g | | | | | | | | | |
| 1h | | | | | | | | | |
| 1i | | | | | | | | | |

For first level complexity assessment, as shown in Table 6.5 and Table 6.6, ADAS has nine interrelationships identified out of 36 potential interrelated feature pairs (25%) among technology features while ADS has 11 out of 36 (30.5%).

Moreover, for second level complexity assessment, five out of those nine interrelationships identified among the technology features of ADAS (55.5%) are interrelationships between features from different aspects (Natural, Social and Human) of technology. Such interrelationships may require cross-department collaboration within the enterprise to deal with. The equivalent ratio for ADS is seven out of 11 (63.6%).

### 6.1.7 Summary of TAF Assessments between ADAS and ADS

The Case Study demonstrates the technology assessment process by using TAF. The results are summarised hereafter.

Based on the TCMs of ADAS and ADS, the contribution assessment results are shown in Figure 6.1 and Figure 6.2.

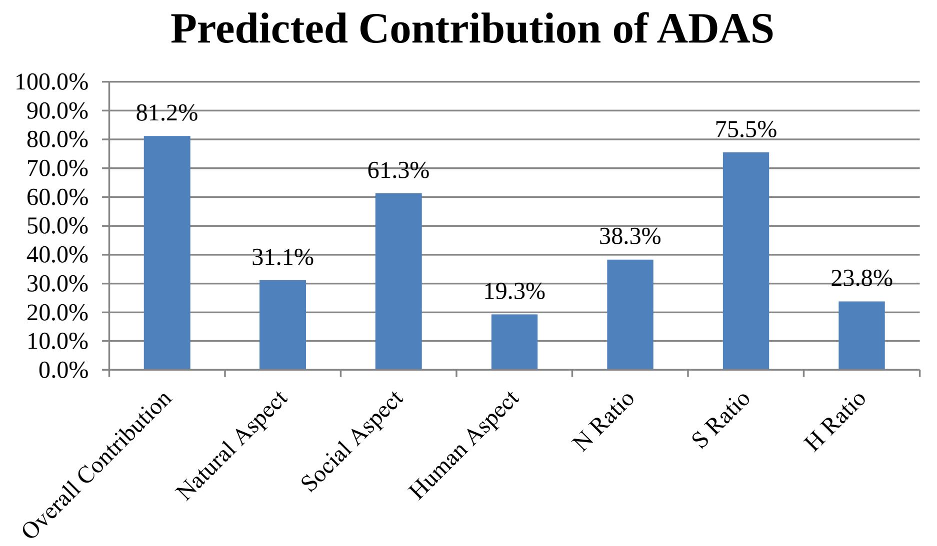


**Figure 6.1 Contribution Assessment Results of ADAS**

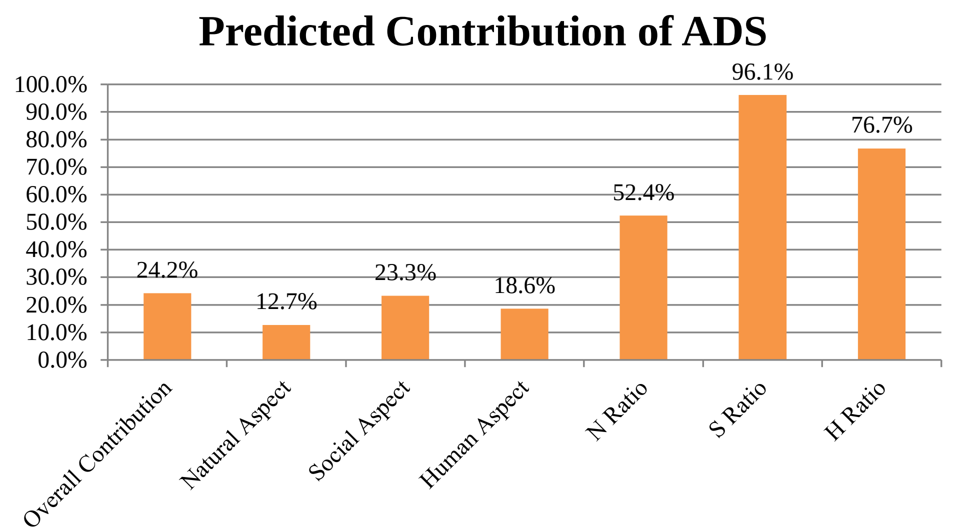


**Figure 6.2 Contribution Assessment Results of ADS**

Based on the interpretation of the percentage representation shown in Figure 5.4 and the results shown in Figure 6.1, ADAS is predicted to be able to make major contribution to the fulfilment of the overall enterprise requirements as the first level rewards assessment of TAF assessment. At the same time, based on Figure 5.4 and Figure 6.2, ADS is predicted to be able to make a minor contribution to the fulfilment of the overall enterprise requirements as the first level rewards assessment of TAF assessment. For second level rewards assessment, both technologies depend the most on the Social aspect suggesting that the success of assimilating these two technologies may require the enterprise to have the collaboration between departments and the support of the legislations and regulations.

The capability assessment results are shown in Figure 6.3. Both technologies fulfil 3 out of 9 (33.3%) capabilities required by the enterprise. The reason behind different results from contribution viewpoint and capability viewpoints is the different weights of enterprise requirements. ADAS has better capability to fulfil the enterprise requirements that are in higher ranks and have heavier weights.

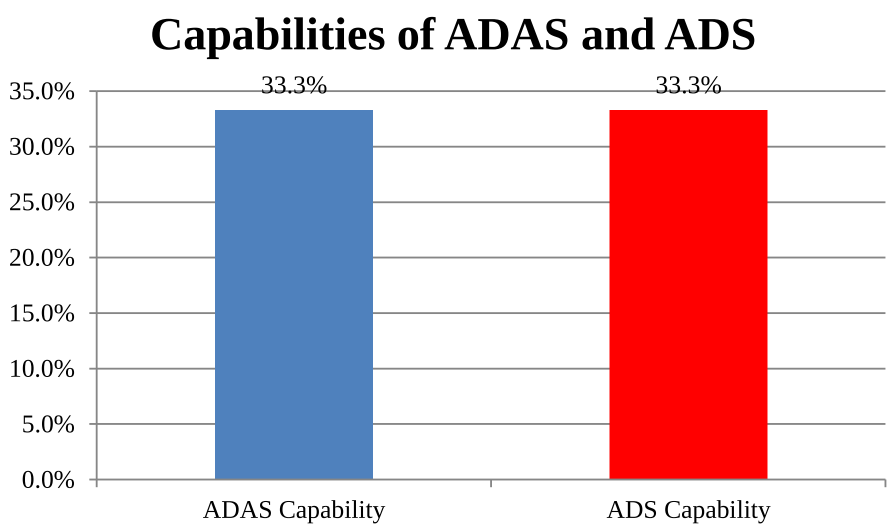


**Figure 6.3 Capability Assessment results for ADAS and ADS**

Last but not least, the complexity assessment results of ADAS and ADS are shown in Figure 6.4. Based on the results, as the first level risk assessment of TAF, ADAS is predicted to have less complexity than ADS. According to the second level risk assessment, ADAS is predicted to require less cross-department collaborations to handle the complexity than ADS.

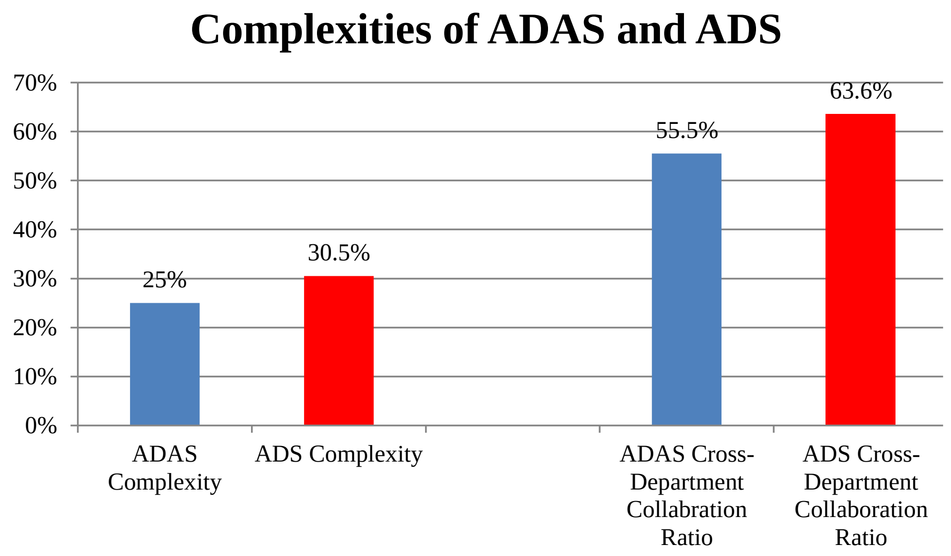


**Figure 6.4 Complexity Assessment Results for ADAS and ADS**

Based on the results and analyses, TAF suggests ADAS is a better choice of assimilation than ADS based on the holistic viewpoint facilitated by TAF. Therefore, TRMA is applied to ADAS to suggest directions of refinement and modification as ADAS is selected in this case study.

### 6.1.8 Refinement and Modification for ADAS

As explained previously, TRMA generates results by using the data from TAF assessment. The programme of TRMA reads the data and produces the results on the trends of changes of overall contribution of technology caused by different degree of changes of different technology features. The TRMA results for ADAS are shown in Figure 6.5.

As shown in Figure 6.5, ADAS could potentially provide a noticeably better overall contribution by reducing the degree of technology features 2, 4, 5 and 7. Technology features 2, 4, 5, 7 are *Coupling, Reliance on ECUs, Reliance on sensors* and *Cost*. The interpretations of such suggestions are provided as follow.

1. By reducing the degree of coupling of the systems in ADAS, the level of independence among different components increases and the possibility of full system break down decreases.
2. By reducing the reliance of ADAS on ECUs, ADAS could avoid malfunctions even if some ECUs are broken.
3. By reducing the reliance of ADAS on sensors, similarly, ADAS could be functional even if some sensors stop working.
4. By reducing the cost of ADAS, ADAS is easier to be assimilated into existing platform and product, and hence the probability of successful assimilation could be increased.

One of the strengths of TRMA is that the suggestions provided are final as the decision-maker does not need to further consider the trade-off and consequence by following suggestions of refinement and modification. This is because this algorithm considers all the interrelationships before providing the suggestions.

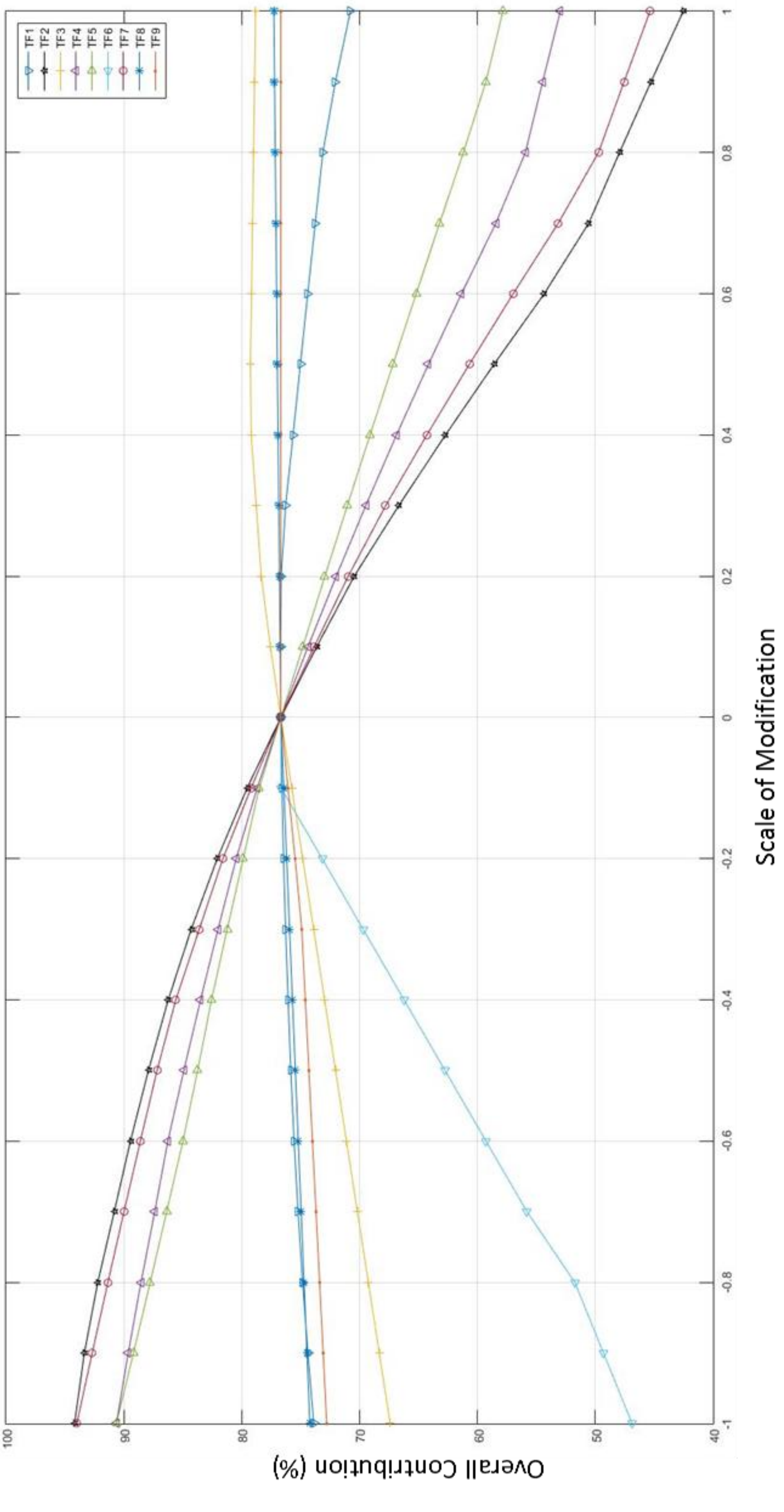


**Figure 6.5 TRMA results for ADAS**

## 6.2 Comparative Assessment Case Study of Centralized and Distributed Gateway Module Architecture

This case study concludes the process and results of the comparative assessments of Centralised Architecture and Distributed Architecture of Gateway Module (GWM) Architecture by using Technology Assessment Framework (TAF) and Technology Refinement and Modification Algorithm (TRMA). Unlike the previous case study, the data and information involved in this case study are all provided by Jaguar Land Rover Limited. The results of this case study were presented at the PSi Programme Steering Group Meeting, Loughborough 2017 that organized by Jaguar Land Rover Limited.

### 6.2.1 Background

EVA3 is aimed to replace Electronic Control Units (ECUs) to reduce ECUs purchasing cost and accelerate deployment, as well as to provide better control of implementation of new vehicle features, and ultimately provide a competitive edge.

In this particular case study, two types of GWM architectures are under assessment. The purpose of this case study is to provide suggestions on which type of GWM architecture is better for fulfilling the enterprise requirements while demonstrating the strength of both TAF and TRMA over the traditional approaches that are currently used by automotive OEMs.

Before the involvement of this PhD research to this project of technology assessment, an assessment of these two GWM architecture was conducted by traditional approaches by the automotive OEM partner. The documents that may contain confidential information are presented in Appendix 3 and 4.

### 6.2.2 Enterprise Requirements for GWM Architecture

As shown in Figure 6.6, ten key attributes of GWM that should be enabled by the GWM architecture are defined by Jaguar Land Rover Limited.

| Sl No | Key Attributes | Definition |
|---|---|---|
| 1 | Latency | Latency is the time delay in the transfer of data from source ECU to the destination ECU.<br>- Millisecond (ms) |
| 2 | Memory Usage | Memory consumed for the execution of the GWM function .<br>- Percentage of Total Memory (%) |
| 3 | Footprint Size | Storage space required for the installation of GWM feature.<br>- MB (MegaByte) / GB (GigaByte) |
| 4 | CPU Usage | Processor usage for the execution GWM feature .<br>- Percentage of Total Processor capacity (%) |
| 5 | Computing Power | Processor speed required for the implementation of the GWM feature.<br>- MegaHertz(MHz) |
| 6 | Deterministic | Deterministic routing is the advance determination of the routes between given pairs of ECUs - Complete end-to-end deterministic forwarding path |
| 7 | Fault Tolerance | Enables a system to continue operating properly in the event of the failure of (or one or more faults within) some of its components.<br>A fault-tolerant system is designed to avoid total |
| 8 | Routing Table | Routing Table is the data table that holds the routes to particular network destinations and metrics associated with those routes. |
| 9 | Cost | Cost of implementation of GWM functionality<br>Total Cost can include the cost of Gateway ECU,MCUs, tranceivers, Communication cables etc |
| 10 | Diagnostic Process Complexity | Complexity of processing diagnostic related functionalities by the gateway module, |

**Figure 6.6 Key Attributes of GWM Architectures Defined by Industry**

The enterprise requirements for the GWM architecture listed and explained hereafter are the results of re-interpretation of key attributes of GWM.

Note: the number of each enterprise requirement does not represent the ranking

ER1. **Low latency**: the functional architecture should enable low latency time in the transfer of data from source ECU to the destination ECU.

ER2. **Low Memory Usage**: the functional architecture should enable low memory consumption for the execution of the GWM function.

ER3. **Low Footprint Size**: the functional architecture should enable low storage space required for the installation of GWM feature

ER4. **Low CPU Usage**: the functional architecture should enable low processor usage for the execution GWM feature

ER5. **Low Computing Power Required**: the functional architecture should enable low processor speed required for the implementation of the GWM feature.

ER6. **Deterministic**: the functional architecture should enable deterministic routing that is the advance determination of the routes between given pairs of ECUs - Complete end-to-end deterministic forwarding path

ER7. **Fault Tolerance**: the functional architecture should enable the system to continue operating properly in the event of the failure of (or one or more faults within) some of its components.

ER8. **Simple Routing Table**: the functional architecture should enable simple routing table is the data table that holds the routes to particular network destinations and metrics associated with those routes.

ER9. **Low Cost**: the functional architecture should enable low cost of implementation of GWM functionality. Total cost includes the cost of Gateway ECU, transceivers, communication cables etc.

ER10. **Low Diagnostic Process Complexity**: the functional architecture should enable low complexity of processing diagnostic related functionalities by the gateway module.

### 6.2.3 Enterprise Requirement Matrix

The first step of the application of TAF is to form the Enterprise Requirement Matrix (ERM) that contains the pair-wise comparison in terms of relative importance between each pair of enterprise requirements. The outcomes of this matrix are ranked enterprise requirements and their respective normalized weights.

The TAF has partially adopted the Analytic Hierarchy Process (AHP) to rank the enterprise requirement that requires pair-wise comparisons of the relative importance between each pair of enterprise requirements.

In this section, two sets of TFM are formed based on different sets of data. The first TFM is based on reverse analysed data from the original assessment of GWM, and the second TFM is based on two responses of questionnaires from Jaguar Land Rover Limited experts. The results from both TFM should reflect the some of the strengths of TAF.

As show in Table 6.7, weightings are assigned to the key attributes by Jaguar Land Rover Limited.

**Table 6.7 Weights of Key Attributes**

| SI No | Key Attributes | Weightage |
|---|---|---|
| 1 | Latency | 5 |
| 2 | Memory Usage | 4 |
| 3 | Footprint Size | 3 |
| 4 | CPU Usage | 4 |
| 5 | Computing Power | 5 |
| 6 | Deterministic | 3 |
| 7 | Fault Tolerance | 5 |
| 8 | Routing Table | 3 |
| 9 | Cost | 3 |
| 10 | Diagnostic Process Complexity | 4 |

In order to generate the pair-wise comparisons of importance, this research attempt to translate the weight differences from Table 6.7 to the intensities of importance that represents the pair-wise comparisons of importance. This translation is shown in Table 6.8.

**Table 6.8 Translation between Weight Difference to Intensity of Importance**

| Weight Difference | Intensity of Importance |
|---|---|
| 0 | 1 |
| 1 | 3 |
| 2 | 5 |

Several pairs of key attributes have the same weights shown in Table 6.7, for example ‘Latency’ and ‘Fault Tolerance’, hence their weight difference is zero meaning they are equally important to GWM. If the weight difference is one, this case study identifies the key attribute with heavier weight is moderately more important than the key attribute which has the lighter weight and assigns the number ‘3’ to this pair-wise comparison of importance. Similarly, If the weight difference is two, this case study identifies the key attribute with the heavier weight is strongly more important than the key attribute which has lighter weight and assigns the number ‘5’ to this pairwise comparison of importance.

Based on this translation of weight differences to the intensities of importance of pairwise comparisons, the ERM can be formed from the reversed analysis of original assessment conducted by Jaguar Land Rover Limited. This ERM is shown in Table 6.9.

Table 6.9 ERM from Reversed Analysis of Original Assessment

| | ER1 | ER2 | ER3 | ER4 | ER5 | ER6 | ER7 | ER8 | ER9 | ER10 |
|---|---|---|---|---|---|---|---|---|---|---|
| ER1 | 1 | 3 | 5 | 3 | 1 | 5 | 1 | 5 | 5 | 3 |
| ER2 | 1/3 | 1 | 3 | 1 | 1/3 | 3 | 1/3 | 3 | 3 | 1 |
| ER3 | 1/5 | 1/3 | 1 | 1/3 | 1/5 | 1 | 1/5 | 1 | 1 | 1/3 |
| ER4 | 1/3 | 1 | 3 | 1 | 1/3 | 3 | 1/3 | 3 | 3 | 1 |
| ER5 | 1 | 3 | 5 | 3 | 1 | 5 | 1 | 5 | 5 | 3 |
| ER6 | 1/5 | 1/3 | 1 | 1/3 | 1/5 | 1 | 1/5 | 1 | 1 | 1/3 |
| ER7 | 1 | 3 | 5 | 3 | 1 | 5 | 1 | 5 | 5 | 3 |
| ER8 | 1/5 | 1/3 | 1 | 1/3 | 1/5 | 1 | 1/5 | 1 | 1 | 1/3 |
| ER9 | 1/5 | 1/3 | 1 | 1/3 | 1/5 | 1 | 1/5 | 1 | 1 | 1/3 |
| ER10 | 1/3 | 1 | 3 | 1 | 1/3 | 3 | 1/3 | 3 | 3 | 1 |

Table 6.9 contains the pairwise comparisons of enterprise requirements reinterpreted from the key attributes from the original assessment of GWM architectures based on the weights of key attributes and the translation from weight differences to intensities of importance described above.

Based on the data in Table 6.9, the ranking and weight assignment results from TAF are shown in Table 6.10 and Figure 6.7.

**Table 6.10 ERM results from Table 6.9**

| Rank | enterprise requirements | Weights |
|---|---|---|
| 1 | ER1 | 0.2028 |
| 1 | ER5 | 0.2028 |
| 1 | ER7 | 0.2028 |
| 2 | ER2 | 0.0854 |
| 2 | ER4 | 0.0854 |
| 2 | ER10 | 0.0854 |
| 3 | ER3 | 0.0338 |
| 3 | ER6 | 0.0338 |
| 3 | ER8 | 0.0338 |
| 3 | ER9 | 0.0338 |

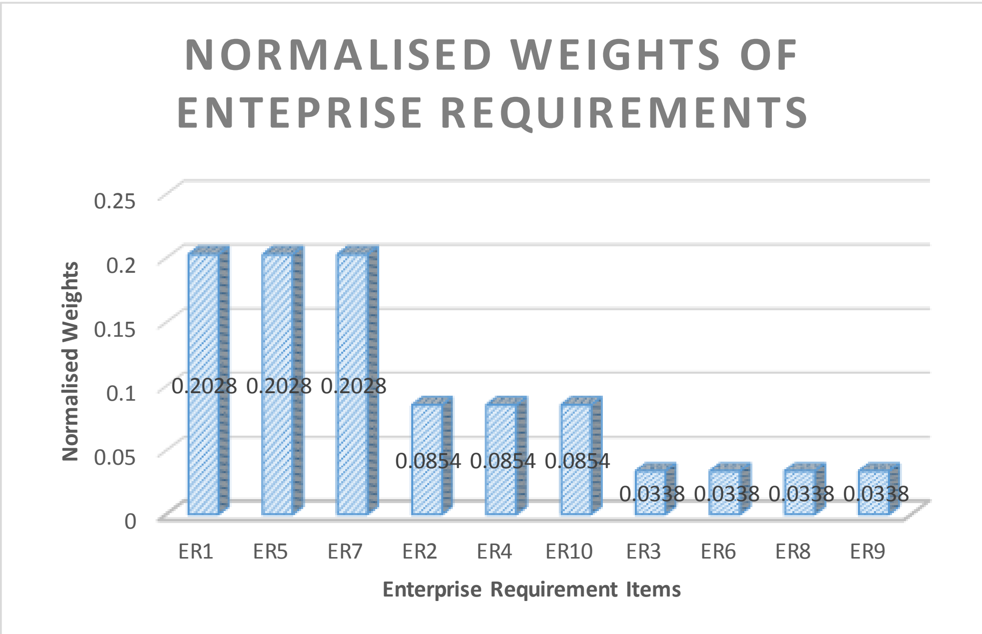


**Figure 6.7 Results of ERM from original assessment**

Based on the results shown in Table 6.10 and Figure 6.7, TAF is proven to be able to incorporate traditional method as the ranking are the same as the original assessment results. However, this ranking is not distinguishable as only three levels of ranks are identified.

The second ERM, as mentioned previously, is formed based on two responses of questionnaires that were conducted based on the TAF method. Therefore, the second ERM, which is shown in Table 6.10, can be recognised as the ERM based on the TAF method.  The responses of questionnaires are presented in Appendix 4 where blue and yellow highlighting represent two responses from JLR engineers.

Based on the responses of questionnaires, the ERM from TAF method is formed. This ERM is shown in Table 6.11.

**Table 6.11 ERM from TAF method**

| | ER1 | ER2 | ER3 | ER4 | ER5 | ER6 | ER7 | ER8 | ER9 | ER10 |
|---|---|---|---|---|---|---|---|---|---|---|
| ER1 | 1 | 5 | 5 | 2 | 3 | 2 | 2 | 3 | 2 | 3 |
| ER2 | 1/5 | 1 | 1/3 | 1/5 | 1/5 | 1/5 | 1/2 | 1/2 | 3 | 1/2 |
| ER3 | 1/5 | 3 | 1 | 1/6 | 1/6 | 1/5 | 1/5 | 1/5 | 1 | 1/4 |
| ER4 | 1/2 | 5 | 6 | 1 | 2 | 1 | 1/2 | 4 | 1/2 | 4 |
| ER5 | 1/3 | 5 | 6 | 1/2 | 1 | 3 | 1/2 | 2 | 1 | 2 |
| ER6 | 1/2 | 5 | 5 | 1 | 1/3 | 1 | 1/4 | 1/4 | 1/4 | 1/4 |
| ER7 | 1/2 | 2 | 5 | 2 | 2 | 4 | 1 | 5 | 4 | 4 |
| ER8 | 1/3 | 2 | 5 | 1/4 | 1/2 | 4 | 1/5 | 1 | 1/4 | 1/3 |
| ER9 | 1/2 | 1/3 | 1 | 2 | 1 | 4 | 1/4 | 4 | 1 | 1 |
| ER10 | 1/3 | 2 | 4 | 1/4 | 1/2 | 4 | 1/4 | 3 | 1 | 1 |

Based on the data in Table 6.11, the ranking and weight assignment results from TAF are shown in Table 6.12 and Figure 6.8.

**Table 6.12 results from ERM shown in Table 6.11**

| Rank | enterprise requirements | Weights |
|---|---|---|
| 1 | ER7 | 0.1830 |
| 2 | ER1 | 0.1816 |
| 3 | ER4 | 0.1319 |
| 4 | ER5 | 0.1069 |
| 5 | ER9 | 0.0989 |
| 6 | ER10 | 0.0836 |
| 7 | ER6 | 0.0661 |
| 8 | ER8 | 0.0652 |
| 9 | ER2 | 0.0485 |
| 10 | ER3 | 0.0343 |

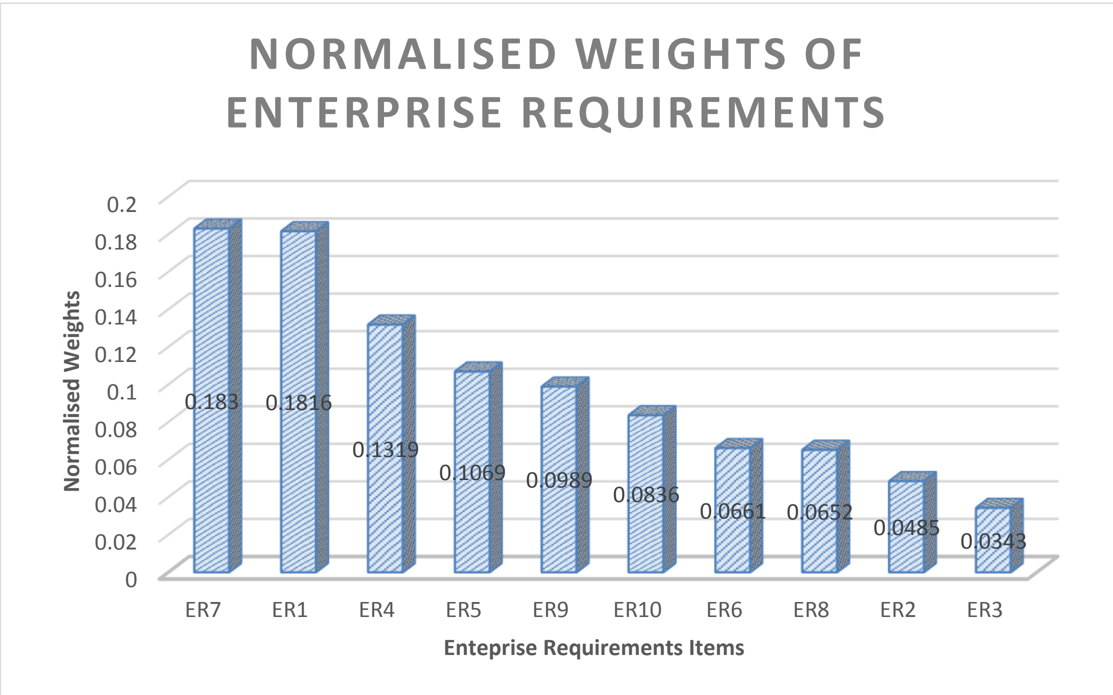


**Figure 6.8 Bar charts based on Table 6.12**

As can be seen in Table 6.12 and Figure 6.8, the ranking and weight assignment results are more distinguishable, and each enterprise requirement has its own rank and weight. More importantly, the ranks are different from what are shown in Table 6.10 and Figure 6.7 meaning that TAF captured the tacit knowledge from engineers that has not been captured by traditional method. Moreover, TAF calculated the inconsistency ratio of this ERM shown in Table 6.11 is 20.8% that is relatively high but acceptable. This is because the human judgements are not consistent and such subjectivities are unavoidable. TAF suggests that more responses to the questionnaire should reduce such inconsistency.

### 6.2.4 GWM Architecture Features Identification

In this case study, two types of GWM architecture are identified with the same set of functionalities by Jaguar Land Rover Limited. The functional architecture features, which are later referred to as the technology features, are shown in Table 6.13.

**Table 6.13 GWM Functionalities**

| | | | | |
|---|---|---|---|---|
| Switching | Diagnostic | Network Management | Safety | Security |

All these five functionalities are recognised as technology features of GWM architectures in this case study. In the original assessment, the contributions of GWM architecture features are marked by 1,2 and 3 which is popular ways in traditional method such as Likert scale methodology. However, before feeding this data in to the TAF, a reinterpretation is required. The original assessments of GWM functionalities for both Centralized and Distributed architecture are shown in Table 6.14

**Table 6.14 Original Assessment of GWM Functionalities for Two Types of Architecture**

| Sl No | Key Attributes | CENTRALIZED | | | | | DISTRIBUTED | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Switching | Diagnostic | Network Management | Safety | Security | Switching | Diagnostic | Network Management | Safety | Security |
| 1 | Latency | 2 | 2 | 2 | 3 | 1 | 1 | 2 | 2 | 1 | 1 |
| 2 | Memory Usage | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 2 | 2 | 2 |
| 3 | Footprint Size | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 4 | CPU Usage | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 5 | Computing Power | 1 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 3 |
| 6 | Deterministic | 1 | 1 | 2 | 1 | 1 | 3 | 3 | 2 | 3 | 3 |
| 7 | Fault Tolerance | 1 | 1 | 2 | 1 | 1 | 3 | 3 | 3 | 2 | 2 |
| 8 | Routing Table | 1 | 1 | 1 | 2 | 2 | 3 | 3 | 3 | 2 | 3 |
| 9 | Cost | 3 | 2 | 3 | 3 | 3 | 1 | 2 | 2 | 1 | 1 |
| 10 | Diagnostic Process Complexity | 0 | 1 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 |
| TOTAL SCORE | | 53 | 54 | 61 | 61 | 51 | 78 | 94 | 83 | 70 | 73 |

The first step of this reinterpretation is to translate such marks (0,1,2 and 3) to vocal representation as shown in figure 6.9.

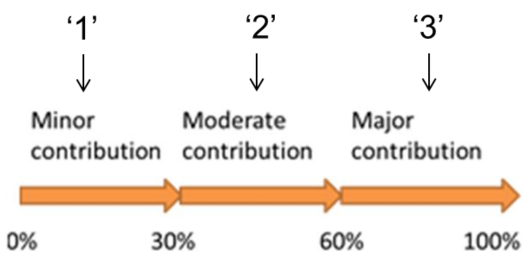


**Figure 6.9 Guidance of interpretation of percentage representations**

Based on Figure 6.9, mark 1, 2 and 3 in Table 6.14 are interpreted into minor contribution, moderate contribution and major contribution respectively. Due to no further information, such interpretations are then represented in percentage as 15%, 45% and 80% as contribution representation respectively. This process of reinterpretation translates the marks shown in Table 6.14 that represented in number to contributions represented in percentages.

After this reinterpretation process, the contributions represented in percentages are fed into TAF to form TCMs. The TCMs for Centralised Architecture and Distributed Architecture based on the ranks, which are shown in Table 6.10, are shown in Table 6.15 and 6.16. The TCMs for Centralised Architecture and Distributed Architecture based on the ranks, which are shown in Table 6.12, are shown in Table 6.17 and 6.18.

**Table 6.15 TCM for Centralized Architecture corresponding with ranks from Table 6.10**

| | 1a | 1b | 1c | 1d | 1e |
|---|---|---|---|---|---|
| ER1 | 45% | 45% | 45% | 80% | 15% |
| ER5 | 15% | 15% | 15% | 15% | 15% |
| ER7 | 15% | 15% | 45% | 15% | 15% |
| ER2 | 15% | 15% | 15% | 15% | 15% |
| ER4 | 45% | 45% | 45% | 45% | 45% |
| ER10 | 0 | 15% | 0 | 0 | 0 |
| ER3 | 45% | 45% | 45% | 45% | 45% |
| ER6 | 15% | 15% | 45% | 15% | 15% |
| ER8 | 15% | 15% | 15% | 45% | 45% |
| ER9 | 80% | 45% | 80% | 80% | 80% |

Table 6.16 TCM for Distributed Architecture corresponding with ranks from Table 6.10

| | 2a | 2b | 2c | 2d | 2e |
|---|---|---|---|---|---|
| ER1 | 15% | 45% | 45% | 15% | 15% |
| ER5 | 80% | 80% | 80% | 80% | 80% |
| ER7 | 80% | 80% | 80% | 45% | 45% |
| ER2 | 45% | 15% | 45% | 45% | 45% |
| ER4 | 45% | 45% | 45% | 45% | 45% |
| ER10 | 0 | 80% | 0 | 0 | 0 |
| ER3 | 45% | 45% | 45% | 45% | 45% |
| ER6 | 80% | 80% | 45% | 80% | 80% |
| ER8 | 90% | 80% | 80% | 45% | 80% |
| ER9 | 15% | 45% | 45% | 15% | 15% |

Table 6.17 TCM for Centralized Architecture corresponding with ranks from Table 6.12

| | 1a | 1b | 1c | 1d | 1e |
|---|---|---|---|---|---|
| ER7 | 45% | 45% | 45% | 80% | 15% |
| ER1 | 45% | 45% | 45% | 80% | 15% |
| ER4 | 45% | 45% | 45% | 45% | 45% |
| ER5 | 15% | 15% | 15% | 15% | 15% |
| ER9 | 80% | 45% | 80% | 80% | 80% |
| ER10 | 0 | 15% | 0 | 0 | 0 |
| ER6 | 15% | 15% | 45% | 15% | 15% |
| ER8 | 15% | 15% | 15% | 45% | 45% |
| ER2 | 15% | 15% | 15% | 15% | 15% |
| ER3 | 45% | 45% | 45% | 45% | 45% |

**Table 6.18 TCM for Distributed Architecture corresponding with ranks from Table 6.12**

| | 2a | 2b | 2c | 2d | 2e |
|---|---|---|---|---|---|
| ER7 | 80% | 80% | 80% | 45% | 45% |
| ER1 | 15% | 45% | 45% | 15% | 15% |
| ER4 | 45% | 45% | 45% | 45% | 45% |
| ER5 | 80% | 80% | 80% | 80% | 80% |
| ER9 | 15% | 45% | 45% | 15% | 15% |
| ER10 | 0 | 80% | 0 | 0 | 0 |
| ER6 | 80% | 80% | 45% | 80% | 80% |
| ER8 | 90% | 80% | 80% | 45% | 80% |
| ER2 | 45% | 15% | 45% | 45% | 45% |
| ER3 | 45% | 45% | 45% | 45% | 45% |

Due to the fact that no interrelationship among those five functionalities has identified from the responses of questionnaire, the last matrix in TAF method namely Technology Feature Matrix (TFM) is not applicable to this case study. The implication of not having this matrix are that no complexity assessment of could be conducted by the TAF. This is not an ideal situation for the TAF assessment. However, this proves the availability of the TAF assessment with incomplete information.

After feeding the data so far into TAF the comparative assessments results are shown in Figure 6.10 and 6.11.

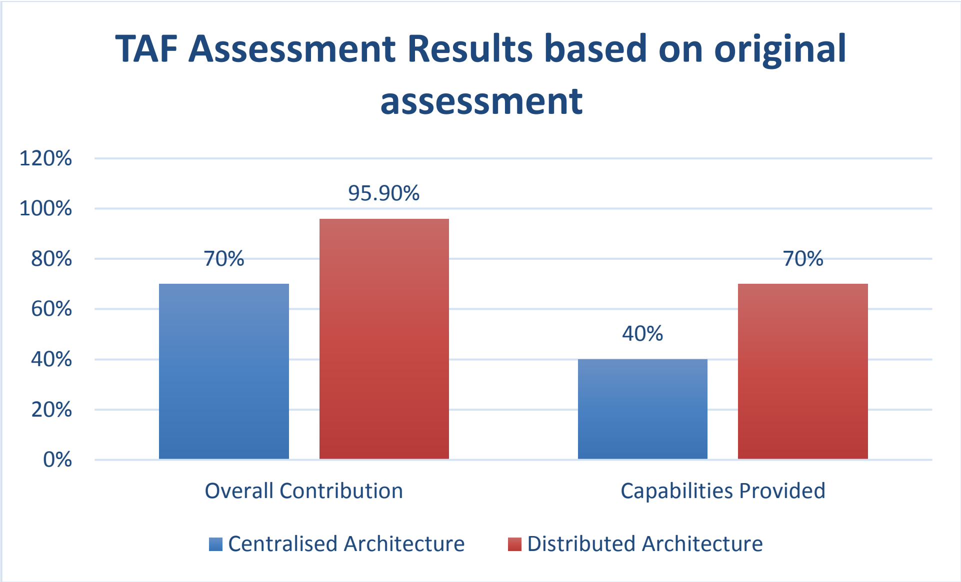


**Figure 6.10 TAF Assessment Results Based on Original Assessment**

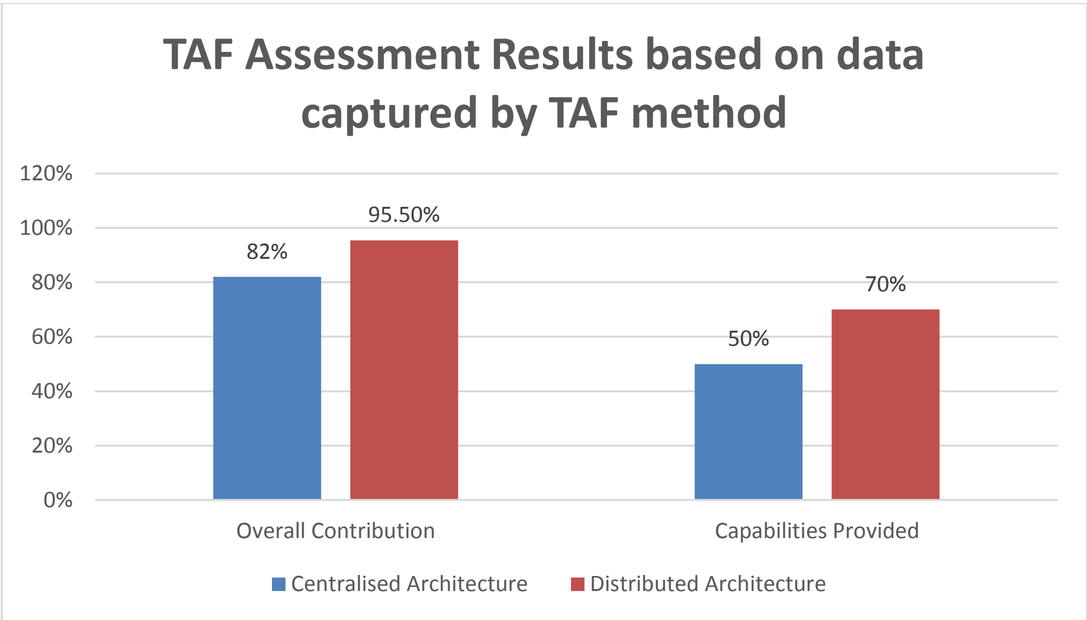


**Figure 6.11 TAF Assessment Results Based on Data Captured by TAF Method**

### 6.2.5 Analysis of TAF Assessment Results

As shown in Figure 6.10 and 6.11, the difference between the predicted contributions of two types of GWM architectures from TAF assessment based on data from original assessment conducted by Jaguar Land Rover Limited (25.9%) is considerably larger than the difference between the predicted contributions of two types of GWM architectures from the TAF assessment based on data captured by TAF methods (13.5%). Similarly, the difference between the predicted capabilities of two types of GWM architectures from the TAF assessment based on data from the original assessment conducted by Jaguar Land Rover Limited (30%) is considerably larger than the difference between the predicted capabilities of the two types of GWM architectures from the TAF assessment based on data captured by the TAF methods (20%).

TAF assessment provides the same results regarding which GWM architecture is relatively better as the original assessment conducted by Jaguar Land Rover Limited following the traditional methods. In this case study, The Distributed Architecture of GWM is better than Centralized Architecture of GWM. However, TAF assessment results are less likely to lead to overconfidence towards Distributed Architecture as the difference between the predicted capabilities of two types of GWM architectures from the TAF assessment is significantly smaller.

Because this case study is based on a real-world project and there is a lack of further information, the risk assessment of TAF is not applicable as well as the dominancy assessment of TAF. This could be improved in future by a closer collaboration with Jaguar Land Rover Limited.

Nonetheless, the information in TAF that captured by TAF methods is enough to apply TRMA to reveal the potentials of both types of GWM architectures.

### 6.2.6 Technology Refinement Suggestions

The final part of this comparative assessment is the application of Technology Refinement and Modification Algorithm (TRMA). The results of the applications of TRMA to both types of GWM architectures are shown in Figure 6.12 and 6.13. Note: the results of TF4 mostly coincide with TF5 in Figure 6.12 and results of TF1, 4 and 5 are coincide with each other in Figure 6.13.

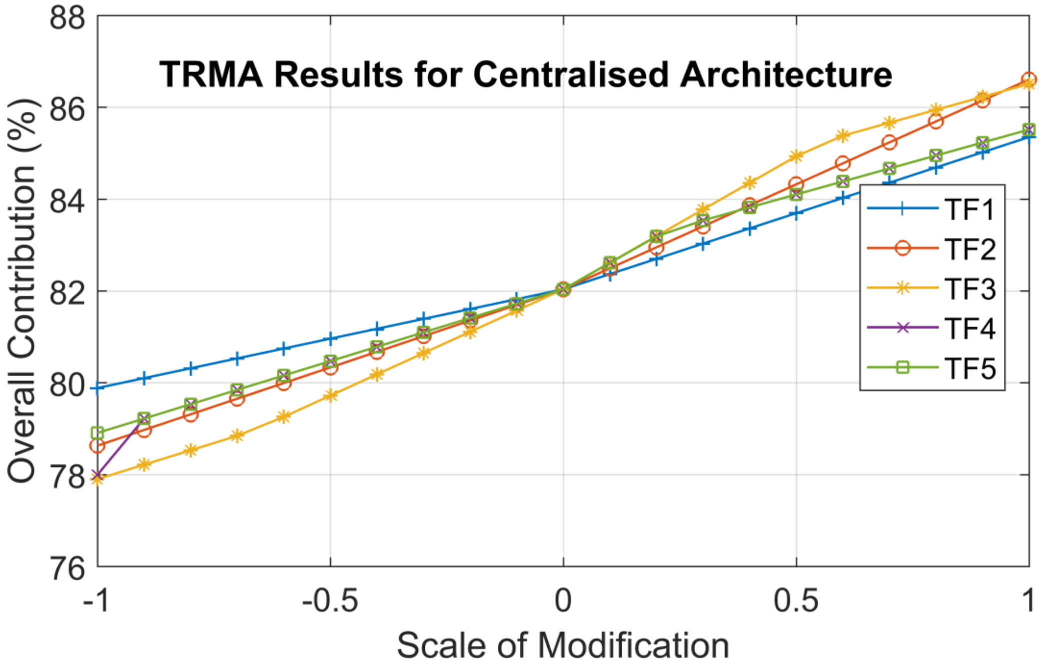


Figure 6.12 TRMA results for Centralised Architecture

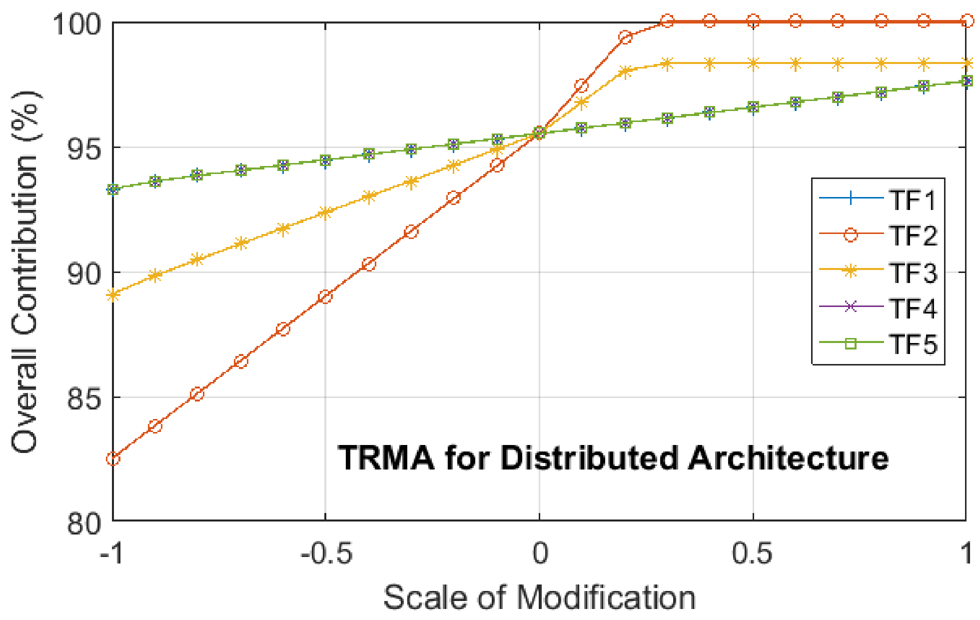


**Figure 6.13 TRMA results for Distributed Architecture**

Based on Figure 6.12, the enhancements of all technology features are predicted to be beneficial for the Centralised Architecture of GWM. However, such enhancements are not efficient as they are not sensitive toward changes. Overall, the features ‘Diagnostic’ and ‘Network Management’ are suggested to be enhanced to reach the relatively better outcomes. However, the enhancement of the feature ‘Diagnostic’ may be too abstract in physical/real world terms. Therefore, the decision-maker may want to follow the latter suggestion to enhance the ‘Network Management’ feature of Centralised Architecture of GWM. This again highlights the importance of subjectivity involved in technology assimilation and the fact that this approach is designed to support the decision-makers instead of replacing them.

Based on Figure 6.13, the enhancements of all functionalities of Distributed Architecture of GWM are also predicted to be beneficial and the feature ‘Diagnostic’ is predicted to reach the best outcome as maximum contribution by enhancing 30%. However, for the same reason, this may not be feasible in a real-world situation.

Similarly, the enhancement of the ‘Network Management’ feature of Distributed Architecture of GWM is a feasible solution for improvement. On the other hand, the results of TRMA for Distributed Architecture of GWM implies that TFs in the Distributed case could be worsen deliberately if the overall cost of Distributed Architecture of GWM can be reduced and still provides the same quality of outcome as the Centralised Architecture of GWM.

By applying TRMA, the refinement and modification directions in general can be suggested for both types of GWM architectures. Moreover, the potential of both types of GWM architectures are predicted. In this case study, the Distributed Architecture of GWM is better in terms of the outcome after refinement and modification and it also has a bigger room for refinements and modifications. Combining with the assessment result from TAF in previous section, this case study suggests that the enterprise assimilates the Distributed Architecture of GWM as it has been predicted to be relatively better at both current state and future state after refinement and modification by the proposed approach of this research.

# 7 Conclusion and Delimitation

## 7.1 Conclusion

In this research, a holistic approach for ameliorating the effect of ‘Valley of Death’ in technology assimilation is proposed. This approach includes 1) a structured framework to technology assessment, the Technology Assessment Framework (TAF), to support decision-making around assimilation of a technology into complex systems and products, and 2) an algorithm based on TAF, the Technology Refinement and Modification Algorithm (TRMA), to suggest refinement and modification directions of technology in order to increase the probability of successful assimilation in a forward-looking manner. To demonstrate the feasibility of the proposed approach, both TAF and TRMA are applied to two case studies of comparative assessments of different technologies that are targets of assimilation in automotive OEMs in Chapter 6.

The explicit exploration of different technological viewpoints, and structuring of knowledge enabled by TAF, offers a novel approach in regards of technology assessment and technology assimilation. One of the deficiencies of current approaches and methods of technology assessment is that they tend to assess one technology at a time. Such approaches and methods assess how good a technology is based on a single criterion. TAF offers comparative assessment of multiple technologies against multiple criteria to support real world decision-making practice, where managers must decide which technology is ready for assimilation, or which technology better meets requirements amongst a number of potentials. The main philosophy behind the development of TAF is that a ‘good technology’ is a relative term that is only meaningful when considering the nature of enterprise and enterprise requirements. Therefore, a cutting-edge technology that has the potential to provide a new feature does not necessarily suit a certain enterprise or a certain project at a particular time.

This PhD research approaches technology assessment and helps to address the challenges in this domain via adopting analysis methodologies such as Multi-Criteria Decision Analysis (MCDA), Analytic Hierarchy Process (AHP) and relational-oriented systems engineering (ROSE). Also, by following the Systems Engineering approaches, TAF is designed and developed to fill in the gaps of current technology assessment methods and tools that defined in the literature review chapter. TAF requires users (stakeholders of technology assimilation) to make pairwise comparisons of requirements in terms of their importance to the enterprise and project and allows users to compare different market positions and strategies through ranking and weighting the requirements differently. This approach also engages experts and practitioners with different expertise backgrounds, to provide a more holistic view of requirements. TAF assessment is based six criteria that are defined as six facets in the Hexahedron Model of Technology (HMT) that represent six aspects of technology. Within the scope of this research, technologies are considered as combinations of different technology features that can be further categorised into Natural aspect, Social aspect and Human aspect. Apart from these three aspects, TAF also includes complexity, contribution and capability (3C) as remaining three aspects. TAF recognises the risks of technology assimilation are related to the complexity of technology whereas the rewards of technology assimilation are related to capability and contribution of technology. In the TAF assessment, the capability of technology and contribution of technology are closely linked with each other. The capability of technology represents the direct results of how well a technology fulfils individual enterprise requirement and the contribution of technology is analysed from a higher-level viewpoint that assesses the rewards of technology assimilation with the combined consideration of capability of technology and the weights of enterprise requirements.

However, the assessment results of TAF are not simply related to the ratio of rewards over risks. Both rewards and risks of technology assimilation are assessed at two levels.

For the first level of rewards assessment, the rewards are related to capability and contribution of technology. The contribution of technology reflects the overall contribution that a technology can make to a set of enterprise requirements. This overall contribution is related to the fulfilments of individual enterprise requirements and the corresponding weights of the enterprise requirements based on a relational - oriented viewpoint. In order to achieve this, TAF provides a transformation between enterprise requirements and technology features and the algorithms to predict the approximate capabilities that a technology can bring to the enterprise based on ROSE. The capabilities are further combined with the weights of enterprise requirements to suggest the overall contribution of technology. For the second level of rewards assessment, TAF calculates the ratios of the sub-contributions made by Natural, Social and Human aspects of technology respectively over the overall contribution of technology. Although these ratios can be interpreted in different ways, such ratios are calculated in TAF to identify which aspect of technology among Natural, Social and Human aspect is the dominate aspect that makes the majority contribution. This assessment result of dominancy among Natural, Social and

Human aspect provides decision makers more insights into any potential risks, for example, by over-reliance on a particular technological viewpoint. For example, if the Natural aspect of a technology is the dominant aspect based on the second level rewards assessment of TAF, the decision-makers (chief engineers and managers) should consider involving more experts of engineering into the project of technology assimilation.

For the first level of risks assessment, TAF requires the inputs of specified interrelationships among technology features. The number of interrelationships and the ratio of the specified interrelationships over the overall number of pairs of technology feature reflect the risks of technology assimilation in TAF. For the second level of risks assessment of technology, TAF provides the ratio of the number of specified interrelationships of two technology features that are categorized into different aspect among Natural, Social and Human aspect of technology over the number of overall number of specified interrelationships. This ratio reflects the needs of cross-department collaborations and communications from an enterprise for the technology assimilation project.

Based on TAF, this research proposes TRMA to support the forward-looking plan for the technology refinements and modifications for the technologies that are selected for assimilation after the TAF assessment. By calculating the overall contribution of technology, with the considerations of interrelationships among technology features, after refinement and modification, TRMA provides suggestions on the general directions of technology refinement and modification.

Through case studies, which includes a hypothetical case study and a case study of real-world technology assessment, the feasibility and availability of TAF and TRMA are verified and validated. Overall, Figure 7.1 illustrates the expected outcomes of the proposed approach of this research. By applying TAF, the Technology Trade Space (TTS) should be reduced giving the decision-making a better focus on the technologies that have better chances to fulfil the requirements of technology assimilation. By applying TRMA, the directions of improvement for technology development and assimilation can be suggested.

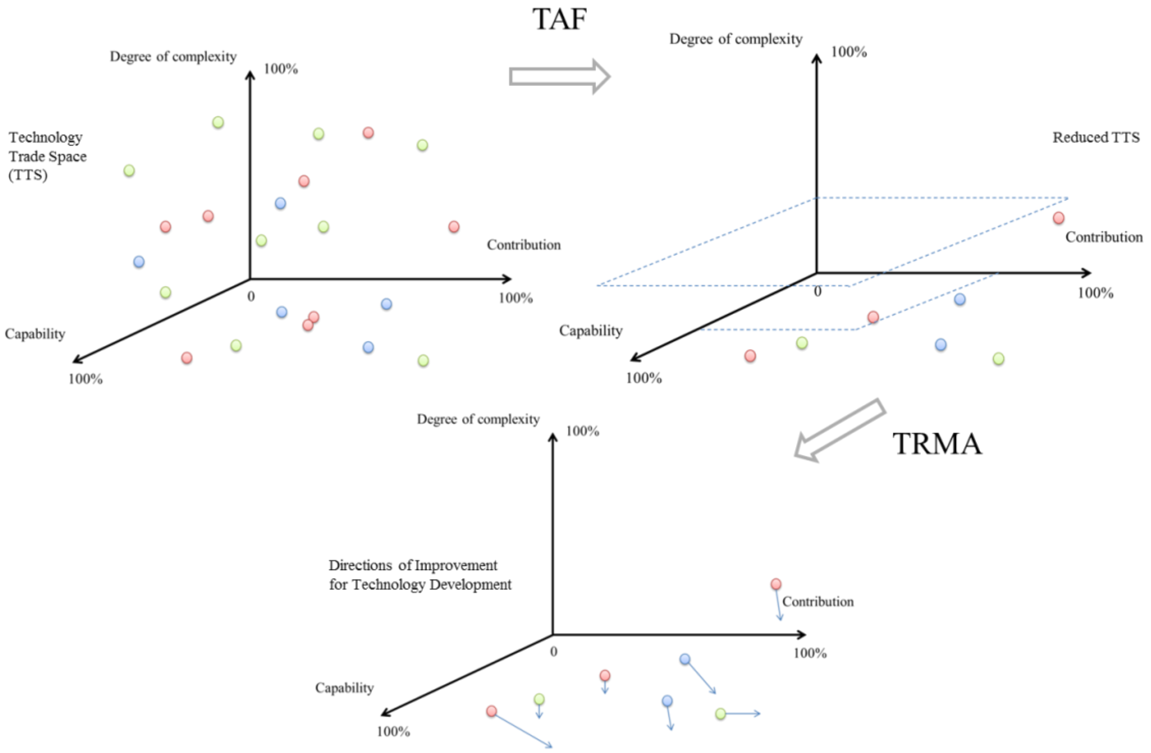


**Figure 7.1 Expected Outcomes of the Proposed Approach**

Moreover, Figure 7.2 illustrates the expected effects of the proposed approach of this research on the ‘Valley of Death’ in technology assimilation with reference to Figure 2.9.

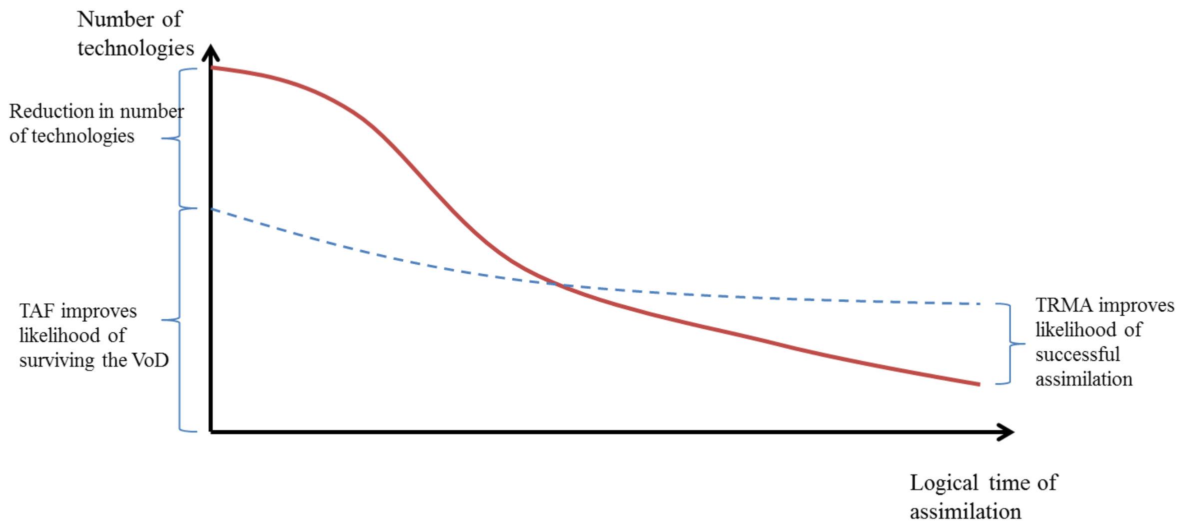


**Figure 7.2 Expected Effects of Proposed Approach in This Research on the Effect of 'Valley of Death' in Technology Assimilation**

As shown in Figure 7.2, the steepness of the dashed curve in blue is considerably lower than the steepness of the original curve in red that representing the problem of ‘Valley of Death’ in technology assimilation. The combined effects of the reduction in number of technologies that enter the ‘Valley of Death’ provided by TAF and the improved likelihood of successful assimilation provided by TRMA are the contribution of proposed approach for ameliorating ‘Valley of Death’ in technology assimilation.

This research provides the following unique contributions to knowledge. First, different technological viewpoints of technology assimilation have been defined to facilitate a more holistic and comprehensive assessment of technology. Second, a Hexahedron Model of Technology is proposed to identify different aspects of technology that matter during technology assimilation.

This research provides the following contributions to practice. First, this research proposes a Technology Assessment Framework and the corresponding method to populate it. This framework facilitates comprehensive and holistic assessment of technology during technology assimilation process. Second, a Technology

Refinement and Modification Algorithm is developed in this research. This algorithm utilise the information stored in TAF to suggest the best direction of technology modification for better fulfilment of the overall enterprise requirements and hence increase the likelihood of technology assimilation success. The combination of these two methods

## 7.2 Delimitation of This Research

The shortcomings of this research can be broadly divided into two categories that associate with the applied methodologies of this research and the proposed holistic approach respectively. In terms of the shortcoming brought from the applied methodologies, the most relevant one, in the view of the author, is the case study methodology for preliminary verification and validation. Due to the limitation of time, only two case studies have been conducted in this research. The first case study at best is a demonstration of the assimilation process using the proposed approach that involves the two new methods (TAF and TRMA) whereas the second case study, though was conducted in a real-world situation, is partially completed due to lack of information from industry. These two case studies combined can only support a preliminary verification and validation. For a complete verification and validation, the author understands a closer and longer collaboration with industry is necessary.

Moreover, as the scope of this research was set in the environment of the automotive OEMs, currently, there is no evidence that the proposed approach in this research can be applied to other environments, such as medical industry, where technology assimilation is also vital. Even though the author of this thesis is confident that the proposed approach should be applicable to other industrial environments, extra efforts must be made in order to support this argument. So far, these two mentioned shortcomings can be solved by more time of researching.

In terms of the proposed approach, there is a major shortcoming that has been identified. The method for capturing tacit knowledge/expert experiences which are required to populate TAF is not automated. As demonstrated in the second case study, when applying in real-world situation, the proposed approach requires questionnaire to extract tacit knowledge from practitioner. This is not only time-consuming but also depending on the how well the questions are asked. The pair-wise structure of the information stored in TAF is theoretically enabling reusability, however, such functionality is not yet implemented in the MATLAB codes in this thesis. Therefore, the implementation of the proposed approach in this research can adopt Machine Learning/Deep Learning capability to automatically capture tacit knowledge in future research. Moreover, the proposed approach is currently implemented in MATLAB for the its wide usage in automotive OEMs environment. However, one of the possible future direction of the further development of the proposed approach is to implement it in Python programming environment to utilise the better database support to enable the reusability of the information stored in TAF. Also, a Python programme implementation of TAF and TRMA will be more appealing to a wider audience for the popularity of Python.

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# Appendix 1: MATLAB codes for TAF

## Appendix 1A: MATLAB codes for ERM

```
clear all
filename1 = 'TAFbody.xlsx';
prompt1 = 'How many enterprise requirements';

% input the number of enterprise requirements of the project.
n = input (prompt1);
for i = 1:n;
    for j= i:n;
        if i==j;
            ERmatrix(i,j) = 1;
        else
            fprintf('what is the relative importance of requirement No.%d over
requirement No.%d? \n', i,j);
            prompt2 = 'ans';
            result = input(prompt2);
            ERmatrix (i,j) = result;
            ERmatrix (j,i) = 1./ERmatrix (i,j);
        end
    end
 %form the AHP matrix

end
RI_ALL = [0 0 0.58 0.9 1.12 1.24 1.32 1.41 1.45 1.49];
RI = RI_ALL (1,n);
% the inconsistance base ratio
save('AHPER.mat','ERmatrix');

load ('AHPER.mat')
rats(ERmatrix)
[V,D,W] = eig (ERmatrix);
priorities = V(:, 1);
allPV = sum(priorities);
normalpriorities = priorities./allPV;
[sortPV I] = sort(normalpriorities,'descend')
EIGV = D(1,1);
% eigenvector of the AHP matrix
CI = (EIGV - n)./(n - 1);
CR = CI./RI;
% inconsistance ratio
fprintf('The consistency ratio of the enterprise requirement matrix
is %.1f%%\n' ,CR.*100)
sheet1 = 1;
xlRange1 = 'B2';
xlswrite(filename1,normalpriorities,sheet1,xlRange1)
xlRange2 = 'C2';
xlswrite(filename1,ERmatrix,sheet1,xlRange2)
sheet2 = 2;
xlRange3 = 'A2';
xlswrite(filename1,I,sheet2,xlRange3)
save('AHPER.mat');
```

## Appendix 1B: MATLAB codes for TCM

```
clear all
filename1 = 'TAFbody.xlsx';
load('AHPER.mat');
fprintf('How many technology features are based on Natural science aspect?\n');
prompt5 = 'ans';
natural_aspect = input(prompt5);
fprintf('How many technology features are based on Social science aspect?\n');
prompt6 = 'ans';
social_aspect = input(prompt6);
fprintf('How many technology features are based on Human science aspect?\n');
prompt7 = 'ans';
human_aspect = input(prompt7);
sheet2 = 2;
middle_matrix = xlsread(filename1,sheet2);
middle_matrix(isnan(middle_matrix))= 0;
middle_matrix(:,1) = [];
[ER_number,TF_number] = size(middle_matrix);
% read middle matrix from excel file
capabilitynumber = 0;
number_check = natural_aspect + social_aspect + human_aspect;
if number_check == TF_number
for i = 1:ER_number;
    if sum(middle_matrix(i,:) == -1)~= 0
       primitive_ER_capability (i,1) = -1;
    elseif sum(middle_matrix(i,:) == -1)== 0
        positive_component = (sum(middle_matrix(i,:).*(middle_matrix(i,:)>=0))+
max(middle_matrix(i,:).*(middle_matrix(i,:)>=0)))./2;
        if positive_component >= 1
            positive_component = 1;
        else
            positive_component = positive_component;
        end
        negetive_component = (sum(middle_matrix(i,:).*(middle_matrix(i,:)<0))+
min(middle_matrix(i,:).*(middle_matrix(i,:)<0)))./2;
        if negetive_component <= -1
            negetive_component = -1;
        else
            negetive_component = negetive_component;
        end
        primitive_ER_capability (i,1) = positive_component + negetive_component;
    else
    end
end
% algorithm of calculate capabilities
primitive_ER_capability(primitive_ER_capability>1)=1;
capabilitynumber = sum(primitive_ER_capability == 1);
capabilitypersentage = 100.* (capabilitynumber./ER_number);
complexpotential = 9.*capabilitynumber;
TCweightedcontrib = primitive_ER_capability .* sortPV;
Original_percentage = 100.*sum(TCweightedcontrib);
% the overall conrtibution of the technology
if Original_percentage >= 100;
    percentage = 100;
else
    percentage = Original_percentage;
end
save ('ERBODYTC.mat');
fprintf('The coefficient of overall contribution of this technology to overall
requirement is %.1f%%\n' ,percentage);
fprintf('%d out of %d enterprise requirements (%.1f%%)will be completely fulfilled
```

```
by this technology' ,capabilitynumber,ER_number,capabilitypersentage);
three_middle_matrix = mat2cell(middle_matrix,[ER_number 0],[natural_aspect
social_aspect human_aspect]);
natural_middle_matrix = three_middle_matrix{1,1};
social_middle_matrix = three_middle_matrix{1,2};
human_middle_matrix = three_middle_matrix{1,3};

for ia = 1:ER_number
    if sum(natural_middle_matrix(ia,:) == -1)~= 0
       natural_middle_matrix_capability (ia,1) = -1;
    elseif sum(natural_middle_matrix(ia,:) == -1)== 0
        positive_component_natural =
(sum(natural_middle_matrix(ia,:).*(natural_middle_matrix(ia,:)>=0))+
max(natural_middle_matrix(ia,:).*(natural_middle_matrix(ia,:)>=0)))./2;
        if positive_component_natural >= 1
            positive_component_natural = 1;
        else
            positive_component_natural = positive_component_natural;
        end
        negetive_component_natural =
(sum(natural_middle_matrix(ia,:).*(natural_middle_matrix(ia,:)<0))+
min(natural_middle_matrix(ia,:).*(natural_middle_matrix(ia,:)<0)))./2;
        if negetive_component_natural <= -1
            negetive_component_natural = -1;
        else
            negetive_component_natural = negetive_component_natural;
        end
        natural_middle_matrix_capability (ia,1) = positive_component_natural +
negetive_component_natural;
    else
    end
end
natural_middle_matrix_capability(natural_middle_matrix_capability>1)=1;
natrual_capabilitynumber = sum(natural_middle_matrix_capability == 1);
natrual_capabilitypersentage = 100.* (natrual_capabilitynumber./ER_number);
natrual_weightedcontrib = natural_middle_matrix_capability .* sortPV;
Original_natrual_percentage = 100.*sum(natrual_weightedcontrib);
% the contribution made by natural science aspect related technology
% features

for ib = 1:ER_number
    if sum(social_middle_matrix(ib,:) == -1)~= 0
       social_middle_matrix_capability (ib,1) = -1;
    elseif sum(social_middle_matrix(ib,:) == -1)== 0
        positive_component_social =
(sum(social_middle_matrix(ib,:).*(social_middle_matrix(ib,:)>=0))+
max(social_middle_matrix(ib,:).*(social_middle_matrix(ib,:)>=0)))./2;
        if positive_component_social >= 1
            positive_component_social = 1;
        else
            positive_component_social = positive_component_social;
        end
        negetive_component_social =
(sum(social_middle_matrix(ib,:).*(social_middle_matrix(ib,:)<0))+
min(social_middle_matrix(ib,:).*(social_middle_matrix(ib,:)<0)))./2;
        if negetive_component_social <= -1
            negetive_component_social = -1;
        else
            negetive_component_social = negetive_component_social;
        end
        social_middle_matrix_capability (ib,1) = positive_component_social +
negetive_component_social;
```

```
    else
    end
end
social_middle_matrix_capability(social_middle_matrix_capability>1)=1;
social_capabilitynumber = sum(social_middle_matrix_capability == 1);
social_capabilitypersentage = 100.* (social_capabilitynumber./ER_number);
social_weightedcontrib = social_middle_matrix_capability .* sortPV;
Original_social_percentage = 100.*sum(social_weightedcontrib);
% the contribution made by social science aspect related technology
% features

for ic = 1:ER_number
    if sum(human_middle_matrix(ic,:) == -1)~= 0
       human_middle_matrix_capability (ic,1) = -1;
    elseif sum(human_middle_matrix(ic,:) == -1)== 0
        positive_component_human =
(sum(human_middle_matrix(ic,:).*(human_middle_matrix(ic,:)>=0))+
max(human_middle_matrix(ic,:).*(human_middle_matrix(ic,:)>=0)))./2;
        if positive_component_human >= 1
            positive_component_human = 1;
        else
            positive_component_human = positive_component_human;
        end
        negetive_component_human =
(sum(human_middle_matrix(ic,:).*(human_middle_matrix(ic,:)<0))+
min(human_middle_matrix(ic,:).*(human_middle_matrix(ic,:)<0)))./2;
        if negetive_component_human <= -1
            negetive_component_human = -1;
        else
            negetive_component_human = negetive_component_human;
        end

        human_middle_matrix_capability (ic,1) = positive_component_human +
negetive_component_human;
    else
    end
end
human_middle_matrix_capability(human_middle_matrix_capability>1)=1;
human_capabilitynumber = sum(human_middle_matrix_capability == 1);
human_capabilitypersentage = 100.* (human_capabilitynumber./ER_number);
human_weightedcontric = human_middle_matrix_capability .* sortPV;
Original_human_percentage = 100.*sum(human_weightedcontric);
% the contribution made by human science aspect related technology
% features
sub_contribution = [Original_natrual_percentage Original_social_percentage
Original_human_percentage]
%labels = {'Natural aspect','Social aspect','Human aspect'};
%explode = [1 1 1];
%pie(sub_contribution,explode,labels)
%lables = {'Natural aspect','Social aspect','Human aspect'};
%c = categorical({'Natural Aspect','Social Aspect','Human Aspect'});
bar(sub_contribution);
set(gca,'XTickLabel',{'Natural Aspect', 'Social Aspect', 'Human Aspect'})
ylabel('Sub-contributions (%)')
elseif number_check ~= TF_number
   fprintf('The input numbers of technology features sub-category are
inconsistence with overall number of technology, please double check\n');
else
end
```

## Appendix 1C: MATLAB codes for TFM

```
clear all
filename1 = 'TAFbody.xlsx';
load('AHPER.mat');
load('ERBODYTC.mat');
Auto_s = [];
AC = [];
count = 0;
TCmatrix(1:TF_number,1:TF_number) = 100;
for a = 1:ER_number;
    for b = 1:TF_number;
         if middle_matrix (a,b) ~= 0
             AC (end+1) = b;

         else
         end
    end
    if numel(AC) > 1
        for t = AC;
            for c = AC;
                if t == c;
                    TCmatrix(t,c) = 0;
                else
                    if t < c
                        if TCmatrix(t,c) ~= 100
                            TCmatrix(t,c) = TCmatrix(t,c);
                        elseif TCmatrix(t,c) == 100
                            fprintf('What is the interdependency of technology
characteristic No.%d and technology characteristic No.%d? \n ', t,c);
                            prompt3 = 'ans';
                            strength = input(prompt3);
                            TCmatrix (t,c) = strength;
                        end
                    else
                    end
                end
            end
        end
    else
    end
     AC = [];


end
TCmatrix(TCmatrix==100)=0;
 for g = 1:TF_number;
    for h = 1:TF_number;
       if TCmatrix(g,h)~= 0
           count = count + 1;
       else
       end
    end
 end
sheet3 = 3;
xlRange4 = 'B2';
xlswrite(filename1,TCmatrix,sheet3,xlRange4);
display(TCmatrix)
save ('TCTOTC.mat');
%%
load('AHPER.mat');
```

```
load('ERBODYTC.mat');
load ('TCTOTC.mat');
sheet3 = 3;
xlRange4 = 'B2';
TCmatrix = xlsread(filename1,sheet3);
Overallstrength = sum(sum(abs(TCmatrix)));
interdependnumber = count
overallinterdependnumber = (TF_number.*(TF_number-1))./2;
complexratio = interdependnumber./overallinterdependnumber;
y1 = [66.6 66.6];
y2 = [33.3 33.3];
x1 = [0.33 0.33];
x2 = [0.66 0.66];
x1_3 = [33.3 33.3];
x2_3 = [66.6 66.6];
x_3 = [0 100];
x = [0 1];
y = [0 100];
figure(1)
subplot(2,2,1)
plot(complexratio,percentage, 'o',x1,y,'--',x2,y, '--',x,y1, '--',x,y2, '--')
%ylim([0 100])
%xlim([0 1])
title('Overall contribution percentage vs Complexity ratio')
xlabel('Normalized ratio of complexity ')
ylabel('Overall contribution')

three_roof_matrix = mat2cell(TCmatrix,[natural_aspect social_aspect
human_aspect],[natural_aspect social_aspect human_aspect]);
natural_social = three_roof_matrix{1,2};
natural_human = three_roof_matrix{1,3};
social_human = three_roof_matrix{2,3};
natural_social_count = sum(abs(nonzeros(natural_social)));
natural_human_count = sum(abs(nonzeros(natural_human)));
social_human_count = sum(abs(nonzeros(social_human)));
sub_cross_count = [natural_social_count natural_human_count social_human_count];
cross_aspect_complexity = sum(abs(nonzeros(natural_social)))+
sum(abs(nonzeros(natural_human)))+ sum(abs(nonzeros(social_human)));
cross_aspect_complexity_ratio = cross_aspect_complexity ./interdependnumber;

subplot(2,2,2)
plot(cross_aspect_complexity_ratio,percentage,'o',x1,y,'--',x2,y, '--',x,y1, '--
',x,y2, '--')
%ylim([0 100])
%xlim([0 1])
xlabel('Cross aspect complexity ratio')
ylabel('Overall contribution')
title('Overall contribution percentage vs Cross aspect complexity ratio')

subplot (2,2,3)
plot(capabilitypersentage,percentage,'o',x1_3,y,'--',x2_3,y, '--',x_3,y1, '--
',x_3,y2, '--')
%ylim([0 100])
%xlim([0 100])
xlabel('capability percentage')
ylabel('Overall contribution')
title('Overall contribution percentage vs Capability percentage')

subplot (2,2,4)
bar(sub_cross_count)
set(gca,'XTickLabel',{'Natural-Social', 'Natural-Human', 'Social-Human'})
ylabel('Cross aspect complexity number ')
```

```
save ('TCTOTC.mat');
```

# Appendix 2: MATLAB codes for TRMA

```
clear all
filename1 = 'TAFbody.xlsx';
load ('AHPER.mat');
load ('ERBODYTC.mat');
load ('TCTOTC.mat');
% load all premeters from TAF assessment results
% This optimisation algorthm aim to suggest which technology feature is the
% best to enhance or reduce in order to have the best possible
% contributions of technology

e_l = [-1:0.1:1];
% the range of changes
k = numel(e_l);
% number of iterations
for d_1 = 1:k
enlarge_ratio = e_l(d_1);
%enlarge_ratio = 1.5;
second_order_enlarge_ratio = enlarge_ratio.*0.5;
% the enlargment ratio of technology features
[row,col,v] = find(TCmatrix);
% find the locations of interrrelationship in TCmatrix
originaltestarray = union(row,col);
% the entry of all technology feature that interrelation with others

results = zeros(1,TF_number);
capability_results = zeros(1,TF_number);
for d = 1:TF_number
%for d = 5
    new_middle_matrix = middle_matrix;
    interrelationshiptest = any(d == originaltestarray);
    % test whether the technology feature is interrelated with any other
    % technology feature
    if interrelationshiptest == 0
        % =0 means that this technology feature is not interrelated with
        % any other technology feature
        enlarged_contributions = new_middle_matrix (:,d).* (enlarge_ratio + 1);
        new_middle_matrix(:,d) = enlarged_contributions;
        % replace only the contribution column of this technology feature
        % and form a new middle matrix
        [n,TF_number] = size(new_middle_matrix);
        new_capabilitynumber = 0;
        for i = 1:n;
            if sum(new_middle_matrix(i,:) == -1)~= 0
               optimised_ER_capability (i,1) = -1;
            elseif sum(new_middle_matrix(i,:) == -1)== 0
                positive_optimised_ER_capability =
(sum(new_middle_matrix(i,:).*(new_middle_matrix(i,:)>=0))+
max(new_middle_matrix(i,:).*(new_middle_matrix(i,:)>=0)))./2;
               if positive_optimised_ER_capability >= 1
                   positive_optimised_ER_capability = 1;
               else
                   positive_optimised_ER_capability =
positive_optimised_ER_capability;
               end
               negetive_optimised_ER_capability =
(sum(new_middle_matrix(i,:).*(new_middle_matrix(i,:)<0))+
min(new_middle_matrix(i,:).*(new_middle_matrix(i,:)<0)))./2;
               if  negetive_optimised_ER_capability <= -1
                   negetive_optimised_ER_capability = -1;
```

```
                else
                    negetive_optimised_ER_capability =
negetive_optimised_ER_capability;
                end
                 optimised_ER_capability (i,1) = positive_optimised_ER_capability +
negetive_optimised_ER_capability;
            else
            end
        end
        % loop for calulate capability of this technology after the change
        % of technology feature
        %optimised_ER_capability(optimised_ER_capability>1)=1;
        new_capabilitynumber = sum(optimised_ER_capability == 1);
        new_capabilitypersentage = 100.* (new_capabilitynumber./n);
        TCweightedcontrib = optimised_ER_capability .* sortPV;
        improve_percentage = 100.*sum(TCweightedcontrib);

    elseif interrelationshiptest == 1
        % =1 means this technology feature is interrelated with atleast one
        % other technology feature,
        new_row= [row;col];
        new_col = [col;row];
        new_v = [v;v];
        % these three arrays contains the index of technology features and
        % index of the corresponding technology features as well as the
        % marked interrelationship (+1 or -1)
        related_feature_raw = ismember(new_row,d).*new_col;
        related_feature = related_feature_raw(related_feature_raw~=0);
        directionOfImprove_raw = ismember(new_row,d).*new_v;
        directionOfImprove = directionOfImprove_raw(directionOfImprove_raw~=0);
        % for each iteration, the interrelated technology features of the
        % technology feature that is being examined and the corresponding
        % interrelationship
        changed_features = [d;related_feature];
        changed_direction = [1;directionOfImprove];% !!!!!!!!!!
        [e,f] = size(changed_features);
        first_order_new_middle_matrix = middle_matrix;
        for g = 1:e
            idx_middle_matrix = changed_features(g,:);
            individual_direction = changed_direction(g,:);
            first_order_new_middle_matrix(:,idx_middle_matrix) =
first_order_new_middle_matrix(:,idx_middle_matrix).*((enlarge_ratio.*
individual_direction)+ 1);

        end
        % forming the new middle matrix with all new contribution columns
        % (first order)
        %first_order_new_middle_matrix
        [e_2,f_2] = size(related_feature); % first order related feature as new
changing features
        for g_2 = 1:e_2
            second_d = related_feature(g_2,:);%select one second order changing
feature
            second_related_feature_raw = ismember(new_row,second_d).*new_col;
            second_related_feature =
second_related_feature_raw(second_related_feature_raw~=0 &
second_related_feature_raw~=d);
            second_related_feature_raw(second_related_feature_raw==d) = [0];
            second_related_feature_raw(second_related_feature_raw~=0) = [1];
            second_directionOfImprove_raw = second_related_feature_raw.*new_v;
            second_directionOfImprove =
second_directionOfImprove_raw(second_directionOfImprove_raw~=0);
```

```
            [e_3,f_3] = size(second_related_feature);
            second_order_new_middle_matrix = first_order_new_middle_matrix;
            for g_3 = 1:e_3
               second_idx_middle_matrix = second_related_feature(g_3,:);
               second_individual_direction = second_directionOfImprove(g_3,:);
               second_order_new_middle_matrix(:,second_idx_middle_matrix) =
second_order_new_middle_matrix(:,second_idx_middle_matrix).*((second_order_enlarge
_ratio.* second_individual_direction)+ 1);
            end
        end
        [n,TF_number] = size(second_order_new_middle_matrix);
        new_capabilitynumber = 0;
        for i = 1:n;
            if sum(second_order_new_middle_matrix(i,:) <= -1)~= 0
               optimised_ER_capability (i,1) = -1;
            elseif sum(second_order_new_middle_matrix(i,:) <= -1)== 0
                positive_optimised_ER_capability =
(sum(second_order_new_middle_matrix(i,:).*(second_order_new_middle_matrix(i,:)>=0)
)+
max(second_order_new_middle_matrix(i,:).*(second_order_new_middle_matrix(i,:)>=0))
)./2;
                if positive_optimised_ER_capability >= 1
                    positive_optimised_ER_capability = 1;
                else
                    positive_optimised_ER_capability =
positive_optimised_ER_capability;
                end
                negetive_optimised_ER_capability =
(sum(second_order_new_middle_matrix(i,:).*(second_order_new_middle_matrix(i,:)<0))
+
min(second_order_new_middle_matrix(i,:).*(second_order_new_middle_matrix(i,:)<0)))
./2;
                if negetive_optimised_ER_capability <= -1
                    negetive_optimised_ER_capability = -1;
                else
                    negetive_optimised_ER_capability =
negetive_optimised_ER_capability;
                end
               optimised_ER_capability (i,1) = positive_optimised_ER_capability +
negetive_optimised_ER_capability;
            else
            end
        end
        %optimised_ER_capability(optimised_ER_capability>1)=1;
        new_capabilitynumber = sum(optimised_ER_capability == 1);
        new_capabilitypersentage = 100.* (new_capabilitynumber./n);
        TCweightedcontrib = optimised_ER_capability .* sortPV;
        improve_percentage = 100.*sum(TCweightedcontrib);
        % calculate the new conrtibution percentage
    else
    end
    results (:,d) = improve_percentage;
    capability_results (:,d) = new_capabilitypersentage;
end
%disp(results)
difference = results - percentage;
%disp(difference)
result_matrix (d_1,:) = results;
capability_result_matrix (d_1,:) = capability_results;
end

for i = 1:k
```

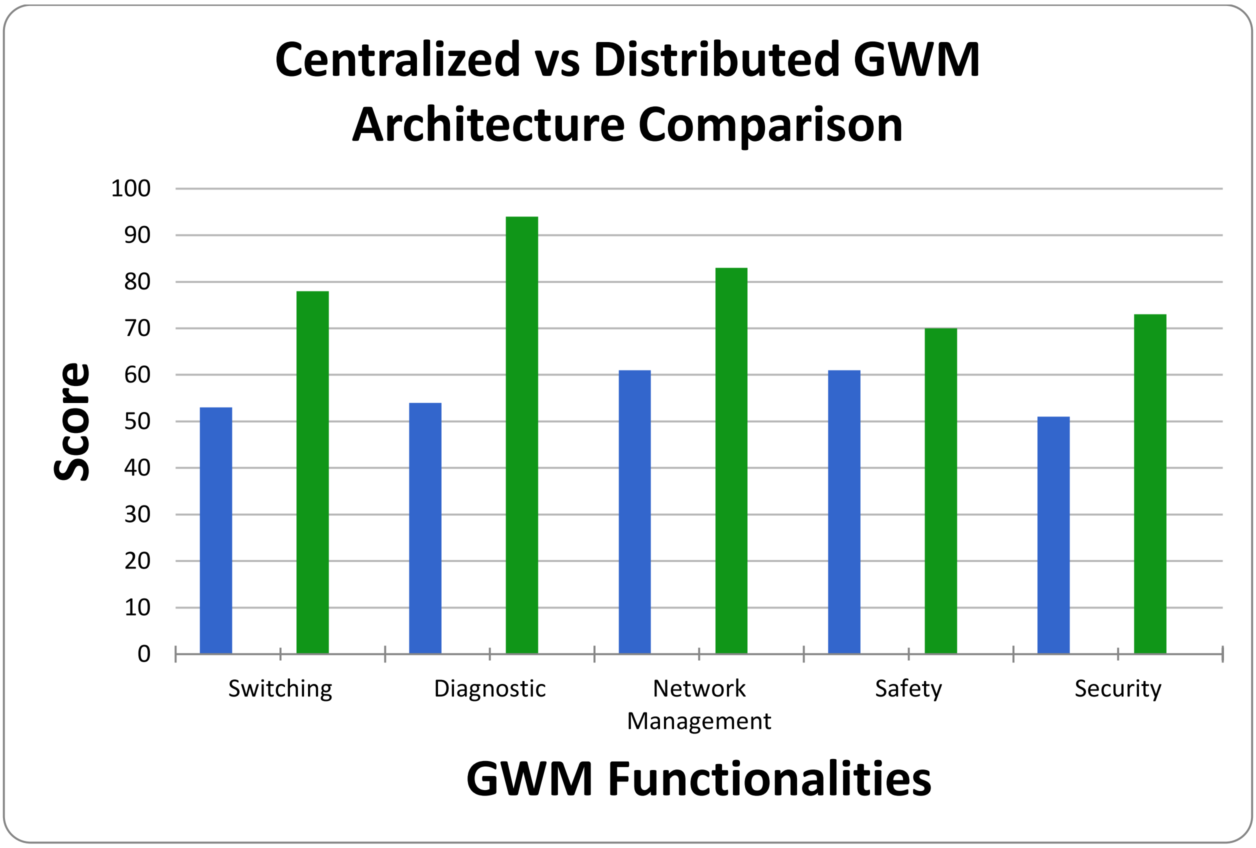
```
    Original_percentage_line (1,i)=Original_percentage;
end
figure
for i_c = 1:d


  plot(e_l,result_matrix(:,i_c))

  xlim = [-1 1];
  ylim = [-10 100];

hold on
grid on
end
```

## Appendix 3: GWM EVA3 Original Assessment by Automotive Partner




This figure shows the original assessment results of centralized and distributed GWM architecture in five criteria. The blue and green represents centralized architecture and distributed architecture respectively. This assessment was conducted by traditional methods, and the results of this assessment suggest that the distributed GWM architecture is better than centralized GWM architecture in all five aspects of GWM functionalities.

## Appendix 4: GWM Architecture TAF Assessment Questionnaire

Thank you for participating this study. This questionnaire is for pure academic usage.

**Enabling low latency is ________________ important than low Memory Usage for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low latency is _________________ important than low footprint size for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low latency is _________________ important than low CPU usage for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low latency is _________________ important than low required computing power for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low latency is _________________ important than deterministic routing for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low latency is _________________ important than fault tolerance for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low latency is _________________ important than simple routing table for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low latency is ___________________ important than low cost for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low latency is ___________________ important than low diagnostic process complexity for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low memory usage is ___________________ important than low footprint size for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low memory usage is ___________________ important than low CPU usage for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low memory usage is ___________________ important than low required computing power for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low memory usage is ___________________ important than deterministic routing for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low memory usage is ___________________ important than fault tolerance for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low memory usage is ___________________ important than simple routing table for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low memory usage is ___________________ important than low cost for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low memory usage is ___________________ important than low diagnostic process complexity for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low footprint size is ____________________ important than low CPU usage for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low footprint size is ____________________ important than low required computing power for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low footprint size is ____________________ important than deterministic routing for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low footprint size is ____________________ important than fault tolerance for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low footprint size is ____________________ important than simple routing table for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low footprint size is ____________________ important than low cost for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low footprint size is ____________________ important than low diagnostic process complexity for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low CPU usage is ____________________ important than low required computing power for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low CPU usage is ____________________ important than fault tolerance for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low CPU usage is ___________________ important than simple routing table for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low CPU usage is ___________________ important than low cost for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low CPU usage is ___________________ important than low diagnostic process complexity for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low required computing power is ___________________ important than deterministic routing for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low required computing power is ___________________ important than fault tolerance for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low required computing power is ___________________ important than simple routing table for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low required computing power is ___________________ important than low cost for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low required computing power is ___________________ important than low diagnostic process complexity for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling deterministic routing is ___________________ important than fault tolerance for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling deterministic routing is ___________________ important than simple routing table for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling deterministic routing is __________________ important than low cost for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling deterministic routing is __________________ important than low diagnostic process complexity for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling fault tolerance is __________________ important than simple routing table for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling fault tolerance is __________________ important than low cost for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling fault tolerance is __________________ important than low diagnostic process complexity for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling simple routing table is __________________ important than low cost for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling simple routing table is __________________ important than low diagnostic process complexity for a GWM architecture**

*A. extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately* more H. demonstratively more I. extremely more

**Enabling low cost is __________________ important than low diagnostic process complexity for a GWM architecture**

*extremely less B. demonstratively less C. moderately less D. less E. equally F. more G. moderately more H. demonstratively more I. extremely more*

# Appendix 5: MTR Meeting Minutes

## Appendix 5A: MTR Meeting Minutes for Theme 2 PSi

For confidentiality purpose, the attendees are referred by their initials. Also, Jaguar Land Rover Limited is referred to as JLR in this appendix.

**Attendees**:

GE, IK, VA, AR, AG, MP, HL

**Summary:**

- **Team work and communication:** MP informed that all the key researchers involved in the PSi programme work in synergy as a team and there is excellent communication within the team.
- **Shared responsibilities:** MP commented that splitting the research into three work packages with a leader assigned for each work package has helped to assess project performance independently and decide on key decisions like resources.
- **Effective use of PhD's:** MP informed that resources were planned carefully at the beginning of the PSi programme to ensure that resources were sufficiently spread across each work package/project. MP said that the strategy was to maximise the number of PhD students by funding them in partnership with the Jaguar Land Rover Limited (60% JLR funding-40% Loughborough funding). MP commented that output from the PhD students can be maximised to produce effective output if they are balanced with the work of a post-doc to ensure that milestones are delivered to JLR requirements. MP further said that it has been an effective model and something that JLR should consider.

- **JLR Brand Effect:** MP commented that the JLR brand name has helped to recruit good talent as researchers and PhD students on the project. MP informed that they have students from diverse academic backgrounds on the Theme. MP further said that a bigger bursary funded for longer periods (3.5 years instead of conventional 3 years) has also helped to attract talented candidates. AR noted that it is essential to ensure that recruitment is in line with the project plan. All agreed that the bureaucracy in academia can be a bottleneck.
- **IP and legal:** Regarding protection of IP, AR noted that expectations should be realistic on both sides (JLR and Universities). MP commented that from an academic perspective, exploitation of IP is difficult in case of mature industries like automotive.
- **JLR Support:** MP reported that the excellent responsiveness of JLR staff has been critical to the success of the projects. AR noted that it is challenging to get enough time from the JLR staff due to other JLR related commitments and agreed that sufficient JLR input is key to the success of the collaborative research programmes.
- MP talked through his slides on post-doc resource plan for the project. MP informed that the initial post-doc allocation was 180 months in total which was split between WP1, WP2 and WP3. MP explained that post-docs were initially given 18 months contract and then depending on the quality of their outputs, contracts were extended by 6 months in some cases.

## Appendix 5B: MTR Meeting Minutes for Theme 1 PSi

For confidentiality purpose, the attendees are referred by their initials. Also, Jaguar Land Rover Limited is referred to as JLR in this appendix.

**Attendees**:

CD, DB, JX, DM, PG, SJ, HL, AR, GE, IK, VA, AJ

**Summary:**

- CD requires a closer working relationship between JLR design engineers and Theme1 in order to achieve the aim of next step of Theme 1 research.
- CD states that the Theme 1 has a clear visibility of current process in regard of the 20% reduction of digital feature integration.

After the introduction section came the progress review section. CD explained other work packages.

- DM explained the future capability of VIDAE. VIDAE should be able to integrate all the systems in JLR for globe simulation online if JLR put VIDAE in place. Up to 70% of manpower can be reduced. He mentioned that the ROSETTA can be integrated into VIDAE as a service.
- PhD topic of DM is about QoS analyses of real-time simulation. DM stated the 8 hour delay related to cultural issues of individual engineers competing for HPC resources.
- DM stated that the academic publication came from every stage of PSi research outcomes.
- DM mentioned the live demo of VIDAE at Gaydon was successful and had positive responses with 50 engineers attended.

- CD then explained that there were two kinds of integrations: functional integration at software level and semantic integration. CD answered positively to the question that asked by AR which is whether there exist a standardisation between the two. CD mentioned FMI aka Functional Mockup Interface. AR said that many people in JLR are also looking at FMI.

After progress review section, the progresses of PhDs were discussed.

- DB explained that the PhD students under project 1.3 are doing fine, but not generally on the critical path towards implementing ROSETTA or VIDAE.

After the update of technical status, the topic of midterm review moved to how to deliver the research outcomes into business.

- AR emphasised that he was interested in what is going to be delivered out of the Theme and how might these be transferred into the business. He expected a range of outcomes, ranging from academic publications right up to tools ready for immediate deployment in the business.

There were several topics discussed after.

- The human resource and skills development.
- Knowledge transfer into business.
- JLR involvement to research
- IP and patent
- Third party development of the tool
- PSi follow-on possibilities

After the discussion, AR talked about his feeling of this midterm review.

AR felt that it had been a good discussion with valuable thoughts and suggestions for the future. He suggested creating a matrix with the main Theme outputs in and what are the enablers for them. This would help to communicate this to seniors like Mark Stanton who are keen to understand the ‘economic returns to JLR’ from the PSi programme.

A lot of things which have been worked on have become even more important since the start of PSi. AR asked if CD could think of any other things which JLR need to work on in terms of exploitation. PG suggested discussions with JLR about the costs of building models, for example how long does it take to integrate models.

AR thanked the team for its efforts in preparing for and hosting the review.

## Appendix 5C: MTR Meeting Minutes for Theme 9 PSi

For confidentiality purpose, the attendees are referred by their initials. Also, Jaguar Land Rover Limited is referred to as JLR in this appendix.

**Attendees**:

AR, EH, IK, HL, CS, CF, MY, XZ, APH, LK, DW, CP, PS, SE, LW

**Summary:**

- CS spoke about the case study of springs, the objective of which is to look at ways to simulate JLR's 12-week corrosion test as experienced by X152 suspension springs. This included discussions of :
- CP spoke about the engine mount case study.
- CP then went on to describe progress on the Instrument Panel (IP) case study.
- LK spoke about the LCA study work package.
- AR said a few words about his expectations for this part of the meeting. He was anticipating talking about what the Theme is expecting to deliver at end of Programme. He pointed out that IK has summarised these for the other Theme mid-term reviews.
- EH presented a slide listing the expected publications.
- AR considered attendees as appropriate.
- CS suggested that Mercedes encourage their suppliers to work on these sorts of emerging technologies. He also described how Boeing encourage their suppliers to work in this way.
- AR said BMW have gone almost mainstream with the technology so JLR are looking at it more seriously as process costs are coming down.
- LK felt that the creation of a competitive position needs a complete cost model through the product's entire lifecycle.

- Doctoral training centres were discussed. These were talked about at the start of this Theme, and JLR's potential support for them in particular. It was agreed that this could be a useful way of structuring follow-up work post-PSi.
- DW conjectured that the 3 case studies span a range of risk vs return – the spring study is low risk and can easily transfer knowledge, whereas the other 2 use cases have increasing uncertainty.
- AR thought it important to clarify what follow-up work is required to make the outcomes useable.
- IK asked about cost-effectiveness of the approaches being developed. EH didn't have a ready answer and said it was hard to put a value on the benefits realised by gaining the knowledge. CS pointed out the large number of JLR staff who have benefitted by the engagement with the Theme 9 team and suggested that PSi is an enabler in this respect. AR agreed that there is a knowledge transfer element to the work. These are intangible benefits. LK suggested that these innovations have the potential to improve business performance in the longer term.
- IK said that he would work with EH to identify additional stakeholders who should attend that review, in line with AR's comments following the recent Theme 3 Deep Dive in Le