A Novel Meta-Synthesis Approach to Technology Maturity Management for Project Risk Control

By

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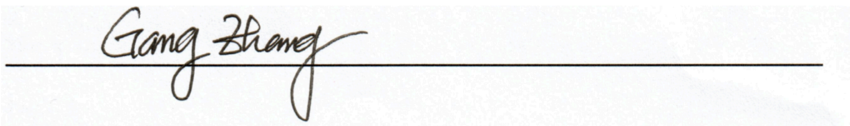
This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: 

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To my dear angels, Xinxin and Eric, and my wife Xiaoyan Rong!

谨以此文献给我可爱的天使，馨心和安安，和我的妻子荣晓燕！

ABSTRACT

With the rapid development of science and technology in modern society, "high-tech" is becoming the main characteristic of complex systems. However, due to the large scale of projects, and the intricate architecture and functionalities involved in these systems, traditional project development processes often encounter schedule delays, cost increases or performance degradation. Most of these are related to technical risk. Moreover, rapid change in both domestic and international markets and the acceleration of technology upgrading are bringing more challenges to risk management for complex system development.

To improve the risk management of key technology developments aiming to ensure the success of technical-critical complex systems, a Meta-Synthesis Approach (MSA) with technology assessment is proposed in this thesis. It combines quantitative and qualitative methods for assessing the maturity of technology (Technology Readiness Level, TRL) and also the difficulty of enhancing the technology maturity (Advancement Degree of Difficulty, AD2). The research focuses on the qualitative analysis of TRL assessment and quantitative assessment of AD2. Concepts and characteristics of technology maturity are discussed. An attributes-based qualitative TRL assessment method was developed and a unified maturity evidence chain is defined to capture and manage the maturity assessment information. A genetic algorithm based Numerical Integration method was developed for the quantitative assessment of AD2, embodying key calculation of parameters for maturity weight factors. After that, a visualisation method with technology maturity diagrams is proposed. All the above methods were integrated into MSA to assist decision-making of technology risk management. The advantages of the MSA are then discussed, detailing the spiral development process of Machine-factor (data modelling, simulation and analysis) and Man-Factor (Expert Decision-making System) to produce an iterative refinement of the technical risk management. The optimised methods and process are supported by an information and procedure management software tool. To evaluate the approach, the author employed nine case studies and questionnaires to illustrate the usefulness and efficacy of new methods and integrated processes. The thesis concludes with a discussion of the research including the limitations of the results and future research.

The key technological innovations of the research conducted in this thesis are listed below:

(1) A multi maturity attributes based qualitative TRL assessment method was proposed, demonstrating four views of the technology risk/maturity aspect, including (a) representation of the formation of the critical technology element state, (b) integration of the critical technology elements towards the system, (c) the fidelity of the testing or demonstration environments, together with (d) key performance indicators.

(2) A computational method for calculating AD2 is presented. Based on the unified assessment evidence chain, the method establishes a numerical integration calculation of AD2. During the numerical integration, a genetic algorithm is used to optimise the assessment features weight factors.
(3) A visualisation modelling based decision-making and information management software was developed in the research. It supports technology risk identification and the management process in aiming to facilitate technical decision-making, which is essential for a complex technology system management.
(4) A systematic approach based on MSA is proposed, which combines qualitative and quantitative assessment methods. Assessment information and a procedural management software platform acting as a "Machine" are concatenated to an experts group acting as a "Man", the whole composing a "Man-Machine System". To enhance the veracity of the TRL and AD2 assessment and apply the assessments to gain insight of technology risks, the "Man" dominates the synthesis procedure, and the "Machine" carries out the supporting quantitative calculations.
The multi-attributes qualitative TRL assessment method could not only identify the best practices origin of technical risk management in western society, but also combine Chinese System Engineering with an oriental system-view philosophy. The quantitative method, including the numerical integration calculation of AD2 proposed in this thesis, is helpful in building mathematical expressions of the technical difficulty and could provide a basis for further system R&D management. The above two methods are based on the unified assessment evidence chain. They are a first attempt to reveal the nature of technology risk. The limitation of the research is that the proposed quantitative method is based on the distinct decomposition of technology efforts and all the decoupled (when needed) efforts could map to a cardinal range value as they constitute a sample set for the numerical integration. In addition, the knowledge database could be embodied in the future to support the "Man-Machine" spiral advancement for understanding and improving the technology maturity.

Keywords: Technology risk, Technology maturity, Technology Readiness Level (TRL), Advancement Degree of Difficulty (AD2), Meta-Synthesis System Approach, Qualitative and quantitative methods

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NOMENCLATURE

Unless stated explicitly, the following abbreviations and symbols are used in this thesis, with their meaning listed below.

Abbreviations	Meaning
AD2	Advancement Degree of Difficulty, Bilbro
AFRL	Air Force Research Laboratory, USA
CTE	Critical Technology Element, NASA
CASC	China Aerospace Science and Technology Corporation
CGWIC	China Great Wall Industry Corp, China
DoD	Department of Defence, USA
ESA	European Space Agency
ETM	Evidence of Technology Maturity
GAO	Government Accountability Office, USA
GEO	Geostationary Earth Orbit
GTO	Geostationary Transfer Orbit
IRL	Integration Readiness Level
ITAM	Integrated Technology Analysis Methodology, Mankins
LEO	Low Earth Orbit
LTO	Lunar Transfer Orbit
MEO	Medium Earth Orbit
MRL	Manufacturing Readiness Level
MTO	Medium Earth Transfer orbit
MSA	Meta-synthesis (System) Approach
NASA	National Aeronautics and Space Administration, USA
NGLV	New Generation Launch Vehicle, CASC, China
R&D	Research and Development
R&D3	Research and Development Degree of Difficulty, Mankins
SRL	System Readiness Level
SSO	Sun-Synchronous Orbit
TCV	Technology Critical Value
TMA	Technology Maturity Assessment, NASA

TNV	Technology Needed Value
TRA	Technology Readiness Assessment, NASA
TRIZ	Theory of Inventive Problem Solving
TRL	Technology Readiness Level, NASA
TRRA	Technology Readiness and Risk Assessments
WBS	Work Breakdown Structure, Project Management Institute
△TRL	Delta of Technology Readiness Level, Mankins

The following variables are used in Genetic Algorithm:

Variables	**Meaning**
fit_{avg}	Average of the Fitness Function of Current Generation
$fit_{\max}$	Maximum of the Fitness Function of Current Generation
l_{cross}	Crossover Location in Gene
l_{cross0}	Predetermined Sensitive Location in Gene
$l_{variate}$	Mutation Location in Gene
n_{end}	Predetermined Maximum Generation
$n_{generation}$	Current Generation
p_{cross0}	Predetermined Crossover Probability
p_{cross}	Crossover Probability
$p_{variate}$	Mutation Probability

Chapter 1 Introduction

1.1 RESEARCH BACKGROUND

With the rapid development of science and technology, high-technology is becoming one of the main characteristics of complex systems. Technology-intensive systems are necessary for the new era of science and technology (Bilbro, 2007b). Traditionally, the project development process goes through "Pre-Research and Demonstration" to “Engineering Development” (Copeland et al., 2015). However, due to the vast and intricate architecture, complex functionalities, and multiple disciplines involved in these systems, it is more challenging to gain technological breakthroughs. The development of these technology-intensive systems nowadays often encountered with schedule delays, increased cost or technical performance degradation if immature technologies passed the critical decision points (GAO, 1999). Moreover, the circumstances of rapid change in open markets and the acceleration of technology upgrading are bringing more challenges to research management and risk control of complex technological innovation. Thus, it has been realised that the traditional project management, especially technology-related risk management, is unable to satisfy the urgent needs of new technological complex systems.

Since the technical risk of complex systems is seen as a significant source of risk during the technical development and product design stage, the National Aeronautics and Space Administration (NASA) of USA developed the concept of Technology Readiness Level (TRL) in the 1970s, which is a measurement scale against the maturity of a technology for the purpose of technology review (Sadin et al., 1989). A formal process of Technology Readiness Assessment (TRA) was then developed, through which the TRL assessment could become an organisation strategy and performed as best practice. The TRLs are usually ranged from the ordinal number “1”, means initiative technology discovery and research, to number “9”, means systems infused with this technology launch or operation at real application circumstances (NASA, 2010). It was then recommended by the Government Accountability Office (GAO) of USA as a best practice for the underlying policy of the Department of Defence (DoD) of USA and also for other departments (GAO, 1999). So far several decades have passed, TRL has been accepted as an essential tool for controlling technical risk of complex systems development and it is currently widely used in other industries in the United States, the European Space Agency (ESA), the UK Ministry of Defence (Olechowski et al., 2015), as well as China, Japan and other countries. ESA is utilising the ISO standard 16290 Space systems – Definition of the TRL and their criteria assessment (ESA, 2015).

NASA pointed out that technical assessment includes two steps: (1) evaluating current critical technologies maturity and (2) evaluating the promotion difficulty of technical maturity (NASA named it for Advancement Degree of Difficulty, AD2). The maturity of critical technologies is evaluated through a top-down decomposition of the technical structure of the target system. AD2 is traditionally evaluated in order to analyse risks and optimise efforts to promote technology maturity. The two steps have become the basic framework of technical risk management of complex technical systems.

The research presented in this thesis is derived from the practices of risk management of the New Generation Launch Vehicle programme (NGLV) of Chinese Aerospace Science and Technology Corp (CASC) (Dong and Tang Ming, 2008). The NGLV Programme is to enhance China's capability in access to space greatly. It includes serial carrier rocket development of non-toxic, pollution-free, heavy or medium-lift capacity and low-cost launch vehicles, such as carrier rocket LongMarch5, LongMarch6, LongMarch7 and LongMarch11 (Long et al., 2018). According to LongMarch5 technology breakdown structure, there are 247 critical technologies of which 12 are significant technology innovations. This is much higher than regular aerospace missions. There were 2100 ground test or demonstration involved, and experiments have been conducted more than 7000 times (Li and Cheng, 2006). Take LongMarch7 as another example. There are 11 significant technologies and 96 technical innovations (Fan et al., 2016). In order to reduce risks involved in developing these new technologies, the NGLV Programme Office decided to introduce technology maturity associated methods to identify and manage technical risks. A quantitative technology mature assessment was needed to support the decomposition and deployment of various research and experiment tasks of the project, especially when the tasks were in the initial inspection stage and post evaluation stage. They all require a quantitative description of the efforts to enhance the technologies maturity, in order to match the project funding and research period. Meanwhile, the office needed a comprehensive visual representation of technical maturity and risk information management software to support decision-making.

Projects in western countries have well embraced the TRL as "Best Practices" for technology critical ones. The research presented in this thesis endeavours to reveal the nature of the technology risk. It is inevitable for the project manager of NGLV to encounter conflicts especially when they try to merge western process into different oriental management philosophy rooted from Chinese engineering culture background. Meanwhile, any previous practices need revivification in the new project due to its uniqueness. Therefore, mastering the true reason why the practices ranked to be best or to be successful, played a much more vital role. Surely there are some common guidelines about how to summarise experience to disciplines, and how to adapt them to new realistic practice, but the situation varies case by case. For the TRL based technology risk management, the essential factor is achieving "shared understanding" of technology maturity status on why and how much it impacts the success of the whole project (Sadin et al., 1989).

Based on the above-stated thinking and universal relevance of the study, the research presented in this thesis focused on processes, methods, synthesis and visual representation of the technology maturity management of complex technological systems for project risk control.

1.2 THE SCOPE OF THE WORK

Risks in a technical system development project involve application-specific domains including technical, financial, operational, social and supply chain risks. The research presented in this thesis focuses on technology risk management. The boundary of the research is defined, and the research focus is shown below in Figure 1-1.

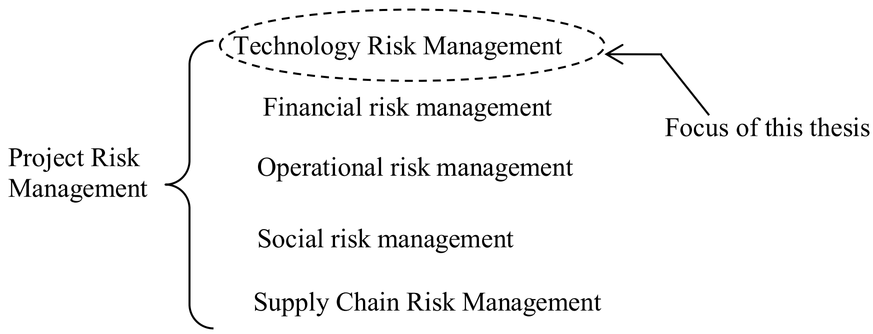

Figure 1-1: Research focus

Technology maturity assessment, as a way of technical risk identification, relies more distinctly on the assessing experts team. In the NGLV project, the Project Management Office has followed the system engineering procedure, which includes a safety review and technical design board responsibility. It requires the western-born TRL assessment method to merge into the review procedure and to capture significant technology risks, ensuring the accuracy of the TRL estimation. From this point of view, it should focus on practical qualitative assessment of TRL, using a suitable alternative way to reflect the technology risk. The research presented in this thesis also focuses on the quantitative assessment of AD2, which could provide evidence of the project's cost, assist in scheduling R&D plans of sub-contractors. Then from a management viewpoint, a method to facilitate decision-making is also needed, such as visualisation of technology maturity or information management software tool.

The followings are the assumed or predefined conditions:

- ✓ Focus on technology risk due to technological immaturity, rather than technology risk to ethical implications.
- ✓ Quantitative assessment of AD2 is needed, which reflects the efforts to increase maturity and could be an indicator to maintain the R&D investment among sub-contractors.
- ✓ Quantitative and qualitative results synthesis for decision-making combined with risk management, rather than the assessment itself.
- ✓ Focus on the new technology impact, rather than heritage technology infusion or transfer, as such technologies are inevitably involved with re-engineering or another technology risk different from new technology development.

1.3 SYSTEM ENGINEERING, RISK MANAGEMENT AND TECHNOLOGY ASSESSMENT

System Engineering is an effective, methodical and disciplined approach to design, realisation, technical management, operations, and retirement of a system (NASA, 2007). It is commonly recognised as a distinct research discipline during World War II, the 1950s and 1960s. The risk is the effect of uncertainty on objectives (ISO, 2009b). Risk management aims to coordinate activities in order to direct and control the factors related to risk, which is an essential part of system engineering. The aerospace engineering system is a typical complex system and should be managed by the concepts and methods of system engineering as immature technology is a significant source of risk in these systems (GAO, 1999).

Technology maturity was first proposed by NASA in the 1980s (Sadin et al., 1989, NASA, 2010). GAO recommended it and accepted by the DoD of USA in order to control the risk of technology development in their weapon system acquisition. It was pointed out that "The traditional management approach will not meet these expectations", for it "much greater cost and time than planned", and the reason lies on "immature technologies have been main sources of problems on weapon systems"(GAO, 1999). Letting the new technologies matured enough before they are included in a product could be the most important to ensure success. In recent years GAO has released an annual audit report on the large-scale projects of DoD and NASA, and the risk of technology maturity is the crucial factor among most of the reports (GAO, 2016).

The above problem occurs not only in complicated system projects of the US DoD and NASA, but also in systems all around the world, including China's aerospace industry. China has developed a systematic management strategy while carrying its space exploration missions since 1970s. A large proportion of the problems in this were related to immature technology. Take the launch of No. 708 international communication satellite (Intelsat 708) as an example. On the early morning of 15th February 1996, China Aerospace Science and Technology Corporation (CASC) prepared a "LongMarch 3B" carrier rocket to deliver this satellite, but the rocket veered and exploded in 22 seconds after ignition. Follow on investigation revealed that the explosion was due to the unexpected opening of the electric circuit of the Integrated Rocket Attitude Control Platform. The failure had multiple exposures and was monitored several times before the launch, but the design team did not fully understand the technical risk of the difference between the test environment and the actual operational environment(CASC, 2016). Thus this immaturity of technology has led to a significant unbalanced damage of the Inertial Attitude Control Reference System, as a consequence, led to the mission failure.

Another example is the Sino-Satellite (with satellite ID of SinoSat-2), China's first Digital Broadcast Satellite, which was sent to the orbit on 29th October 2006. However, after satellite-rocket separation, it could not fully deploy the main solar panels and telecommunications antennae, due to a technical malfunction during the second deployment stage within its orbiting positioning process. The satellite payloads could not carry out their designed main functions, so it resulted in the satellite's inability to provide telecommunication and broadcasting services. The reason was also linked with the technical risk of whether the ground test covers various failure modes related to the operational environment (CGWIC, 2006).

In summary, the need to establish an effective assessment mechanism for project technology maturity was widely studied and evaluated.

1.4 TECHNOLOGY MATURITY AND ADVANCEMENT DEGREE OF DIFFICULTY

According to modern systems engineering principles, the critical technologies of a complex system are the core parts of the project, and they play an indispensable role in the successful completion of the project. Therefore, the critical technologies have been the focus of project evaluation. NASA has put great research focus on the evaluation of technology and technical processes. Technology evaluation includes two steps, technical maturity evaluation

(Technology Readiness Assessment, TRA) and technical maturity difficulty evaluation (AD2) (NASA, 2007).

TRA is a formal, systematic, metrics-based method that assesses the TRL of critical hardware and software technologies to be used in systems (DoD, 2009). Through TRA, the project team can evaluate the maturity of critical technologies in order to determine if the technologies are ready for the application stage. It could enable the technical and project management team to reach an agreement and understanding of the development process and technical risks, and facilitate the design and manufacturing specifications of the project. The application of TRA could not only help identify the technology maturity level so that the technology could be applied at the right time, but also facilitate the design and management team with identification and control ability of high-tech risks.

TRA methods have received more and more attention as the primary technology maturity evaluation method internationally, and it has been gradually applied to the development process of complex technical systems. However, though TRL could reveal the technical maturity, it could not adequately reflect how difficult it would be for a technology to be promoted to a higher level of maturity. Therefore, TRL could only act as a reference "ruler" of technology management maturity. The management officer and design teams concern more about how to promote a technology from a certain level of maturity to a higher level. It is defined as "Advancement Degree of Difficulty" (Bilbro, 2002). Then based on the assessment of the AD2, the risk level may be obtained in the process of technological development in order to assist the project management team to develop a practical technological research plan and derive more effective management strategies and methods.

Since the concept of AD2 was proposed, it has gradually been accepted by the industry as a follow-up technical skill of technology assessment. Related research and application are being put into the practice internal technology transfer (Stig et al., 2011) and whole life cycle cost management (Robinson, 2009). The TRL and AD2 are clearly defined as two parts of the evaluation in current NASA Systems Engineering Handbook. Some examples of using TRL and AD2 in space exploration missions such as solar sail technology (which could be demonstrated useful for future deep space missions) and James Webb Space Telescope to promote maturity of critical technologies (Macdonald, 2011). However, the research and application of AD2 are far less than those of TRL and TRA.

Nowadays, the assessment method of AD2 has been mainly based on the checklist method. The primary purpose of the method is to identify the lack of technical maturity elements, as well as to provide technology-based guidelines for complex technical systems for further development. Meanwhile, the traditional assessment method is a qualitative method that relies on the unique performance of individual participating experts, with somehow subjectivity and limitations. It is not enough to support the establishment of quantitative project management, for the assessment of the difficulty to mature pertain to a "prediction of future" technology (Bilbro, 2008). As a consequence, quantitative assessment method is required if more objective and accurate results are to be achieved.

1.5 RESEARCH AIM AND OBJECTIVES

1.5.1 Research aim

Overall, the research presented in this thesis aims to investigate the fundamental rules of the technology risk management for complex projects, merge the best practice of maturity readiness assessment and Meta-Synthesis Approach (MSA) process from different system engineering phenomenon, and develop a qualitative and quantitative combined framework to ensure project success.

1.5.2 Research objectives

This research is originated from participating in the independent risk assessment of complex technological systems (NGLV Programme as background mission) in recent years. Consequently, the work presented in this thesis focuses on the need to provide engineering and technical risk analysis and scientific decision-making management support to the NGLV Project Management Office (PMO). From this point of view, the first step of technology risk control is to ensure the accuracy of the TRL assessment; then the second step is to give a data-represented further R&D work schedule (AD2 assessment) to tackle the technical issues. Then it is required to provide a software platform to assist the information management and decision-making process. All the above leads the fusion of TRL/AD2 based technology risk management and Meta-Synthesis Approach (MSA) of the established Oriental System Engineering Procedure. This could achieve a mutual understanding of technological risk within the engineering design team and the manager. It carries out research related to technology maturity, AD2, qualitative and quantitative assessment methods and visualisation aided decision-making support. It also investigates the innovation management process, merging both advantages of qualitative and quantitative methods into a spiral “Man-Machine” interactive Meta-Synthesis Approach. In addition, case studies are also needed to demonstrate and evaluate the approach. Therefore, the objectives of the research are:

- ✓ (O1) TRL assessment method refinement: develop a practical method which could focus on technology risk, marge into the Oriental System Engineering Process;

- ✓ (O2) Research to carry out quantitative AD2 assessment technology for complex technology systems. The data-represented efforts could be used as a project R&D cost indicator.
  - ■ (O2.1) Propose a macro framework and process of quantitative assessment method of AD2, covering the backbone procedure of a quantitative calculation process
  - ■ (O2.2) Algorithm design supporting the quantitative assessment of AD2
  - ■ (O2.3) Solutions of key parameters estimation, using accumulated engineering data to improve the veracity of the result.
- ✓ (O3) Provide visualisation of technology maturity and AD2 to assist the decision-making process, based on the intuitive judgment and analysis of project technical characteristics.
- ✓ (O4) Complete a Meta-Synthesis Approach based working process, define framework and algorithm supporting the qualitative and quantitative assessment of TRL/AD2, and develop a prototype of a software platform to assist the TRL/AD2 assessment information and process management.
- ✓ (O5) Conduct the case studies of new TRL/AD2 assessment methods and integrated MSA approach for illustration and improvement.

1.6 THESIS STRUCTURE

The structure of the thesis is organised as below:

Chapter 1 is the introduction. A brief description of the research background, history of technical maturity evaluation, as well as AD2 assessment, are given. A brief overview of technical maturity is presented which defines the research background. Research aim and objectives are presented.

Chapter 2 is the literature review. Related research literature investigation is carried out, describing and analysing the research literature gathered. Technical evaluation, risk management, TRL/AD2 related maturity assessment, Meta Synthesis Approach (MSA), and other related topics are analysed. The research gap is then identified which leads to the research focus and content of this thesis.

Chapter 3 presents the research methodology. Both qualitative and quantitative research methods of technology maturity are presented. A method of top-down technology maturity assessment in order to eliminate the significant technical risks is presented. Also, an integrated approach based on the MSA is proposed, combining qualitative and quantitative evaluation methods. The research design with a road-map of the whole thesis is then presented.

Chapter 4 demonstrates a qualitative assessment method of TRL, which combines the technology risk identification of the Chinese System Engineering process. It conducts multi-attributes based assessment features (a common practical framework of crucial questions to answer), reforming an extended TRL technology maturity evaluation procedure to ensure the accuracy of the risk assessment.

Chapter 5 presents a quantitative assessment method of AD2. Based on the maturity evaluation chain, the definition and basic properties of AD2 are given. Conditions and constraints of quantitative evaluation are deduced. Then it follows by the critical steps of the quantitative evaluation method, including the establishment of an integral formula for calculating AD2 and the realisation of the integral calculation. Two important parameters are used in the integral formula: the numerical weights factors of assessment features and a state density function for each feature. The determination of the two set of parameters are discussed in detail, which completes the algorithm of the calculation process

Chapter 6 presents the visualisation of technology maturity, which could be used to facilitate decision-making management. The visualisation of both the maturity of technology and AD2 are presented, and visual state distribution figures as well as data used in the figures are determined and established.

Chapter 7 presents integrated qualitative-quantitative analysis and risk management based on TRL/AD2. The process is given by combining qualitative and quantitative methods in order to enhance the accuracy of the assessment and gain insight of the risks. A supporting computer prototype tool for the evaluation is designed. The risk management process is improved using the MSA approach.

Illustrations are presented in **Chapter 8** through case studies. Demonstrations of the new assessment method of the TRL, quantitative AD2 assessment and integrated MSA approach are carried out. Results of the case analysis are used to improve the research findings.

Finally, a discussion and conclusion of the significant research contents and innovation points are given in **Chapter 9**. Future research work is proposed based on the work presented in this thesis and analysis of the limitations of the study.

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Chapter 2 Literature Review

This chapter will describe and analyse the research background, give every literature definition of the research. The research gap is derived which leads to the research focus and content of this thesis.

The literature review mainly focuses on such fields as the technical risk management method, TRL/AD2, qualitative/quantitative research method, and visual expression of technical maturity.

2.1 BACKGROUND PROJECT AND PHD RESEARCH CONTEXT

As the research background project, New Generation Launch Vehicle project (NGLV) was initialised by the China Space Administration in 2001(ChineseGovernment, 2001), with aiming to develop "non-toxic, pollution-free, high-performance and low-cost carrier rockets" of "LongMarch (CZ series)" launch vehicles families. The NGLV project has the carrier rocket type ranged from LongMarch-5 (CZ5), LongMarch-6 (CZ6), LongMarch-7 (CZ7), LongMarch-8 (CZ8) and LongMarch-11 (CZ11), to upgrade the original developed LongMarch-1 to LongMarch-4 (CZ4). The NGLV was endowed with supporting future space activities of China including Manned Mission, Deep Space Exploration and TianGong Manned Space Station.

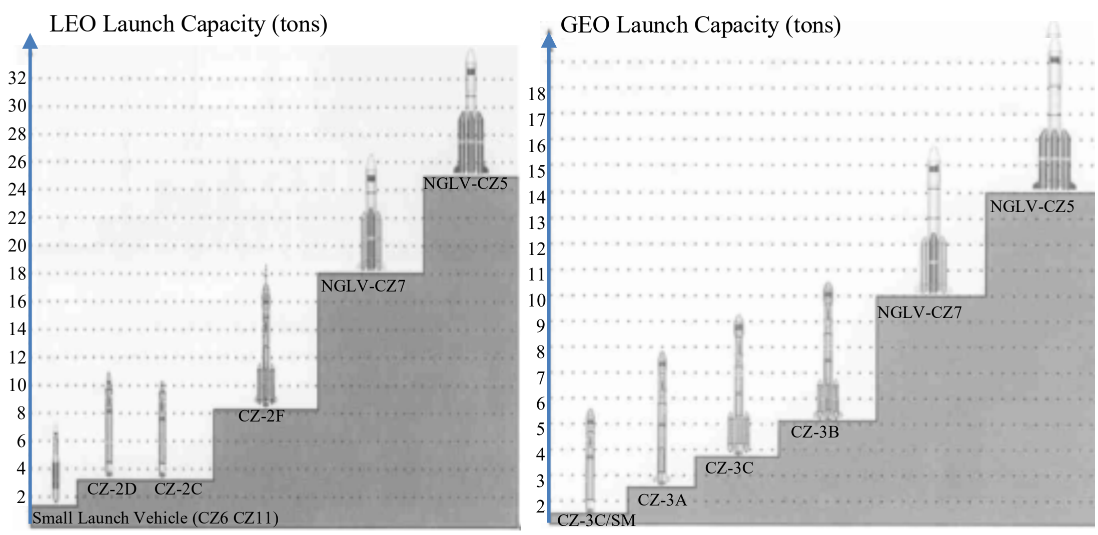

Figure 2-1 NGLV launch LEO/GTO capacity (Li and Cheng, 2006)

The NGLV project would cover several Five-Year Programs for National Economic and Social Development of China. The newest report has given a brief review of the NGLV as it was the fifth development phase of China Space Transportation System. Lately, the Heavy Carrier Rocket LangMarch-9 (CZ9) was added to expend the launch capacity to 140 tons of LEO and 40 tons of LTO after argumentation and demonstration. So the NGLV is updating its "NEW" connotation to include new types of Long-March launch vehicles families and still ongoing by submission time of this thesis.

The NGLV was characterised by "generalised, serialised and combined" carrier rocket module development requirements (Dong and Tang Ming, 2008). As the following figure shows (the pink coloured annotation is to identify the rocket engine configuration), the first stage and booster have configured with rocket engine of YF-100 and YF-115, liquid rocket engine burning LOX and kerosene. Moreover, the second stage, third stage or upper stage could be the rocket engine of YF-75, liquid hydrogen and oxygen engine (Zhang and Wang, 2016).

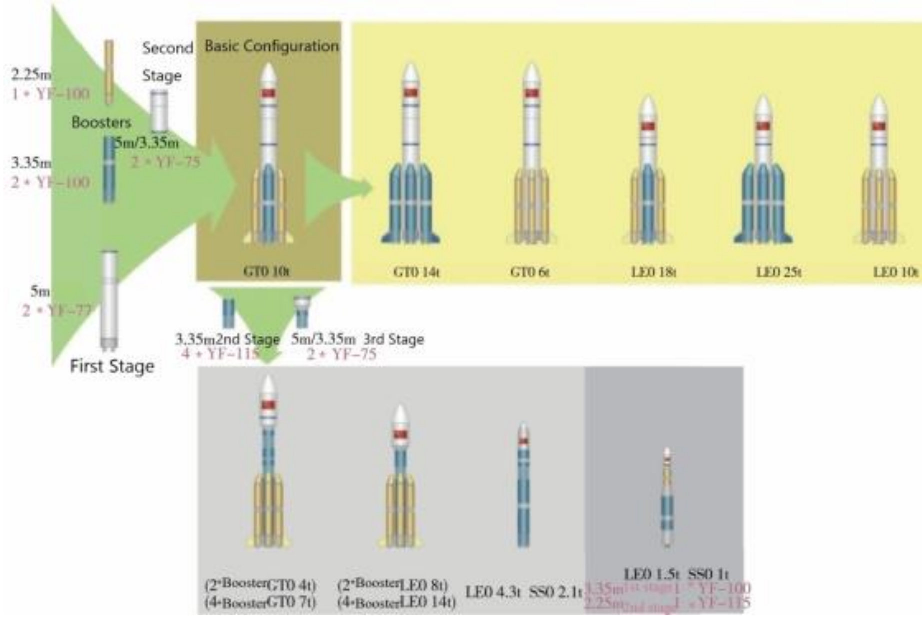

Figure 2-2 Profile and Configuration of Multistage NGLV Project(Long et al., 2018)

Technical innovation and system risk are critical management contents of the NGLV project. Mr Li, the Chief designer of the CZ-5 launch vehicle, has represented a profile of the NGLV project and concluded that the CZ-5 has made breakthroughs of 247 key technologies and 12 among them have significant impacts (Li et al., 2017). The number of ground tests or experiments number has reached 7000. Fan also gave the general design of CZ-7 and concluded that it derived 11 fundamental technological breakthroughs and 96 innovative technologies (Fan et al., 2016).

The research of NGLV Programme falls into the category of technical risk management of complex technical systems. Consequently, the literature review of this research is mainly dominated by the technical risk management in the aerospace-related fields in China, America and Europe. Also, case analysis and best practice of similar fields such as nuclear power plant, transportation systems were also taken as references. Unavoidably, the research should include the engineering management culture impact on the different understanding of the System Engineering between eastern and western society.

2.2 RISK MANAGEMENT

According to the definition of modern project management, risks mainly aim to describe the uncertainty of the system; Risk is "the effect of uncertainty on objectives" (ISO, 2009b, ISO, 2009a). For instance, introducing new technologies to bring changes for the matching of the system design in the research and development process, such changes can be considered as a root of risk. Risk analysis is an essential part of the complex system development process, as well as the core of system engineering and project management.

The risk management process is a systematic application of management policies, procedures and practices to the activities of communicating, consulting, establishing the context, and identifying, analysing, evaluating, mitigating, monitoring and reviewing risk (ISO, 2009b). The risk management process consists of risk identification, risk analysis, risk treatment and risk control. Risk control means that risk managers would take all kinds of measures and methods to eliminate or reduce all possibilities of risk events or reduce the pernicious consequences. With the development and progress of science and technology, there are various technical approaches to accomplishing the system target, and the risk analysis becomes the critical content of the technical decision. According to the general development trend of risk management, the technical risk has progressively become an important factor determining the success of the system, while the adoption of evaluation of the technology maturity and the technology maturity plan is a significant approach to resolving technical risks of the system.

Current risk management often adopts such strategies as risk avoidance, risk transfer, risk reduction and risk acceptance by aiming at the known risks. If the main internal mechanism and form of expression of risks are well understood, it will not be difficult to manage these risks. Targeting at some known uncertainty that may occur in the technology development process, some alternative methods can be prepared, or sufficient time and other resources can be reserved, for the convenience of alleviating the enormous impacts of system development in case of the "**known unknowns**". These risks of technology maturity are of medium level, and the maturity difficulty is also of medium level. If whether the risk would occur cannot be determined in the future by relying on existing knowledge and experience, the risk of technology would be greater ("**the unknown unknowns"**). If the risk is further increased, it may bring chaos to the technology management, and the relationship between the internal mechanism and technology maturity can be displayed in the following Figure 2-9 (Bilbro, 2008).

The study of the technical risk of a complex system and adoption of technology maturity difficulty aims to improve the technology maturity, while the technical risk of the system keeps declining so that the "unknown unknowns" can be declined as "known unknowns", and then down to "well understood". For these high-level "chaos" risks, it can reduce the possibility in the earlier project development stage.

In aerospace-related projects, technology innovation was becoming the main driving force since the early stage, as one of the essential factors that have affected project success(Sadin et al., 1989). As a consequence, the risk management of aerospace missions was mostly involved in technology maturity impacts. So the origin of the TRL assessment is that maintaining the risk being kept the technology factors under control.

In 1999，GAO issued a report named "Best Practices: Better Management of Technology Development Can Improve System Outcomes". GAO underlined that the risk management of technology maturity becomes the main factor of project success (GAO, 1999). Annual reports continued to newer missions in 2016. In a report, NASA revealed that there still has two major projects experiencing significant cost growth or schedule delay, although overall performance has improved. The report has a title "NASA: Assessment of Major Projects". Also, it pointed out that NASA has maintained recent improvements in the technology maturity and design stability of most projects, in the critical decision point most projects have passed the maturity criteria, resulting in technology risk reduced (GAO, 2016).

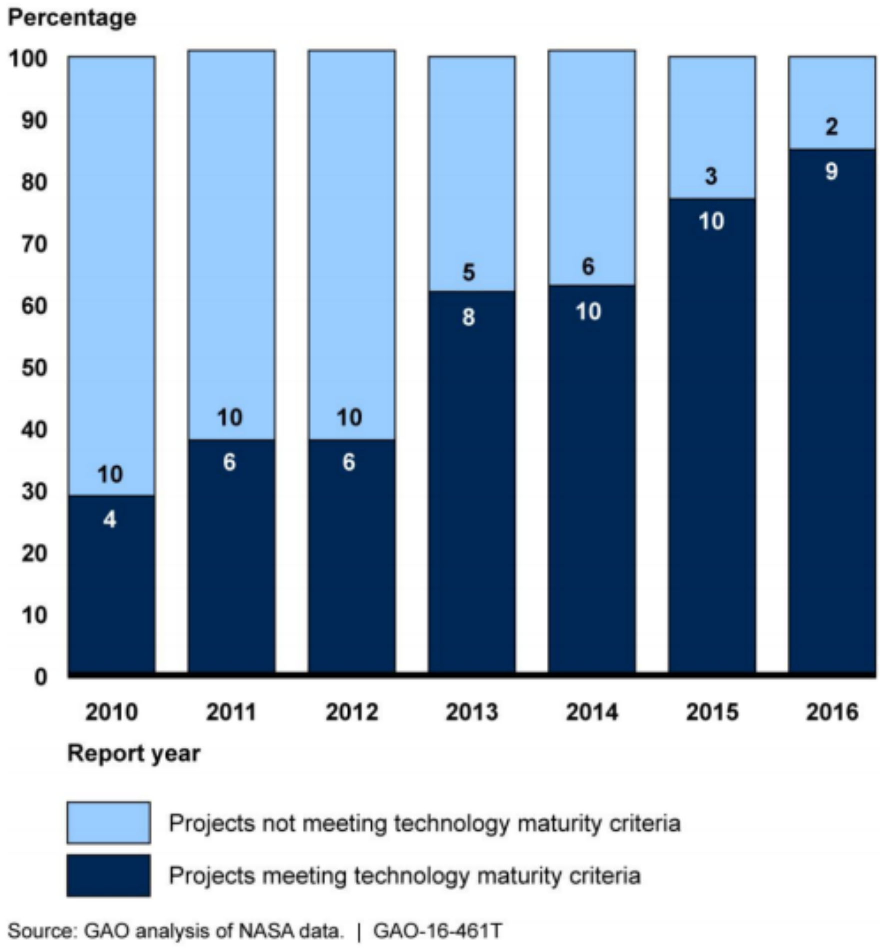

Figure 2-3: NASA Projects Meet the TRL criteria (GAO 2016)

The Chinese space industry has also gained experience in risk management and learned lessons. For instance, on February 15, 1996, Long March 3B carrier rocket unsuccessfully launched the international 708 communication satellite from Xichang Satellite Launch Centre. The analysis report shows that the reason for the failure of the launch was that the function of an electronic circuit component in the control system, this resulted in an open 28V Voltage power-supply circuit of the following-up ring stable loop. Afterwards, the inertial reference data of the control system changed to exceeding the designed scope.

Consequently, the rocket finally deviated from its designed trajectory and exploded. The investigation revealed that the fault had already been exposed several times during the test and integration phase. However, the design team failed to realise the correlation between the device-level failure and platform malfunctions, or the internal mechanism of the single device failure and launching failure transmission. Ground test verification failed to emulate the corresponding relevant environment of the launch. Most of the engineer on the launch suite believed that the control system was matured enough for this mission. From the rules of technology maturity, there were considerable differences between the test environment (related environment) and the actual application environment, which would lead to severe deviation in the understanding of technology maturity.

2.3 TECHNOLOGY MATURITY ASSESSMENT

The research of the assessment of technology maturity has been carried out a lot both in China and internationally. Many assessment methods (LIU et al., 2010, Guo, 2010, Yang, 2011, RU et al., 2011, Li and Liu, 2014, Ma et al., 2014) are proposed and most frequently use maturity assessment models including patent based maturity analysis models, maturity analysis models based on bibliometric data and TRL based maturity models (Daim et al., 2005, Dubos et al., 2007) and other references.

The maturity analysis model based on a patent is represented by Altshuller(He et al., 2010, Gibson, 1999, Kowalick, 1997). The relationship (Slocum, 1998) among the variation tendency of patent number, product's patent level, patent number, product's technical performance, profitability and technology life cycle illustrated by the S-curve is built through the statistical analysis of a vast number of patents. The curve is called the Four Relationship Curves Operator (FRCO) (Kowalick, 1997). After that, this method is used for the analysis of the trend of technical development. The maturity analysis based on bibliometric data is supported by Roper, Godin and so on. They proposed that the ratio of the number of journal articles and that of conference papers, the qualitative change of keywords and the analysis of changing the rule of reference types can be used to determine the technological maturity of new products. When there are many conference papers, it is shown that the technology is still under discussion and is far from being mature; when the number of journal articles increases, the technology starts to approach to the maturity stage (Porter et al., 2011). When the keywords turn to the description of material characteristics and processing properties or the analytical characteristics of technology implementation systems, then the technology starts to move into the mature stage. As for the types of reference, the number of papers in the SCI (Science Citation Index) increases dramatically in the fundamental research stage. In the stage of experimental design, the number of patents increases gradually, if the number of invention patents starts to decrease and the number of design patents starts to increase, the technology has entered into the mature stage.

TRLs are levels from 1 to 9 scale developed by Stanley Sadin for NASA (and used by NASA first at ordinal scales "1" to "7") that describes the maturity of technology concerning a space application usage (Mankins, 2009). In 1995, John Mankins from NASA submitted the white-paper of TRL (Mankins, 1995). Then, GAO concluded that "Maturing new technology before it is included on a product is perhaps the most important determinant of the success", GAO went further by encouraging the use of "a disciplined and knowledge-based approach of assessing technology maturity, such as TRL" (GAO, 1999). GAO mainly suggested the use of TRL to make sure that technologies are mature enough before integrating them in the acquisition cycle. TRL was accepted by NASA Guide Book (NASA, 2007) after that. DoD later required the use of TRL as criteria to pass Milestones B and C in the Acquisition cycle (DoD, 2009). DoD has uncounted with cost growth of $296 billion on its 96 major acquisition programs in the fiscal year 2008, for it poorly addressed its challenges for many technologies. In another performance audit of 72 DoD programs, the GAO reported more than 25% cost growth for 44% of the programs in the fiscal year 2007 with an average schedule delay of 21 months (GAO, 2008). Other GAO reports (GAO, 2008, GAO, 2000, GAO, 2010) also noted failure to meet capability and performance requirements. The DoD also faces problems with increasing systems complexity and integration. The F-35 aircraft is an example of cost overrun of more than 50 percent. The study also identified 13 areas of concern (some of which are critical) due to system complexity and concurrency (GAO, 2011).

As their definition, the terms of "readiness" and "maturity" are two different concepts. They should have their meanings only within the contextual such as "ready for what purpose?" and "mature enough for doing what?" From the context of the overall System Lifecycle point of view, they are answering completely different enquires within the System Engineering scope. System Maturity is to assess if there achieved a pre-defined and implemented system. One needs to judge Readiness to assess when a system is fit for purpose for a particular context. One could notice that the "maturity" is encapsulated within the "readiness" for a system specified, for the system must first be fully "mature" before it can be "ready" for use. From the System Engineering aspect, "System Maturity" is to answer the question that the system was developed matured step by step, so the verification of each step within the development lifecycle was the focus. "System Readiness" then need to answer either the system is "ready" for use, so it focuses on the validation of the whole system. The following Figure 2-4 shows the relations between the two. It is common meaning that the two notions are not treated as two distinct concepts and are often used interchangeably.

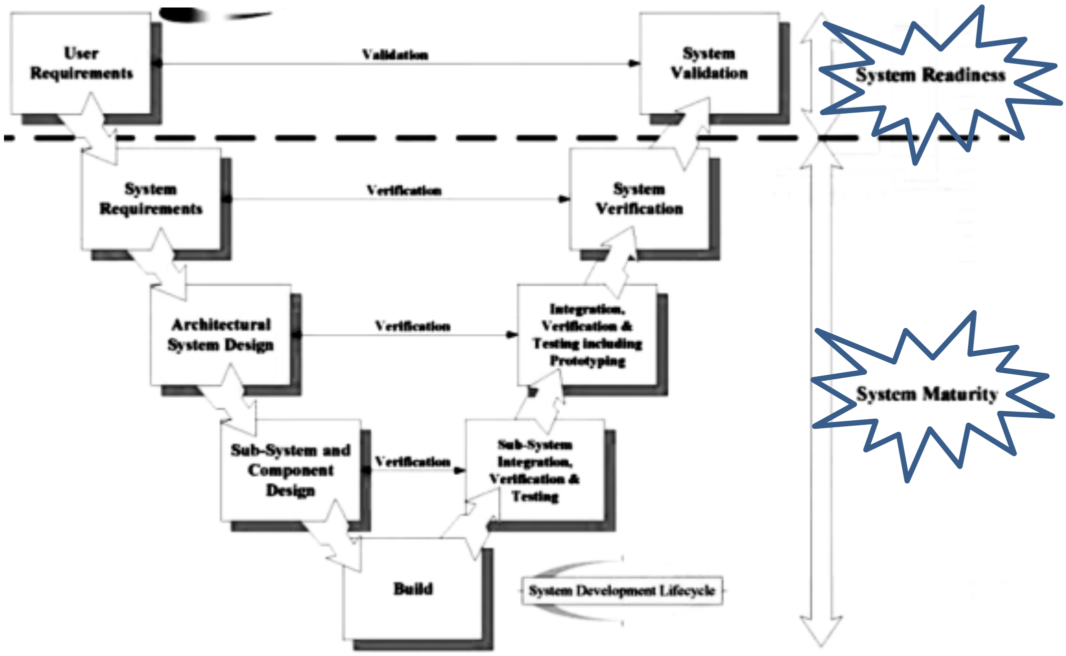

Figure 2-4: Maturity and Readiness within System Engineering (Tetlay and John, 2009)

A road-map of TRL developing and its applications in NASA has been summarised by Mankins (Mankins, 2009), which is shown below.

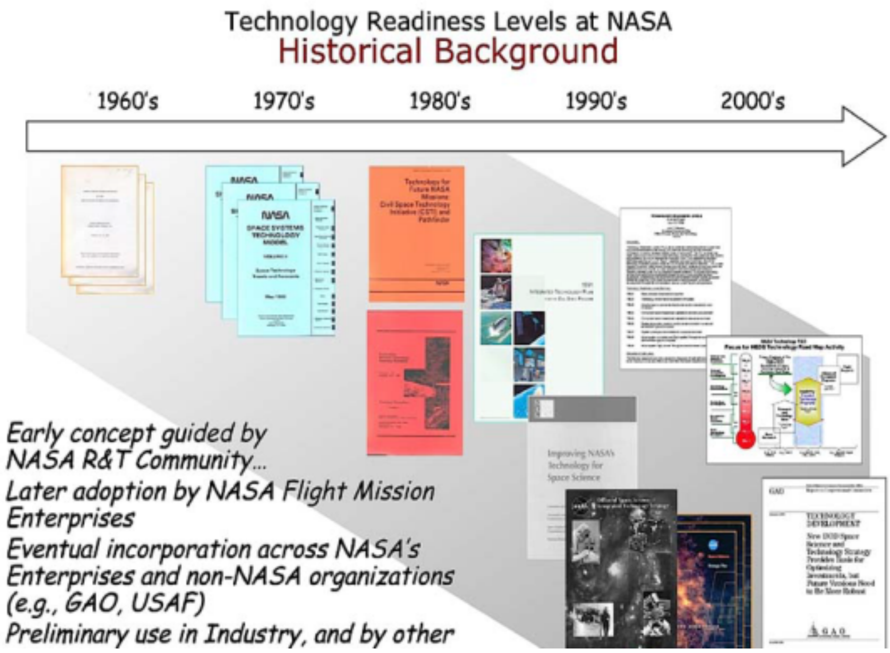

Figure 2-5: Timeline for the emergence of the TRL scale (Mankins (2009))

Guo(Guo, 2010) has extended the literature review of TRL and related TRA to the end of the 2010s. We can see that TRL was wildly recognised after GAO of the USA pushing it as the annual audit program content.

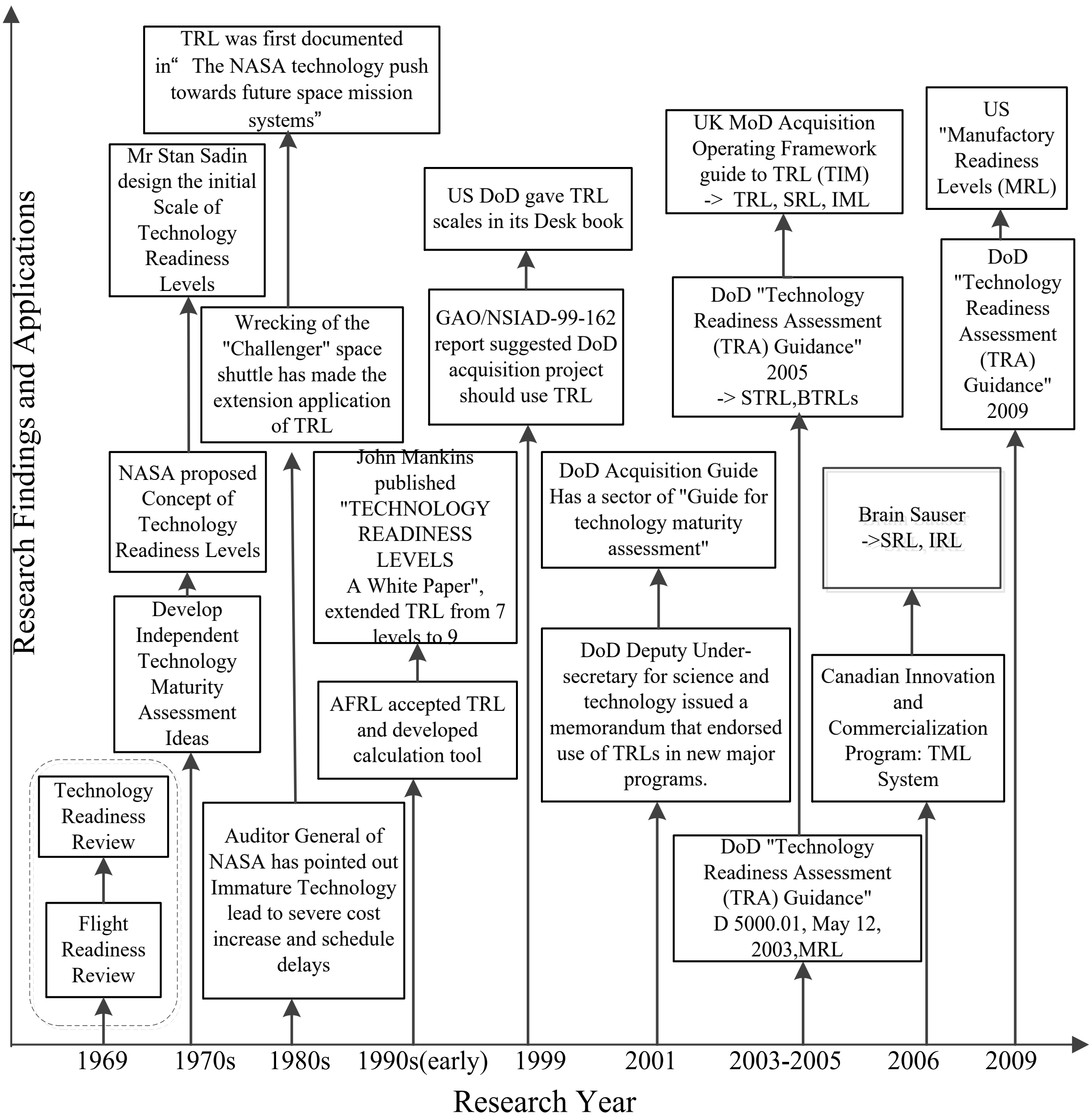

Figure 2-6: Development of TRL related research (Guo, 2010)

Besides the technology, there are also other "maturity" models acts as different tools/metrics to assess the maturity states of organisation, manufacturing, and systems. After 2010 the following are most commented by Olechowski (Olechowski et al., 2015a), that the Integration Readiness Levels (IRL) and System Readiness Levels (SRL), introduced by Sauser and others (Sauser et al., 2008a); Manufactory Readiness Levels By Morgan(Morgan, 2008); Maturity of the production process (Fernandez, 2010); Software Maturity Model etc. (Bicego and Kuvaja, 1996, Quah, 2009). IRL is used to evaluate the integration maturity between technologies, then accumulated to a high hierarchical structure (Gove, 2007); SRL, a kind of quantitative method, is used to provide the maturity of the system(Sauser et al., 2008b) (Ramirez-Marquez and Sauser, 2009). Each technology in the system is composed of multiple small technical combinations. Several technologies and the connections among them make up the SRL matrix, which is based on TRL and IRL.

An uncompleted list could be found at the following(Olechowski et al., 2015a):

√ Capability Readiness Levels	√ Human Readiness Levels
√ Integration Readiness Levels (IRLs)	√ Logistics Readiness Levels
√ System Readiness Levels (SRLs)	√ Operational Readiness Levels
√ Design Readiness Levels	√ Software Readiness Level
√ Innovation Readiness Levels	√ Programmatic Readiness Levels

Joseph Fernandez, from Sandia National Laboratories, has summarised the Benefits(6 clauses) and Limitations (11 clauses)(Fernandez, 2010). The main benefits include "Provides an ontology to evaluate component technologies", "Provides for a component TRA", "Initiates a discussion among the stakeholders to consider other factors", "Provides a mechanism whereby the process can be easily repeated", "Easy to understand and use", and "Conveys a great deal of information in its relative risk in the life cycle". Also, the main disadvantages of TRL include "does not tell anything about how difficult it will be to achieve the next TRL" and "lacks a standard guideline for implementing". All the shortages lead to several methods about how to assess the AD2 of upgrading an immature technology.

In the late 1990s, China also started to emphasise the research of technology maturity and gradually of theoretical research and evaluation methods. TRL is a widely used for evaluation of technology maturity which is significant and suitable for the establishment of the criteria of technology risk. For example, Qian Dong, with other researchers, studies the grading standard of imported equipment technology maturity, the corresponding R&D phase and the evaluation method which has been applied in practice. Concerning the TRL assessment method of the DoD of USA, the application example of technology maturity in the field of undersea warfare equipment is proposed (QIAN et al., 2006, ZHU, 2008), Those researches analyse and study the meaning of technology and technology maturity and the relationship between them. The grading condition of representative technology maturity in foreign countries is introduced. Suggestions are provided to TRL or similar technics in the field of space technology in China. The "technology progress state" in each level is also explained. The State Administration of Science Technology and Industry for National Defence formulates the assessment method of Pre-research technology maturity to a recommended standard for National Pre-research Programme Audit, and the General Armaments Department of People's Liberation Army China organises and formulates the assessment method of technology maturity to project guidance of Manned Space Mission. Several publications about TRL, MRL or applications have emerged in large numbers.

It has been several decades since the technology maturity was proposed in the 1970s.

Tremendous concepts of TRL have raised the definitions and assessment methods for technology-related maturity in each field. When reviewing the progress of technology maturity, it is pointed out that the development of TRL has been approved by all kinds of international industries and research institutions. Different categories and extensions are developed in practice. However, there still exists a deficiency in the application. By a large number of expert investigations, 15 challenges of the next step of TRL development are summarized (Olechowski et al., 2015a). The challenges were grouped into three categories: (1) system complexity, (2) planning and review, and (3) assessment validity. Just cite some related to assessment method, such as “Scope of the TRL assessment”, “Influence of new components or environment”, “Prioritization of technology development efforts”, “Visualization”, “Subjectivity of the assessment” and “Imprecision of the scale”, etc.

In aiming of accurate results of TRA portraying technology maturity, it is proven that the results should not be more “optimistic”, meaning that some of the technology risks are concealed if one assumes that the technologies were well-developed for commending the R&D team. The reasons may vary, but the most common thing is that TRL can be used as a marketing tool for the provider to “sell” their products. Another reason is that TRA is frequently self-assessments and the result reports can hardly validate before delivery.

Inaccurate results of TRA will lead to high potential in cost/schedule growth and increased risk for the project, while they all will be conscious of the lower technology maturity late in project development, especially when encountered with system failure. It is recommended that more practical assessment should be developed and employed, and independent third-party validates the TRL assessment results, reducing ambiguity and variability by the decision authorities.

2.4 TECHNOLOGY READINESS ASSESSMENT PROCESS

TRL was introduced accompanied with a TRA process shortly after. NASA suggested that the first step executes an assessment related to TRL, It starts from a WBS(Work Breakdown Structure) or PBS(Product Breakdown Structure) decomposition of the system or service. Then it identifies which are the critical technical factors that most influence the success of the system, confirms the TRL of the chosen factors, or put them at the list of CTEs (Critical Technology Elements) of the essential component of the WBS tree, combines TRL assessment of the top-down decomposition hierarchy and then, from subsystem bottom-up to system according to the principle of TRL, forms the baseline of TRL assessment of component, subsystem and system. The assessment of system technology risk then proceeded to the phase of AD2 assessment. According to the CTE level, the subsystem level or even system level, whose TRL is not enough achieved during the TRL assessment phase, will be followed by an AD2 assessment to collecting enough information of the R&D Plan or Risk Assessment.

The assessment method and process, given by Bilbro, is as follow (Bilbro, 2008).

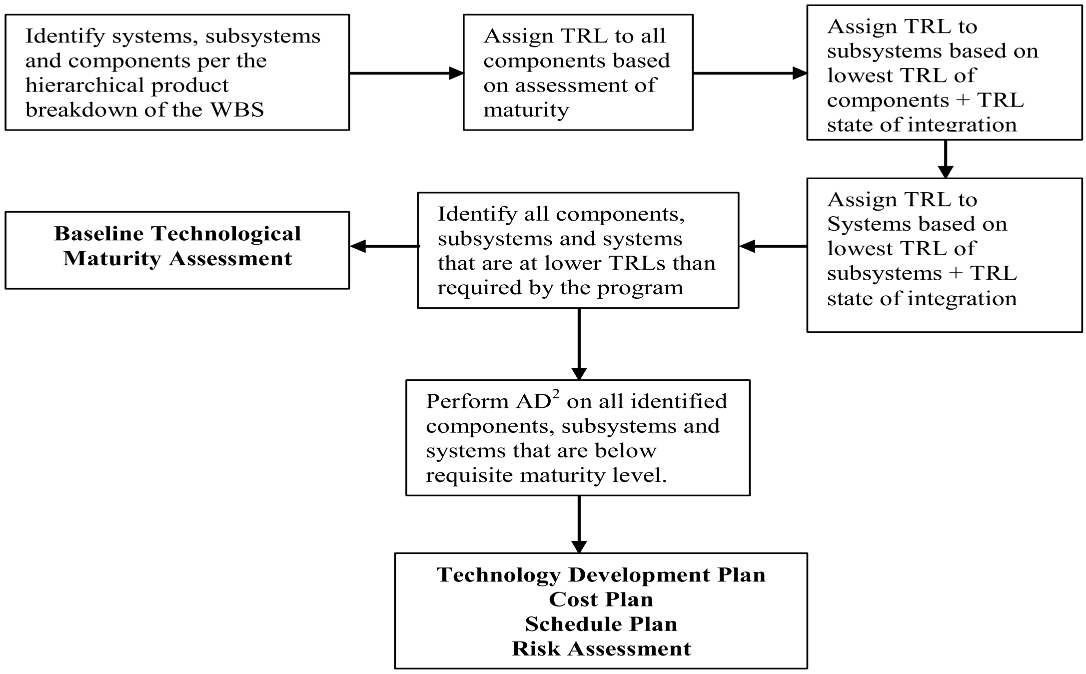

Figure 2-7: TRL and AD2 Process in a Project Risk Management(Bilbro, 2008)

According to the general principles of assessment theory, the assessment of TRL includes assessment related organisation, object, method and result management. The assessment object is the Critical Technology Elements (CTEs). It is a sub-set of technology which has to be relied on to accomplish the critical functions and performance of the project within the specified schedule and cost. CTEs could be software technologies, design technologies, manufacturing technologies, new material and so on. The assessment criterion of technology maturity includes the definition of the TRL levels, the connotation of each level, assessment criteria and the checklist of technology maturity items.

(I) TRL assessment from definitions to assessment attributes

The definition of TRL could be adopted for the assessment purpose. NASA (the originator), GAO, Transport Department, Energy Department, and DoD of USA are all developed the specific definition of the TRL, but NASA's definition could be the typical one, which is shown in table 2-1.

Table 2-1: NASA Technology Readiness Levels(Mankins, 1995)

TRL Level	Description/Detailed definition
1. Basic principles observed and reported.	The lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include thesis studies of a technology's basic properties.
2. Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative, and there is no proof or detailed analysis to support the assumption. Examples are still limited to thesis studies.
3. Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development are initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4. Component and/or breadboard validation in laboratory environment.	Basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in a laboratory.
5. Component and/or breadboard validation in a relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.
6. System/subsystem model or prototype demonstration in an operation environment.	Representative model or prototype system, which is well beyond the breadboard tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or the simulated operational environment.
7. System prototype demonstration in an operational environment.	Prototype near or at the planned operational system. Represents a major step up from TRL 6, requiring the demonstration of an actual system prototype in an operational environment, such as in an aircraft, vehicle, or space. Examples include testing the prototype in a test bed aircraft.
8. Actual system completed and "flight qualified" through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases this TRL represents the end of true system development. Examples include developmental test and evaluation of the system and in its intended weapon system to determine if it meets design specifications.
9. Actual system flight proved through successful mission operations.	The actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last "bug fixing" aspects of true system development. Examples include using the system under operational mission conditions.

All the process would conduct a decomposition of the technology risk factor into a preliminary assessment item, from a general definition to a series of questions need to be answered with supporting data (assessment features and items). The more the different team from researcher and user get agreed on assessment items, the more accuracy would be achieved.

To simplify, when the assessment is for an acquisition propose, the assessment is typically organised by the end user, if the government take responsibility for the civil construction or infrastructure project, there usually will be a third-party assessment.

(II) Assessment attributes and detailed assessment items

The TRL assessment attributes are the basis for the formulation of detailed roles of TRL assessment of specific CTE. Detailed roles of TRL assessment are generally formulated by experts in the technology field of CTE by refining assessment criteria according to TRL assessment principle and criteria and with the combination of specific technological attributes and requirements. In the practical application, according to each assessment attribute of each level of TRL, the references for assessment of TRL level are formulated one by one. According to each specific roles of TRL assessment, the maturity level of CTE is obtained.

The TRL based assessment method of technology maturity belongs to the qualitative method. The evaluating process is to find whether a CTE "has" or "hasn't" reached the technology state showed by each specific attribute of TRL assessment. In order to acquire more information, well understanding of the CTE and further obtain the technology maturity difficulty, it is necessary to adjust and improve the existed TRL assessment method according to specific requirements. The Deputy Director of the United States Department of Defence claimed that the TRL is a kind of single axis which is used to explain the technical capacity and it cannot tell the complete picture of risk when technology is integrated into the system. In order to obtain a relatively comprehensive understanding of technology maturity and readiness level in the project, it is necessary to establish multidimensional maturity assessment criteria (Fathian et al., 2008, Khalfan et al., 2001).

Bilbro also summarised the research focus of TRL with the aim of control the technology related risk from "unacceptable" to "acceptable", even to "desirable" or "well known" (As the following diagram showing).

TRL	Adv. Tech Demo	TRL Increasing Maturity	Level
Actual system flight proven through successful mission operations	Too well known for Advanced Tech Demonstrator		9
Actual system completed and flight qualified through test and demonstration	Too well known for Advanced Tech Demonstrator		8
System/subsystem model or prototype demonstration in a relevant environment	Desirable		7
System/subsystem model or prototype demonstration in a relevant environment	Desirable		6
Component or breadboard validation in a relevant environment	Acceptable		5
Component or breadboard validation in laboratory	Unacceptable -- Too Risky		4
Analytical and/ or experimental critical function or characteristic proof-of-concept	Unacceptable -- Too Risky		3
Technology concept or application formulated	Unacceptable -- Too Risky		2
Basic principles observed and reported	Unacceptable -- Too Risky		1

Figure 2-8: TRL Research focus (Bilbro 2007)

2.5 Assessment Methods of Advancement Degree of Difficulty

The purpose of the assessment of technology or project maturity is to provide the manager with the information of the difficulty and required resources or other efforts when the technology develops from one level to a higher level in the life cycle. Together with TRL, it can help the decision maker to have a deeper understanding of the difficulty and risk of the project. Therefore, the assessment of the AD2 contributes the significant reference value for decision making.

In 1998, John Mankins, from the NASA HQ, proposed the Research and Development Degree of Difficulty (R&D3) which linked with technology maturity evaluation (Mankins, 1998). With the combination of technical risk management, Integrated Technology Analysis Methodology (ITAM) is formed. Based on TRL difference and Technology Need Value (TNV), quantitative calculation and analysis of technical risk index are carried out (Mankins, 2002). After that, Mankins proposed that it should be extended to the Risk Matrix in 2009 (Mankins, 2009).

The AD2 is proposed by Bilbro, and it is divided into nine levels, which is the highest in the ninth level and the lowest in the first level. The definition of the level of AD2 is shown in Table 2-2.

Table 2-2: Definition of AD2 scale in NASA (Bilbro 2007)

AD2	Description
9	Requires new development outside of any existing experience base. No viable approaches exist that can be pursued with any degree of confidence — basic research in key areas needed before feasible approaches can be Defined.
8	Requires new development where the similarity to existing experience base can be defined only in the broadest sense. Multiple development routes must be pursued.
7	Requires new development but the similarity to existing experience is sufficient to warrant a comparison in only a subset of critical areas. Multiple development routes must be pursued.
6	Requires new development but the similarity to existing experience is sufficient to warrant comparison on only a subset of critical areas. Dual development approaches should be pursued in order to achieve a moderate degree of confidence for success. (Desired performance can be achieved in subsequent block upgrades with a high degree of confidence.
5	Requires new development but the similarity to existing experience is sufficient to warrant a comparison in all critical areas. Dual development approaches should be pursued to provide a high degree of confidence for success
4	Requires new development but the similarity to existing experience is sufficient to warrant comparison across the board. A single development approach can be taken with a high degree of confidence for success.
3	Requires new development well within the experience base. A single development approach is adequate.
2	Exists but requires major modifications. A single development approach is adequate.
1	Exists with no or only minor modifications being required. A single development approach is adequate

The AD2 is similar to Mankins' R&D3 in that it also tries to determine the remaining efforts/risks in maturing the technology (El-Khoury, 2012). The primary extension to R&D3 of AD2 is that it provides a method and framework (whereas R&D3 on its own has no accompanying methodology on how to determine those risk levels). It depends on expert groups to determine the steps necessary for maturing the technology; then estimates the expected degree of difficulty. A framework of 4 specific areas (lately become 5, to be described late in this section) checklist was presented (Bilbro, 2007b), which shows that

AD2 is intended to give the best practice by measuring "everything" about the difficulty of advancement. Nolte says that AD2 is the best predictive method for determining the difficulty of advancement because of its comprehensiveness and available procedure (Nolte, 2008).

A research focus was put forward of the AD2 assessment method to resolve the problem of "Unknowns", which is the source of the risk. The research focus is demonstrated as the following figure.

Level	AD2 Increasing Risk	AD2		Risk
9		Chaos	Requires new development outside of any existing experience base. No viable approaches exist that can be pursued with any degree of confidence. Basic research in key areas needed before feasible approaches can be defined.	90+%
8		Unknown Unknowns	Requires new development where similarity to existing experience base can be defined only in the broadest sense. Multiple development routes must be pursued.	80%
7			Requires new development but similarity to existing experience is sufficient to warrant comparison in only a subset of critical areas. Multiple development routes must be pursued.	70%
6			Requires new development but similarity to existing experience is sufficient to warrant comparison on only a subset of critical areas. Dual development approaches should be pursued in order to achieve a moderate degree of confidence for success. (desired performance can be achieved in subsequent block upgrades with high degree of confidence.	50%
5		Known Unknowns	Requires new development but similarity to existing experience is sufficient to warrant comparison in all critical areas. Dual development approaches should be pursued to provide a high degree of confidence for success.	40%
4		Well Understood	Requires new development but similarity to existing experience is sufficient to warrant comparison across the board. A single development approach can be taken with a high degree of confidence for success.	30%
3			Requires new development well within the experience base. A single development approach is adequate.	20%
2			Exists but requires major modifications. A single development approach is adequate.	10%
1			Exists with no or only minor modifications being required. A single development approach is adequate.	0%

Figure 2-9: AD2 Research focus (Bilbro 2007)

It is believed that the AD2 can be used to predict technology or a system (subsystem) as well as the resources needed by the development of one TRL scale to a higher one. It can provide more accurate support in detail for the cost and working schedule planning of a project. The assessment of AD2 included five specific fields: Design and Analysis, Manufacturing, Test and Evaluation, Operation, and, software development. Bilbro has given specific description information of one to nine of AD2. In addition, the assessment features of detailed questions need to be evaluated at each level are put forward (Bilbro, 2008, Bilbro, 2010).

The assessment of AD2 is significantly crucial for large-scale complex technology system. The establishment of time schedules, project investments plan, the setting of project milestone and the obtaining of final outcomes, all above could be benefit from the accurate assessment of AD2. The existing method is to establish assessment criteria of AD2 according to the assessment method of TRL. The AD2 is confirmed according to each assessment criteria. At the same time, the assessment of AD2 needs the ability of "future precognition". The ability to "predict" depends mainly on the grasp of development law of the field of professional skill: the insight of the designer capacity, the personal evaluation of assessment experiences, the ability of an independent consultancy of the technology, the validity of the regulation of assessment process of the target state.

In the checklist based assessment method of AD2, the process of the assessment of AD2 is performed for the CTE in a project. The specific process includes problems in the following specific fields: design and analysis, manufacturing, test and assessment and operation (Bilbro, 2007b). In each specific field, there exist many specific detailed roles of assessment. The specific roles of assessment to be followed respectively include the four parts. In later papers, Bilbro takes the "software development" as an isolated dimension, which is used as the primary reference for the evaluation of AD2 together with the other four parts.

In each field, there are some questions need to answer, which include the availability of necessary methods, tools, machines, personnel, etc. Also, the required developments of those essential elements need to be allocated. The questions have the pattern of "Do/does the essential element(s) exist and if not, what level of development is required to produce them?" All the answers are bringing up together to form the whole picture of the ingredient efforts of AD2.

The field of "Design and Analysis" includes nine elements which are (1) databases, (2) design methods, (3) design tools, (4) analytical methods, (5) analysis tools, (6) appropriate models with sufficient accuracy, (7) available personnel have the appropriate skills，(8) the design been optimized for manufacturability, and, (9) the design been optimized for testability.

The field of "Manufacturing" includes twenty elements which are (1) materials, (2) manufacturing facilities, (3) manufacturing machines, (4) manufacturing tooling, (5) metrology, (6) manufacturing software, (7) personnel have the appropriate skills, (8) the design been optimized for manufacturability, (9) the manufacturing process flow been optimized, (10) the manufacturing process variability been minimized, (11) the design been optimized for reproducibility, (12) the design been optimized for assembly & alignment, (13) the design been optimized for integration at the component, subsystem and system level, (14) breadboards required, (15) brass boards required, (16) subscale models, (17) engineering models, (18) prototypes required, (19) breadboards, brass boards, engineering models and prototypes at the appropriate scale and fidelity for what they are to demonstrate, and, (20) qualification models.

The field of “Operations” includes nine elements which are (1) the design been optimized for maintainability and servicing, (2) the design been optimized for minimum life cycle cost, (3) the design been optimized for minimum annual recurring/operational cost, (4) the design been optimized for reliability, (5) the design been optimized for availability “ratio of operating time (reliability) to downtime (maintainability/ supportability)”, (6) ground systems facilities & infrastructure, (7) ground systems equipment, (8) ground systems software, and, (9) personnel have the appropriate skills qualification models.

The field of “Test & Evaluation” includes thirteen elements which are (1) test facilities, (2) test equipment, (3) test tooling, (4) test measurement systems, (5) test software, (6) personnel have the appropriate skills, (7) the design been optimized for testability, (8) breadboards required to be tested, (9) brass boards required to be tested, (10) subscale models required to be tested, (11) engineering models required to be tested, (12) prototypes required to be tested, and, (13) Qualification models.

The assessment method proposed by Bilbro still category to human-depended assessment process by experts based on pre-established experience. Subjective factors which make the assessment not entirely objective and accurate. All the required efforts in the future cannot be easily determined by the managers. Therefore, from risk management experiences, the quantitative method is needed to gather information and establish a relatively objective understanding of the difficulty among the researcher and other technicians.

At present, the method is the practical assessment method of AD2. It inherits the questionnaire checklist based assessment method. As an example of Bilbro’s AD2 method application, Macdonald has created a road-map to enable rapid, near-term solar sail technology (it is a technology used in space missions aiming for deep space exploration) future advancement using AD2 as an indicator to optimise the technology combination. (Macdonald, 2011) Solar sail technology is using Solar Radiation Pressure (SRP) as a propulsion source. It consists of a large, lightweight and highly reflective surface that relies on the momentum transferred from solar photons for passive propulsion, usually used in interplanetary space exploration. Solar sail technology is a published example of using

TRL/AD2 to manage the technology risks. As such the near-term technology readiness level of traditional solar sailing is increased, while simultaneously reducing the AD2 along the solar sail application-pull technology development road-map (Macdonald and Minnes, 2011). The AD2 of CTE developing from a particular scale of TRL to another higher scale is obtained.

In the process of evaluation of AD2, the selection of the experts is critical. Those experts include the scientific and technical personnel of each subject, the engineers, the project managers and the consultant experts to be invited if necessary. According to the predefined checklist, the experts conduct the assessment of AD2 of the CTE to be evaluated, and results regarding AD2 are obtained. The assessment method of AD2 was the best method to qualitatively forecast and evaluate difficulty level of the improvement of technology maturity in the future (Nolte, 2008).

However, from the perspective of the project manager, due to the difference of the liability subject and method and connotation of the evaluation, the current assessment of TRL and AD2 needs to adopt two different assessment processes. In particular, in the process of the evaluation of TRL, the information about the technology level has been collected. In order to forecast the future maturity difficulty, the relative information should be collected from another process. A lot of the data accumulated in the process of assessment cannot be shared, which increases the workload significantly. That derived the requirement of research for the combined process of the two in one framework.

2.6 META-SYNTHESIS SYSTEM APPROACH

As stated in the research goal, it is necessary to carry out the quantitative AD2 assessment method. However, the difficulty of such research is trying to predict the future. Therefore, it is required to sufficiently integrate the expert experience and data of similar project as references. The qualitative and quantitative study method is argued in detail in Chapter 3: Methodology. Moreover, this section analyses the research overview of a comprehensive integration approach in perspective of reference.

Along with system rethinking trend in the western, oriental system thinking, eastern modes of inquiry philosophies have also been noticed due to their intuitively systemic ideas and emphasis on human relationships. On the other hand, oriental researchers also explore their methodologies to deal with system complexities or thinking about the system of science and technology. Japanese scientist Sawaragi developed an adjective system approach which concerns more on human roles in system modelling (Sawaragi and Nakamori, 1991). The approach aims to develop a well-defined system by emphasising of three factors which include humanity in system designing, honesty in modelling, and harmony within the group (Gu and Tang, 2005).

At the beginning of the 1990s, Xuesen Qian(H. S. Tsien), a Chinese scientist, nominated the approach of Open Complex Giant Systems (OCGS) processing as the "Meta-Synthesis System Approach"，a comprehensive integration approach from qualitative to quantitative. This paper has a significant impact on engineering thinking with its English version(Qian et al., 1993). GU has reviewed the research and application of MSA that, "in parallel to many western schools in approaches and methodologies for unstructured problem solving, eastern inquiry modes are studied and new system approaches have also been proposed based on comparisons between western and eastern system thoughts by oriental system scientists". The most basic road path of MSA is that "confident hypothesis with rigorous validation" approach, spiral insight gained by expert quantitative knowledge arising from qualitative understanding, or another expression of "a combination of human judgment (qualitative) and mathematical models (quantitative)".

Just give a brief comparison, the MSA is rooted in engineering design and is more "systematic". By studying the natural characteristics in system sciences, Qian gave his classification of systems based on the complex level and openness of the system. The most complex systems are the open complex giant system (OCGS) where exists "a large variety of subsystems with hierarchical structures and complex interrelations". (QIAN,1993)

The so-called system is a functional ensemble formed by massive constituent parts which relate, interact and affect each other. One of its important characteristics is that the system emerges distinct nature which the constituent parts do not have, so it is called the integrity of the system (Yu and Zhou, 2005). Qian emphasises that considering and resolving the problems as one whole system, which integrates the successive decomposition of the reductionist method and the comprehensive integration of the holistic approach. In essence, it combines the expert system, data and information system as well as the computer system, and forms a highly coupled "Man-Machine" integration system. The successful application of such an approach is attributed to the comprehensive advantage and intelligent advantage of the system. It is more advantageous than merely relying on a human (expert system) or machine system. It can integrate human thought, human experience, knowledge, wisdom and intelligence, data and information, as well as developing the qualitative perception from various aspects to the quantitative perception (Yu and Zhou, 2002).

Concerning universal research method, the comprehensive integration approach adopts both top-down and bottom-up strategy, carries out the research from system level down to component level, as well as from component level up to system level, and eventually studies and resolves the problem as a whole system. Due to the particular demand of the system as a whole, it is impossible to obtain the overall optimised result for the system from the component analysis (Yu and Zhou, 2005). In the recommended research method, it adopts the expert system formed by "Man" with the computer system as "Machine", and combines the integrated and creative thought of "Man" with the utilisation of extraction of information. By comprehensively using the integration of the expert system, machine system and knowledge system, it makes spiral iteration and reciprocation to fulfil the constant improvement of the understanding of a complex problem.

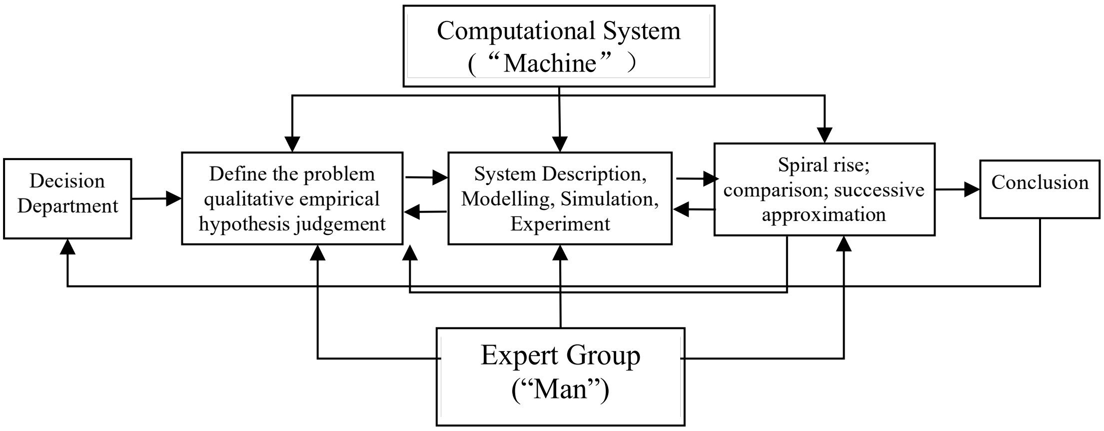

Figure 2-10: Meta-Synthesis System Approach (Yu and Zhou, 2005)

In such process of qualitative analysis and creative hypothesis, it's necessary to understand the scientificity, logicality, stringency and abstractness of the mathematical model. The currently impenetrable difficulty is caused by the organization systematic behaviour characteristics of the uncertain and unknown factors, such as randomness and fuzziness of quantitative model description. The complexity of the organisational system is rooted in the human-related complicated psychological phenomenon of high intelligence, uncertain behaviour model and nonlinear interaction (Guo, 2007). Similarly, if a mathematical model which seems to be highly theoretical is used to depict the essential characteristic of a complicated system and make strictly quantitative forecasts of potential behaviour rules of the social system, the result will be "somewhat farfetched and divorced from reality"(Xu et al., 2000).

Based on the research method mentioned above on the experience and data integration approach, the following conclusion can be drawn:

(1) Considering the quantitative AD2 assessment required by this study, it is necessary to integrate the advantages of a qualitative analysis approach and a quantitative analysis approach to fulfil the comprehensive systematic integration.

(2) To assess the predictability of unknown technology readiness difficulty, it is necessary to

adopt the approach of a combination of expert experiential hypothesis and quantitative tools, such as computation, multiple iterations and a successive approximation method.

(3) Considering that the current TRL and AD2 assessment is targeted to the critical technology obtained from Work Breakdown Structure (WBS) or Product Breakdown Structure (PBS) decomposition of the project, the following are necessary to further achieve the close connection between the technology and the target characteristic at system level: fulfil the top-down decomposition of WBS to figure out the critical technology; the bottom-up holism to determine the effect of the AD2, including its influence on the system; method to accomplish the goal of systematically optimized decision-making as a whole, etc.

2.7 TECHNOLOGY RISK ASSESSMENT METHOD BASED ON TRL AND AD2

The main aim of the research and application of TRL and AD2 is to take the mature technology into the project management framework as a tool for technology risk analysis and management. The methods named "Integrated Technology Analysis Methodology (ITAM)" (Mankins, 2002) and "Technology Readiness and Risk Assessment (TRRA)" (Mankins, 2007) are typical quantitative technique risk analysis methods which have been accepted in the Systems Engineering Handbook of NASA. The main ideas and procedures are the following:

ITAM: Integrated Technology Analysis Methodology was proposed based on the research of Highly Reusable Space Transportation (HRST) of NASA from 1995 to 1997. The ITAM has a quantitative technique risk matrix method base on TRL, using Delta-TRL(ΔTRL)to represent the difference value of current TRL mature scale and higher desired scale in a specified time point after that. Moreover, TNV, which represents Technology Need Value, stands for the critical degree of the impact of some technologies on the functional performance of the system.

The Individual Technology Index is calculated as the following:

$$\text{Technology Index} = \Delta\text{TRL} \times \text{R\&D3} \times \text{TNV}$$

Moreover, Integrated Technology Index (ITI) is ：

$$\text{ITI} = \frac{\sum_{\text{subsystem Technologyies}} (\triangle\text{TRL} \times \text{R \& D3} \times \text{TNV})}{\text{Total\# of Subsystem Technologies}}$$

The ITI and other results will be introduced to traditional risk analysis and management process, acting as the assessment index of the technology risk.

TRRA: Technology Readiness and Risk Assessment, is also a quantitative technology risk analysis model. It combines TRL, R&D3 and TNV, and expands TNV to a five scale. It also gives an extension of the risk matrix concept, which y-axis stands for the probability of failure, which R&D3 related, x-axis stands for the consequence of failure, relating to ΔTRL x TNV. Thus the TRRA makes the connections between risk matrix and TRL/R&D3, becoming the fundamental part of risk management.

All the methods mentioned above could be linked the TRL, R&D3 with the current risk management process, to emphasise the technology risk among the system risk management, leading a step forward in the project management. It is also required integration of quantitative assessment method of the degree of difficulty with the risk management in this thesis.

2.8 VISUALISATION AND DECISION-MAKING SUPPORT

To show critical information to support decision-making, a visualising method is needed to apply visualisation technology to AD2 assessment of visualising the readiness status of the technology to a graph to denote the AD2 of the technology developing.

Olechowski (Olechowski et al., 2015a)has pointed out that the typical means of sharing and reviewing TRL assessment is in a spreadsheet. As feedback stated, “we generate lists [of TRLs], and then pretty much use them listlessly.” Figure 2-11 gives an example of the bar chart to show a typical complex project with over 500 components TRLs, using different colours to show the technologies as low, medium or high development difficulty.

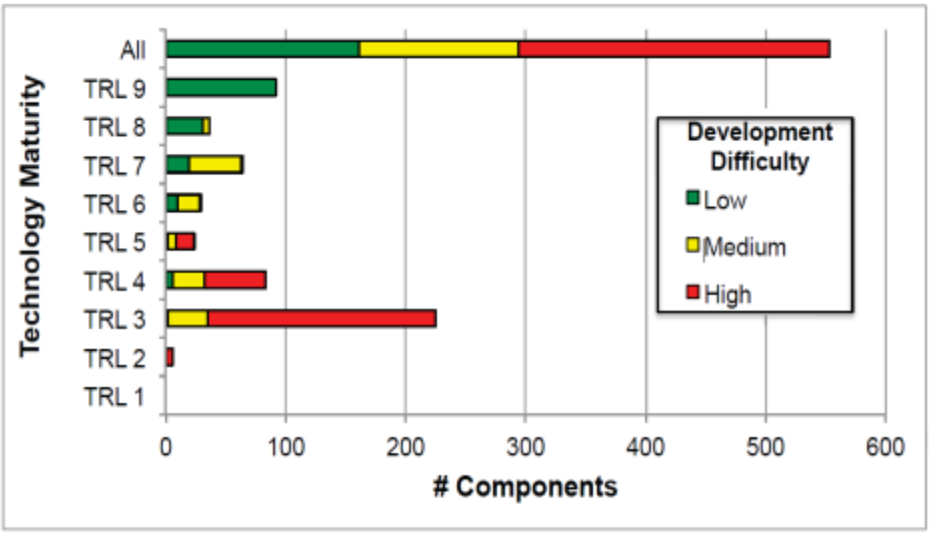

Figure 2-11: Visualisation of TRL (Olechowski 2015)

Information visualisation has been widely applied in many fields, which could be adopted in technology maturity visualisation. By visually representing data in the format of diagrams to facilitate intuitive understanding information, it has been implemented in many disciplines (J. R. Cooper et al., 2009, Elmqvist and Fekete, 2010). This does not only intuitively show the data, but also could provide accurate input for decision-making.

Based on the types of data, information visualisation methods could be categorised into one-dimensional, two-dimensional, three-dimensional, multi-dimensional visualisation, sequential information visualisation, layered structural information visualisation and network information visualisation, etc.

(1) One-dimensional information visualisation: simple linear information, such as text, programming code and statistical table. TRL and AD2 visualisation involve two main elements, which could not be represented by one-dimensional information.

(2) Two-dimensional information visualisation: composed of two elements, which possess space characterisation. The figure above is a two-dimensional diagram. Based on the number of representing, two-dimensional visualisation method matches TRL and AD2 visualisation requirements. Moreover, the two-dimensional coordinate is easy to understand, which could represent both the current and target readiness level.

(3) Three-dimensional (3-D) information visualisation: It introduces volume and could be applied to some fields such as virtual reality, and computer-aided design. 3-D visualisation is mainly applied to simulate real objects in reality so that real objects could be shown directly. TRL mainly contains two fundamental properties; it does not require 3-D as it could bring in redundant information which impacts the visualisation effect.

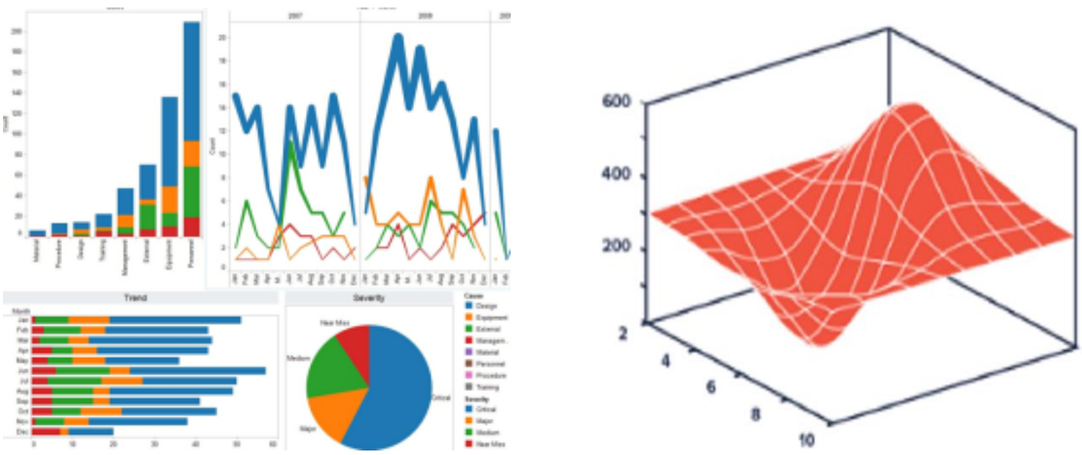

Figure 2-12: Examples of Two/Three Dimensional visualisations

(4) Multi-dimensional information visualisation: used to describe objects with more than three attributes; hence it does not suit TRL and AD2 visualisation.

(5) Time sequential information visualisation: It is used to describe time attributes. However as there are no time attributes in TRL visualisation, it is not suitable for TRL and AD2 visualisation.

(6) Layered information visualisation: The most common relationship of abstract information is a layered relationship, such as document management, library classification and disk index structure. However, this structure is not suitable to represent TRL concept.

(7) Network information visualisation: Network information has no fixed layered structure, and multiple paths could exist between two nodes. As the relationship and number of attributes are varied between different nodes, this is not suitable for representing TRL.

Based on the above discussion, the two-dimensional information visualisation method is sufficient to present TRL and AD2 accurately. In the research presented in this thesis, two-dimensional coordinates can meet visualisation requirements and will be used to present the status of TRL and AD2.

An example of Time sequential information and Network information visualisation is demonstrated as the following.

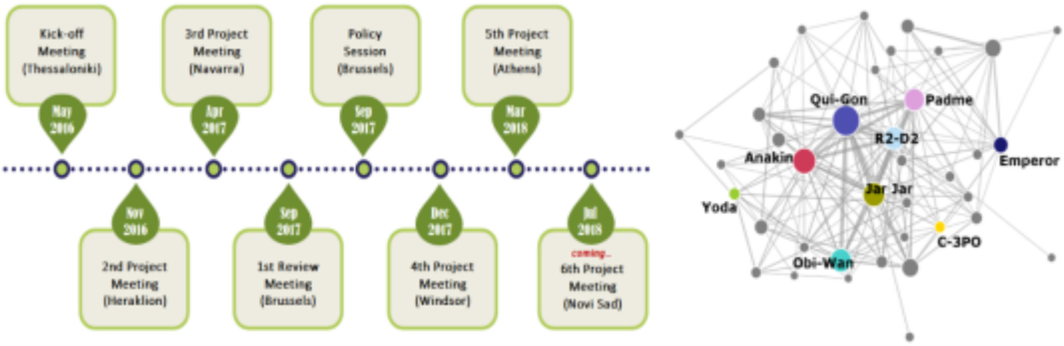

Figure 2-13: Examples of Timed/Network Dimensional visualisations

2.9 Summary

In this chapter, literature involving the technology maturity and difficulty research are analysed and categorized, research achievements related to the technical evaluation and risk management, for instance, TRL assessment, AD2 assessment and meta-synthesis, are compared and analysed, and the research connotation and fundamental thoughts of the thesis are analysed and confirmed according to the research targets.

The research gap was concluded to lack of seeking the nature of the technology risk, quantitative estimated of efforts to achieve the success of the project and how to bridge the gap between different engineering culture such as western and oriental system philosophy.

Chapter 3 Research Methodology

The evaluation of technology risk and assessment of TRL/AD2 requests the assessor to involve with the research team or related individual. The methods are categorised into qualitative or quantitative. Since traditional research related is the mainly concentrate on the qualitative TRL assessment, so the systematisation method, like the qualitative and quantitative research, as well as the system engineering research method, is illustrated respectively in this chapter, performing a design of the research road-map.

3.1 THE QUALITATIVE AND QUANTITATIVE METHOD

Azizian (Azizian et al., 2009) from MIT and Joseph et al. form Sandia National Laboratories have given a report (Fernandez, 2010) summarising qualitative and quantitative methods of technical evaluation and risk management, shown in Table 3-1.

Table 3-1: Qualitative Maturity Assessment Techniques

No.	Tools	Description
1.	Manufacturing Readiness Level (MRL)	The MRL is a 10-level scale used to define the current level of manufacturing maturity, identify maturity shortfalls and associated risks, and provide the basis for manufacturing maturation and risk management (GAO, 2010).
2.	Integration Readiness Level (IRL)	The IRL is a 9-level scale intended to measure the maturity, compatibility systematically, and readiness of interfaces between various technologies and consistently compare interface maturity between multiple integration points. Further, it provides a means to reduce the uncertainty involved in maturing and integrating technology into a system (Gove 2007).
3.	TRL for Non-System Technologies	Expansion of the TRL definitions to account for non-system technologies such as processes, methods, algorithms, and architectures (Graettinger et al., 2002).
4.	TRL for Software	Expansion of the TRL metric to incorporate other attributes specific to software development (DoD, 2009).
5.	Technology Readiness Transfer Level (TRRL)	The TRRL is a 9-level scale describing the progress of technology transfer to a new application. It expands and modifies the TRL definitions to address the transfer of space technology into the non-space system (Azizian et al., 2009).
6.	Missile Defense Agency Checklist	A simple version of the TRL metric specifically in support of hardware maturity through the development lifecycle of the product (Mahafza et al., 2005).

No.	Tools	Description
7.	Moorehouse's Risk Versus TRL Metric	A 9-level metric mapping risk progression analogous to technology maturity progression. The TRL descriptions are explicitly tailored toward UAV (Moorehouse 2002 in Azizian et al. 2009).
8.	Advancement Degree of Difficulty (AD2)	Leveraging the concept of R&D3, the AD2 augments TRLs by assessing the difficulty of advancing technology from its current level to the desired level on a 9-level scale (Bilbro, 2002).
9.	Research and Development Degree of Difficulty (R&D3)	The R&D3 is a 5-level scale intended to supplement the TRL by conveying the degree of difficulty involved in proceeding from the current TRL state to the desired level, with FIVE being very difficult and ONE being least difficult to mature the technology (Mankins, 2002).

The following methods are quantitative based ones. The primary purpose is to discover the relations between the system variables of the TRL/AD2 assessment process, using data statistics related means.

Table 3-2: Quantitative Maturity Assessment Techniques

No.	Tools	Description
1.	System Readiness Level (SRL)	The SRL is a normalised matrix of pair-wise comparisons of TRLs and IRL of a system. It is a quantitative method providing insight into system maturity as a product of IRL x TRL (Sauser et al., 2008c).
2.	SRL Max	The SRL Max is a quantitative mathematical model aiming to maximise the SRL under constraint resources. The objective of the SRL max is the achievement of the highest possible SRL based on the availability of resources such as cost and schedule (Ramirez-Marquez and Sauser, 2009).
3.	Technology Readiness and Risk Assessment (TRRA)	TRRA is a quantitative risk model that incorporates TRLs, the degree of difficulty (RD3) of moving a technology from one TRL to another, and Technology Need Value (TNV). The TRRA expands the concept of the risk matrix by integrating “probability of failure” on the y-axis and “consequence of failure” on the x-axis (Mankins, 2007).
4.	Integrated Technology Analysis Methodology (ITAM)	ITAM is a quantitative mathematical model that integrates various system metrics to calculate the cumulative maturity of a system based on the readiness of its constituent technologies. The system metrics include TRLs, delta TRL, R&D Degree of Difficulty (R&D3), and Technology Need Value (TND) (Mankins, 2002).
5.	TRL for Non-Developmental Item (NDI) Software	A mathematical method to assess the maturity of Non-Developmental Item (NDI) software using orthogonal metrics in combination with a pair-wise comparison matrix to examine two equivalent technologies that are a candidate for insertion into a system. Incorporate other attributes such as requirement satisfaction, environment fidelity, criticality, product availability, and product maturity (Smith, 2005).

No.	Tools	Description
6.	Technology Insertion (TI) Metric	TI involves the integration of various metrics that deal with insertion of technology and subsystems into a current system to develop an "enhanced system." The TI Metric is a high-level metric computed from sub-metrics or dimensions intended to evaluate the risk and feasibility of technology insertion from a subsystem and a system level (Dowling and Pardoe, 2005).
7.	TRL Schedule Risk Curve	This is a quantitative model that does not communicate the maturity of technology at a certain point in time but instead leverages the TRLs metric to identify the appropriate schedule margins associated with each TRL level in order to mitigate schedule slips (Dubos et al., 2007).

The AD2 was traditionally assessed using Bilbro's checklist method, and it was based on the subjective evaluation TRL framework. However, such a method relies too much on the predefined checklist and experts' subjective judgment of technology. The result based on this method is subjective, and it cannot guarantee the status of the technology development for managers accurately or assist managers in the adequate resource and investment the future development of the technology. Consequently, a relatively objective assessment method of TRL/AD2 in the technology development process shall be established.

TRL has already developed an assessment method, focusing on the combination of risk management, or the integration of technologies or the maturity assessment from the system level. More specifically, project authorities also need to get the immature technologies well-developed. It aims to gain quantitative decision support data to manage the investment among the sub-contractors, and this thesis need seek for the nature of technology risk and provide a quantitative method for the project. The traditional AD2 evaluation is based on the qualitative method (Azizian et al., 2009). It is to inherit the qualitative studies revealing the "quality". Meanwhile, the data generated in the TRL and AD2 analysis process shall be analysed and sorted out by the reinforcement on the acquisition of first-hand data and grasp of the technology maturity difficulty. It shall be extracted for integration well maintaining, and accumulating the data-bank (Kujawski, 2013), and realising the advantages of both the qualitative and quantitative methods.

3.2 SYSTEM ENGINEERING AND META-SYNTHESIS APPROACH

The traditional approach of TRL assessment was to decompose the system or product, figure out the critical technology elements (CTEs) with WBS approach, and then to carry out the technology readiness assessment for CTEs. If such technology is not mature enough, it could be concluded that the project does not pass the periodical review. It intends to figure out the critical condition for the specific technical issues. Without satisfying such a condition, the success of the project will encounter significant risk. In the point of view of the project stakeholder, it is expected to obtain sufficient conditions, in the project management words, the technical risks can be controlled by achieving them to ensure the project successful (at least system should not fail because of this technical reason). It requires that such critical technology maintain the connection with the top success goal of the system to study and observe the risks caused by each technology change in perspective of a systematic integration.

Modern project management relies on a reductionist approach, for it believes that a variety of complicated phenomena can be understood by decomposing them into more primitive elements and their interacting relations. It is the fundamentally guiding idea of WBS or PBS decomposition project management. Traditional risk management also decomposes the system or its preparation process into more fundamental units until approaching independent and more manageable processes for further study. TRL or AD2 also abides by such ideas to decompose the system hierarchically into a tree structure, and conduct assessment and management of the chosen CTEs which are firmly related to the outcome of the system. When such CTE does not reach the relevant readiness level, it will cause more severe uncertainty and risk to the system success. System managers prefer to explain how the system can achieve success in the perspective of holism, which requires system engineering approach. System engineering is the integration of reductionism and holism. AD2 and TRL emphasise the assessment at CTE level after decomposing the project goal into CTE by WBS to extract the system theory behind the risk conclusion.

The study of Yu, Zhou and Gu, etc.(Yu and Zhou, 2005, Gu, 2016) put forward the qualitative and quantitative combination and the "Man–Machine" structured "Hall for Workshop on Meta-Synthetic Engineering (HWMSE)" for getting comprehensive resolution of complex problems (Yu and Zhou, 2004). Taking full advantage of human creativity and the accuracy of the computer is the basic approach of exploring the unknown world. For example, a research team of a complicated system can take a reference to such solutions for breaking through the development rule of new technology. It can improve the accuracy of technology readiness difficulty estimation by setting up a spiral iteration and continuously rising perception process formed by an expert team and computer system.

3.3 Information Management Supporting Software Tool

As stated in the research aim and goal, an assessment method need assist by a computer software tool and be given the detailed information management ability.

Computer Aided System Engineering is well-recognised important by all means. TRL-based technology maturity assessment information is collected, and then the maturity difficulty state of the technology developing from the current maturity state to the target maturity state is processed. All the procedural data management for decision-making is carried out. The essential function of the software is to assist the risk management in data handling and process acceleration.

The schedule of software development includes requirements analysis, design and implementation, test and deployment. Then the software will be applied when studies are launched with the case analysis. Then quantitative results are obtained through the case analysis of models in the software tool. Afterwards, methods and processes are improved with these cases, and feedback to improve the software functionalities.

3.4 RESEARCH DESIGN AND ROAD-MAP

After an analysis of the major steps of technology risk management, this section accomplishes all parts to form the research roadmap of the thesis. It starts from the TRL and AD2 assessment, then technology readiness visual decision-making support, the qualitative and quantitative integration approach, and puts forward the solution and process for research focus problems by analysis and methodology mentioned above.

In such way, it completes the following research design of the thesis:

(1). Deep insight into the origin of the technology maturity assessment, refining a qualitative assessment method of TRL and integration with the process of The Chinese System Engineering in order to ensure the accurate identification of technology risk.

This thesis is based on the modified TRL-based technology assessment method, preserves and extends the assessment evidence information on detailed features of each level within the specific assessment process. Meanwhile, it further studies the “necessary and sufficient” condition which can support the assessment features of such technology to reach a higher level, and establish the “unified assessment evidence chain” from the lower level to the higher level of such technology assessment features.

From the viewpoint of reductionism, it believes that “the system can be equivalently decomposed into more primitive units or process and their interaction”. Then it can assess the readiness of CTEs and expand to figure out the “sufficient” and “necessary” conditions for technology readiness improvement. Such conditions permit engineering managers to transform the difficulty composition elements into numerical expression at their focused aspects (such as cost or duration of tasks) and make meaningful numerical integration with the weight relationship between distinct elements.

(2). Study and apply the quantitative assessment method of AD2, and integrate it with the result of the qualitative analysis in order to put forward the comprehensive R&D plan.

For the purpose of computing AD2, It is required to modelling the existing technology readiness assessment evidence accordingly, i.e., transforming the judgements of feature satisfaction by "Yes-No" into the degree of assessment feature $S \in [0,1]$, where $S = 0$ indicates totally unsatisfied, $S = 1$ indicates fully satisfied, $0 < S < 1$ indicates the satisfaction degree of the technology to the specific readiness assessment feature characteristic. The S closer to "1" indicates that the technical approaches the status of meeting the readiness assessment feature characteristic. Oppositely, it indicates that a significant gap exists between the goal and its assessment. It reflects the necessary effort for improvement of technology readiness in the aspect of such assessment feature and its mathematical function.

To evaluate the difficulty of the assessed technology to develop from a specific readiness level to the higher level is to "fill-in the GAP" between two readiness status levels. The difference between two readiness levels is $n \geq 1$. Then an integral integrate formula could be performed over this integral "domain", based on the status density of each integral domain. As the difficulty of status improvement is different in distinctive status areas, the difficulty density of each feature is not constant, but varies along with the technology assessment features; then the weight coefficient of each characteristic dimension could introduce as an important parameter in the integral formula of technology readiness difficulty calculation.

(3). The precision of future "forecast" of improving technology readiness

It applies the comprehensive integration method from a Meta-synthesis System Approach which combines the experience of experts group ("Human" factor) and quantitative calculation data by computer software tool ("Machine" factor) to combine a "Man-Machine System", and mainly relies on the experimental judgement of an experts group to guide the direction by the feedback from the data analysed. It increases the accuracy of forecast the insight of the technology risk.

(4). Visualisation of technology readiness and AD2 for decision-making support

The two-dimensional visualisation method can create the current readiness status distribution diagram for the assessed technology. The visualisation process could help the technology readiness assessment in different diagram forms (curve or surface), including assessment feature characteristics of each readiness level and the status value of readiness assessment feature characteristic of the technology, etc.

The chosen visualisation chart could express the technology readiness status clearly, and be easily adapted to facilitate decision-making support. This thesis initially chooses the curve chart for the visualisation process and creates the technology readiness status distribution diagram (bar chart), in which the abscissa for the dimension of characteristic, while the ordinate stands for the dimension of status. The value at the status dimension is between[0,1]. When acquiring the status values of technology at each readiness characteristic (maturity attributes), they are visualised in the coordinate diagram to generate its technology readiness distribution diagram. The background of the technology readiness distribution diagram is unevenly distributed between[0,1], showing the different distributes of efforts to improve a step of readiness level accordingly.

According to the design mentioned above determined in the study process, the research road-map can be summarised as shown in Figure 3-1.

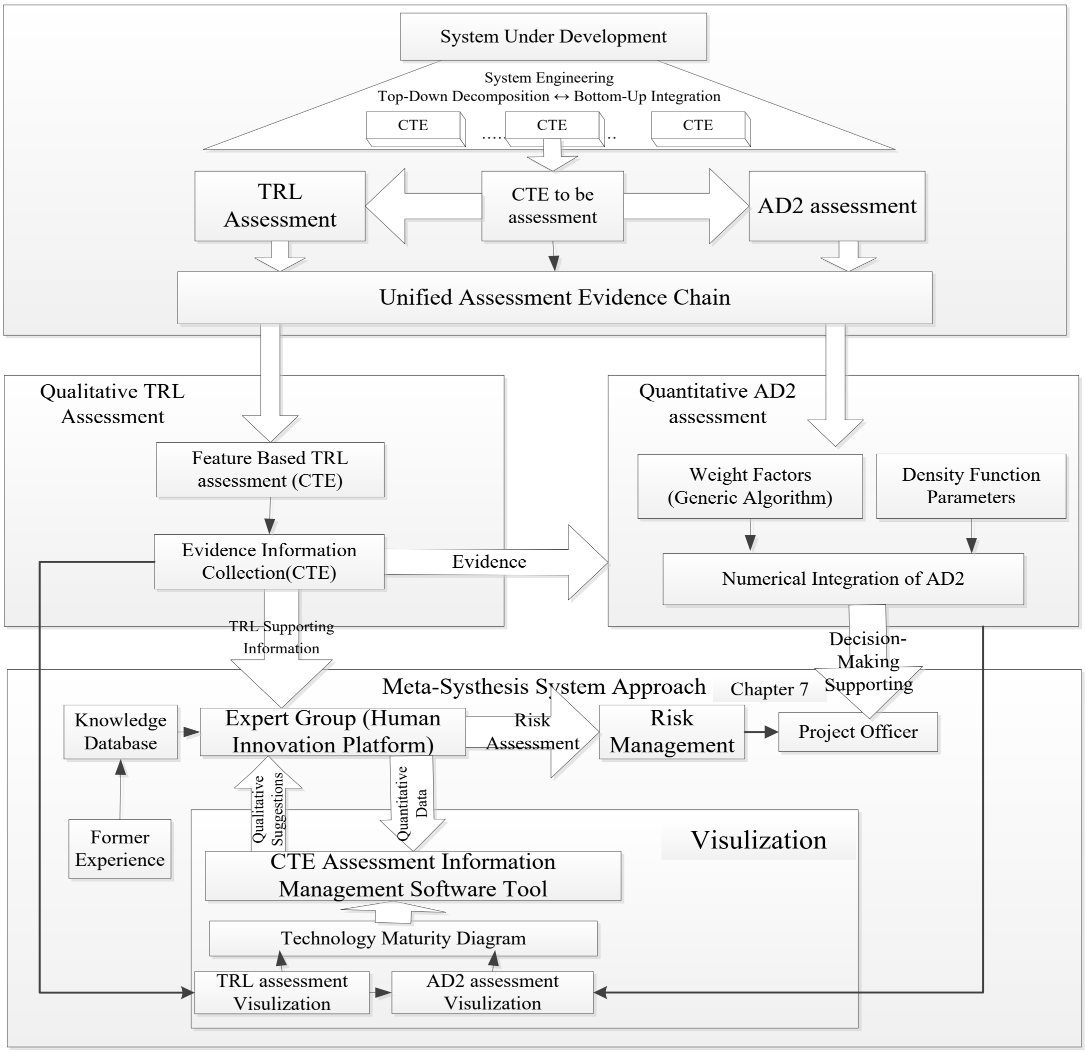

Figure 3-1: Research Structure and Road-map

The thesis focuses on discussing and proposing the "unified evidence chain", essential technology study of TRL and AD2 based on the unified evidence chain and its integral method; as well as the implementation and illustration of visualised decision-making support. It eventually puts forward the process of determination by qualitative and quantitative integration of the MSA approach to achieve the technology assessment and risk management.

From the research point of view, the methods proposed should be validated or verified to show its capacity or performance. As technology assessment is mainly focused on engineering management with different kind of human's experiences involved in, the most suitable way to validated or verified is case studies.

3.5 SUMMARY

The research methodology of the work carried out in this thesis was presented in this chapter. Qualitative and quantitative study methods were discussed, and a comprehensively integrated approach was presented with multiple case studies for illustration or demonstration. A research road-map was summarised based on the research methods adopted in the research.

Chapter 4 Maturity Attribute Based Qualitative TRL Assessment

As mentioned in the chapter "research methodology", the first step of the technology maturity management in project development is to identify the technology risk, which focuses on the technology maturity assessment. This chapter is mainly deal with technology risk identification. Inevitably, the key technologies are getting matured within the system developing process. It should adapt to the project management process. In this thesis, the technology maturity management methods need to be integrated with System Engineering of Chinese Procedures.

Firstly, the traditional TRL assessment process is analysed with the system engineering management procedure. Secondly, an attribute focused TRL qualitative assessment method is proposed to ensure the accuracy of the assessment. It also builds technology assessment supporting the information model as an evidence chain to facilitate the future assessment of Advancement Degree of Difficulty. The method in this chapter is to perform on the Critical Technology Element (CTE), not on system level assessment.

4.1 TRADITIONAL TRL ASSESSMENT METHOD

The TRL level definitions are well recognised by the stakeholders of the project, technical engineer and the TRL assessment team. While they are succinct descriptions, it is a common practice that they cannot be used directly in assessment. So those definitions are recognised as the assessment principles, and each level definition should decompose to several related questions, which cover the overall meaning of this TRL level definition. But easy to understand and easy to find answers. Those questions are assessment features. When a TRL principle is transferred to more detailed assessment features, it should keep the ability to identifying the technology risk. Then every assessment feature will lead to several assessment items to capture the assessment supporting information. The assessment features and items are customised for the specific application domain background of the project and technology. They are derived from the common assessment questions in the field of the CTE and should be practical to do the TRL assessment (as the following diagram shows).

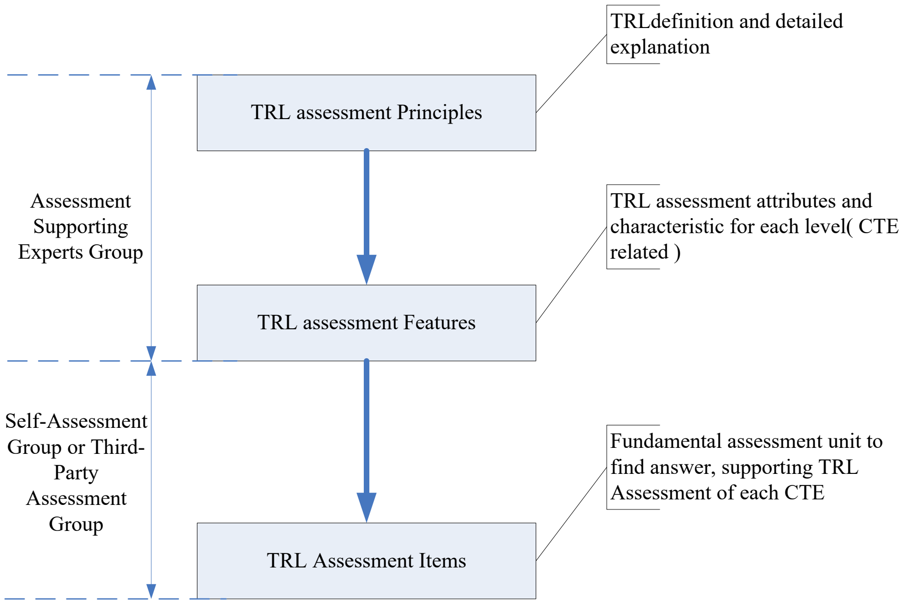

Figure 4-1: Decomposition of TRL Definitions to Assessment Features and Items

Let's take TRL5 as an example. The definition of TRL5 is "Component and/or breadboard validation in a relevant environment". The term "component", "breadboard", "validation" or "relevant environment" all has a different meaning in the different technology domain. Just nominate "relevant environment" for the optical mouse sensor technology, it could include the environment of the sensor would contact (mouse movement surface, or mousepad). So there should be an assessment feature about "was the mouse sensor tested and validated functional in the most relevant environment". Moreover, the relevant environment evidence of the sensor would be answered for "the optical mouse sensor component finished testing on the most office or home usage surface" with the test result of the wooden desktop surface, tempered glass, rubber tablecloth, concrete surface, bedspread, or another surface the mouse could contact, etc.

As recommended in the assessment guidance desk book of DoD, USA (DoD, 2009), the technology readiness assessment process could divide into several steps.

First, a technology risk management plan should be established, give the responsibility for the assessment group and technology researcher. If it is needed, there could be a third party assessment team. Then the project manager should lead a team to provide a technology breakdown to identify a list of critical technology elements (CTEs). The assessment will address specific technology separately which is "Great Significance" and "High Risks". In this step, the manager and the sub-contractor of the project will gain insights into the whole structure of technology within the product or service.

Next, the dominated CTE in the list needs to deploy detailed assessment questions (features derived from TRL definition of each level). Those supporting information will be collected using the checklist method. The checklists are coordinative developed and mutual consent with technology specialists of the CTE.

Then each CTE will be assessed by collecting the supporting information to answer the questions, analysed and gave a TRL level suggested. The CTEs with the level assigned would combine using bottom-up strategy, from the component level to the subsystem, proceed to system level until to determine the technology risk related to the project/mission goal. At last the assessment reports would be evaluated and approved.

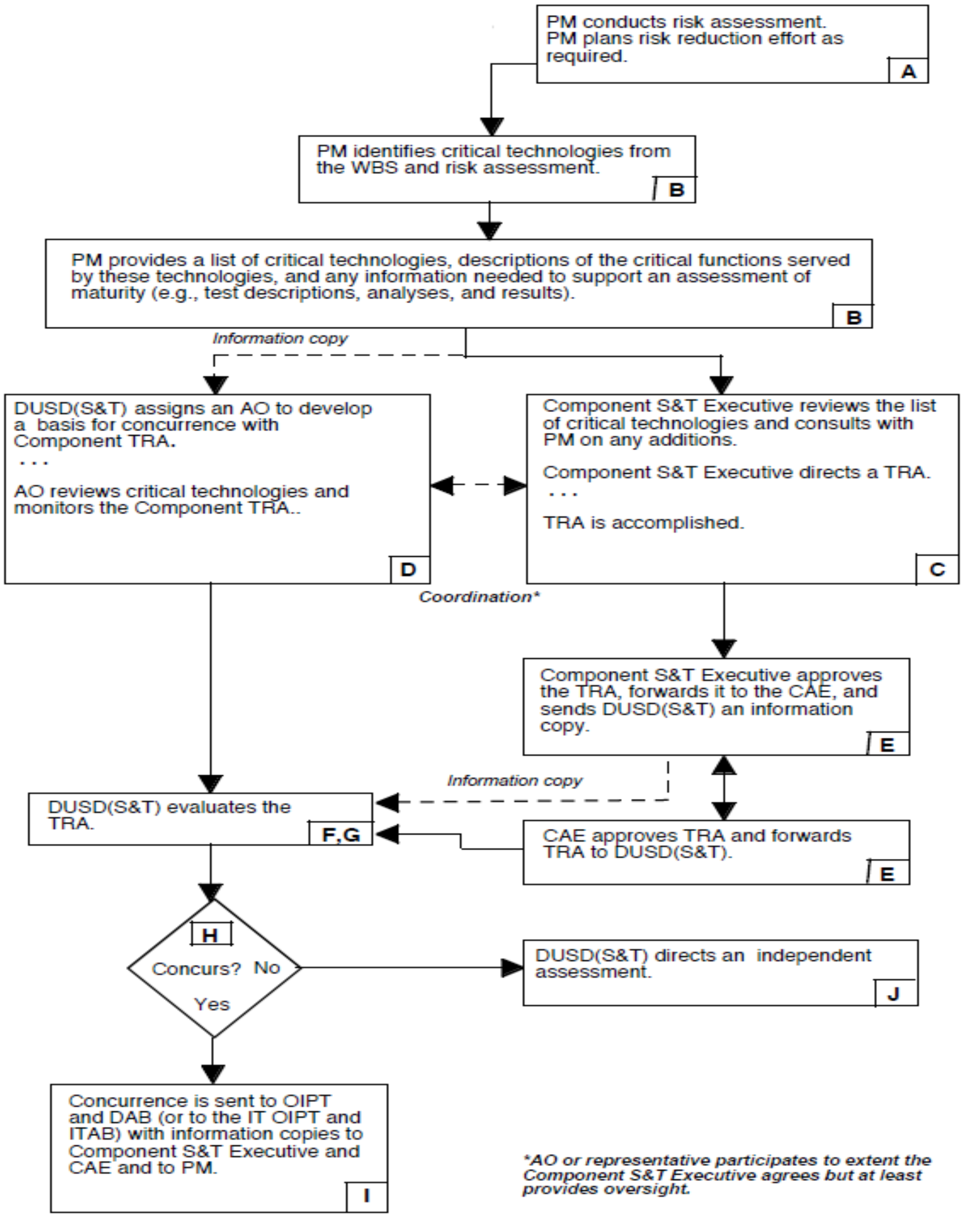

Figure 4-2: TRL Assessment Procedure from Guidebook (DoD, 2009)

The guidebook of TRL, issued by the US Department of Transportation, also gives a detailed process and document templates (Towery et al., 2017). They recommend a "TRL Description Requirements" as the questions list to perform the assessment, but they mention all the requirements of an individual level should be answered with "YES".

The TRL assessment process proposed in the NASA and ESA instruction manuals determines the CTE to be assessed according to the system WBS decomposition. Then it will determine the TRL assessment features according to the technical area where the CTE is located and confirms that these features are satisfied and obtain whether the CTE is at the corresponding level of assessment. Next, the conclusion will be drawn that the technical risk of the project meets the management requirements according to the level of CTE in the system. The critical step in this assessment process is to decompose the CTE assessment features (need the specialists in the CTE technical field to complete) and, to what extent the assessment data satisfies the items pass criteria (ESA, 2015).

AFRL (Air Force Research Laboratory, USA) developed and deployed an assessment software tool (MS Excel-based TRL calculator) to help the assessment team with the information collection and documentary; it recommends a level passing criteria (typically 80% of all the assessment items have passed the 70% percentage satisfaction). It is being used within AFRL and accepted by some users besides AFRL (see below figure showing passing criteria).

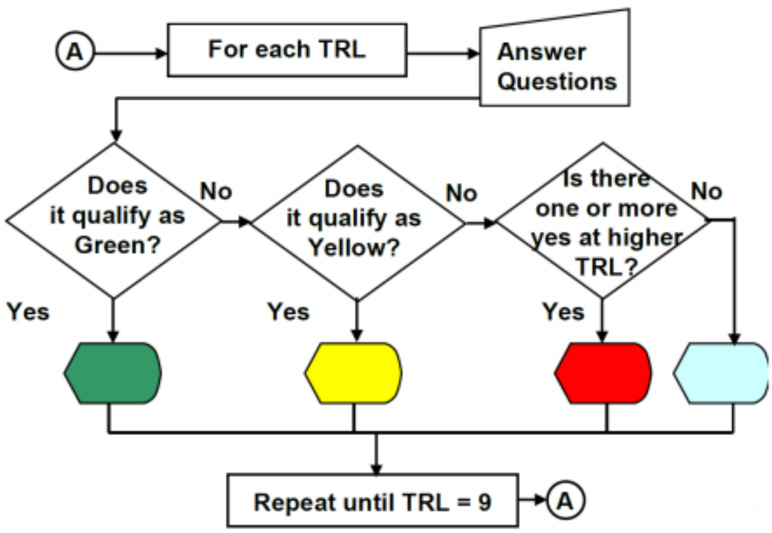

Figure 4-3: TRL level passing criteria algorithm in AFRL's calculator (Bilbro, 2007a)

A Software calculator could speed up the assessment procedure, but it also as fallible as other calculators, for the TRL assessment is not an only calculation of numbers. If the software user intended to let the CTE get TRL "passed", the assessment data separated from the R&D documents or the priority would be perjury for their convenience.

It is necessary to start from the overall goal of the system and solve the problem of risk consensus between management decision-making and technical institutions under the complicated technical conditions of the project. Therefore, it is necessary to keep the strong links between the mission goal and the technology maturity, that is to say, the TRL/AD2 assessment process should merge into the R&D strategy and procedure of project management. So it is required to introduce the assessment method of technical risks and integrate it into China's system engineering management system.

As mentioned above, the traditional TRL assessment is based on the checklist method, which decomposes the definition of each level of TRL to a questionnaire, and then collects supporting information, gives the assessment result. The main shortages are the following:

(1) The questions are mainly focused on the specific level of TRL. As a consequence, the definer and user of the checklists are easy to overlook the whole maturity levels and make the wrong decision. To exemplify, a technology TRL7 has "System prototype demonstration in an operational environment". If the "system prototype" and "operational environment" of TRL7 is not clearly defined within the whole R&D process, the lower TRL6 ("system/subsystem model or prototype" and "relevant environment") and TRL5 ("component and/or breadboard" and "relevant environment") may mislead the TRL assessor.

(2) The assessment process has not set up specific supporting information (the facts collected) requirement. As to a self-assessment, it could easily lead to a wrong decision. As requirements of TRL Guide Book from U.S. Department of Transportation, two of the three questions of TRL5, "Are external and internal system interfaces documented?" and "Are target and minimum operational requirements developed?" All the two questions could match to the different type of supporting information. Naturally, they could produce confusions during assessing.

(3) All the checklists are divided into specific detailed questions within the assessment, but they merely give guidance how to strongly link or reuse the information both in TRL and AD2 stage. This could draw the assessor forth to the wasteful duplication of efforts.

As an imported method from the western culture, the TRL assessment method needs understanding the origin of the assessment, the critical step to ensure the technology risk management.

4.2 CHINESE SPACE MISSION ADMINISTRATION PROCESS

As analysed in Chapter 2, the Chinese Systems Engineering has arisen with the aerospace missions, and they defined "one headquarters and two lines of command," which incorporated technical aspect and project overall administrative management into one command structure of space mission, as it shows in the following diagram (Sanders and Xue, 2016).

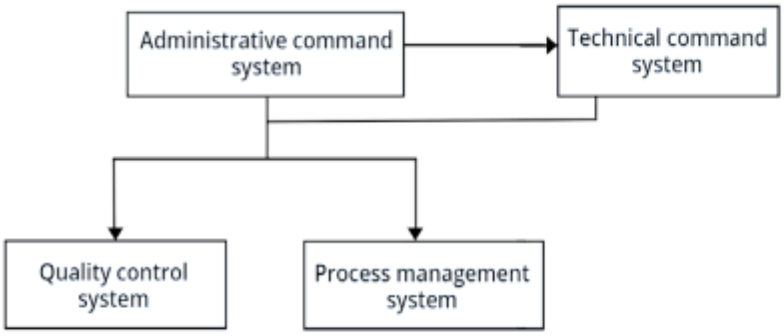

Figure 4-4: Command Lines of Chinese Aerospace Missions(Sanders and Xue, 2016)

More specific, the administrative command system will lead by Commander-in-chief, while the Chief Designer will be responsible for the technical system. As shown in the following diagram, technical issues are the primary object of the designer team.

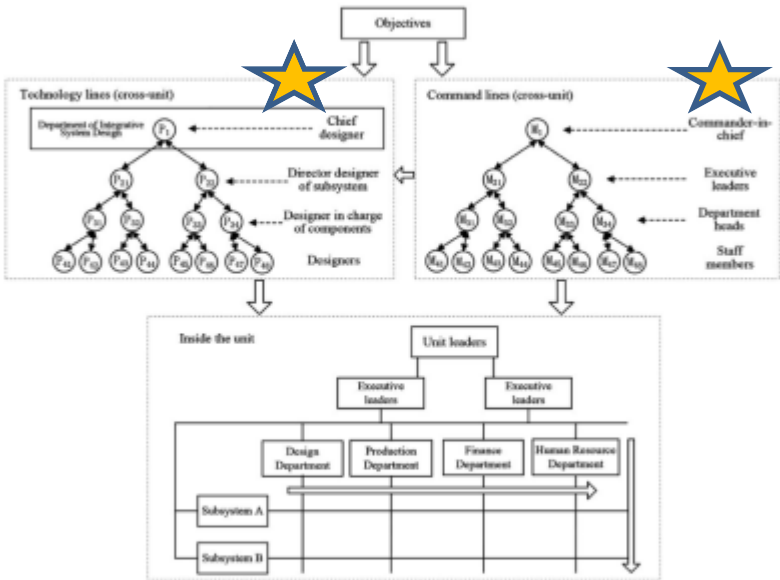

Figure 4-5: Chief Commanders of Chinese Aerospace Missions(Sanders and Xue, 2016)

Chinese culture of Systems Engineering involves technology review such as System Definition Review (SDR), Preliminary Design Review (PDR), Critical Design Review (CDR), etc. They also set up some expert groups including quality and reliability control, components and parts, technological process, and software.

Also, it is required to have a formal review of the design, the safety, test coverage audit, failure emergency plan, etc. Most of the above processes are focused on technology issues. While the TRL was introducing to China aerospace mission management and new technology risk tool, it should be integrated into the system design and validation procedure.

4.3 ATTRIBUTES BASED TRL ASSESSMENT METHOD WHIT PROCESS INTEGRATED

As designated in the process, the assessment features of each CTE would be a determinative factor in the accuracy of the assessment. TRA is original to identify the remaining technology risk. From the process viewpoint, to ensure the assessment accuracy, the assessment team should set up an agreement between the mission manager, research personnel and the assessment team. To be more specific is to build a threshold of the technology attribute to reflect all the diversities of the current state of technology compared to the application state, avoiding the risk caused by immature technologies “slipped through the net”.

As the best practice of aerospace missions, “test as you fly” is a well-recognised principle that assures the success of space missions. It is an approach that provides a unique assessment process that focuses on determining the “mission-related” or “fly as you test” risks associated with potential flaws in space systems. As discussed in the previous chapter, the risk is the “effect of uncertainty on objectives” (ISO, 2009a). The most uncertainty of technology is derived from the chief diversity of technology within a product or service in a complex project.

After collect and analysed the develop problems or failures related to space missions, the diversity elements could be categorised from the product and its environment (Appendix A.2 “Patent for Invention” for more detail). Consequently, the key attribute of the diversity should be put into four categories as the main indicators of the technology risk. The following diagram shows the relation between the diverse aspects and technology risk.

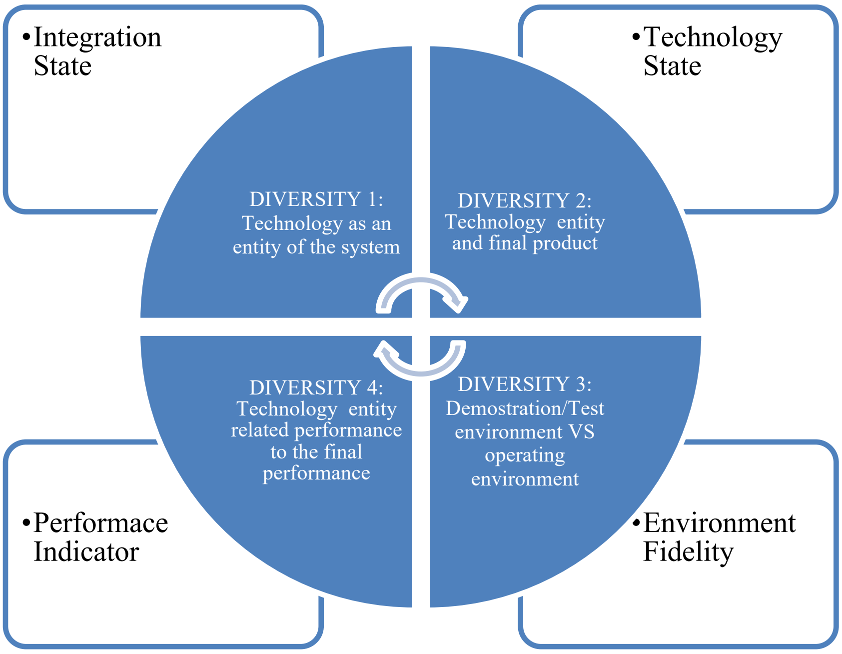

Figure 4-6: Different Diversity Indicates Aspects of Mature Attributes

The method can be used for working out a TRL evaluation criteria according to an international standard definition and principle on TRL, by attributes in four aspects of the following:

- ✓ Integration level of technology entity and system (namely the integration state)
- ✓ Fidelity of technology entity relative to final products(namely the technology state)
- ✓ Fidelity of demonstration environment relative to the operating environment(Verified or Validated environment)
- ✓ Conformity of demonstrated performance to the desired performance(namely performance indicator)

According to the processes of continuous development and upgrade of the essential attributes at each level, thereby recognising and evaluating the TRL of one CTE in escalating levels, scientifically and objectively. Finally, the fidelity of the environment and technology itself will conform to the application state.

The four maturity attributes assessment could set up a common decomposition framework for the assessment principles to the assessment features and items. They also give the management team and design team a mutual understanding of why and how is the technology risk sourced and identified.

As maintained above, with the aim to introduce TRL method to China aerospace management and ensure the accuracy of the assessment, an interconnection between the technician review team and TRL assessment team will be established. Experts from the sub-contractor will perform a self-assessment of TRL and technician review team designated by the project office carry out the stand-alone assessment. The modified process is shown below.

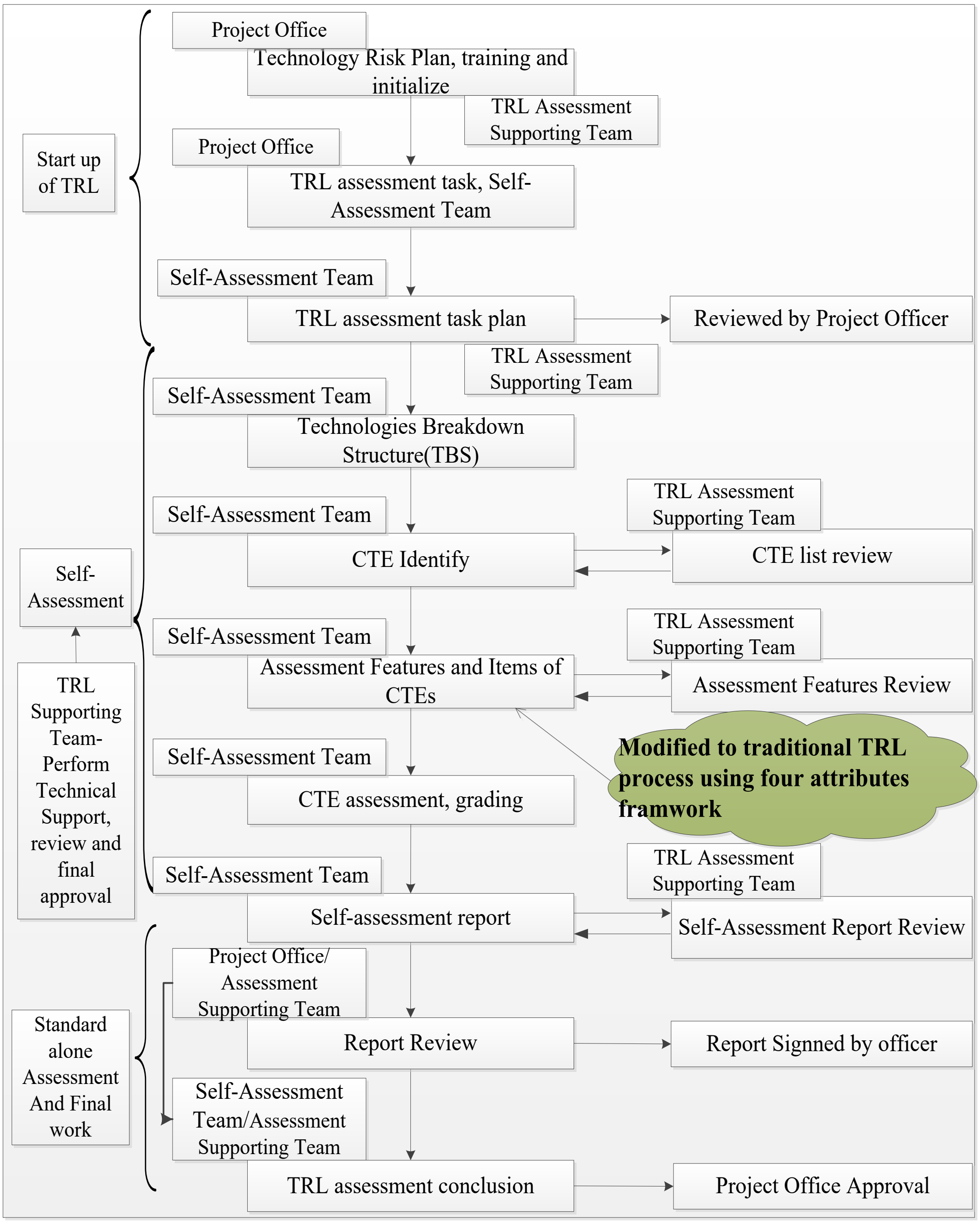

Figure 4-7: Modified Procedure of China Aerospace TRL Assessment

In this process, the decomposition assessment features of CTE selected will embody with a TRL attribute-based method, which emphasises the critical criteria of the technology mature state to avoid "slipping through the net" of the immature technology.

The information flow of the assessment process could be demonstrated in the following diagram (figure 4-8), which has had several iterations with the Experts Group. It could use a Meta-Synthesis Approach to facilitating the integration of qualitative and quantitative method.

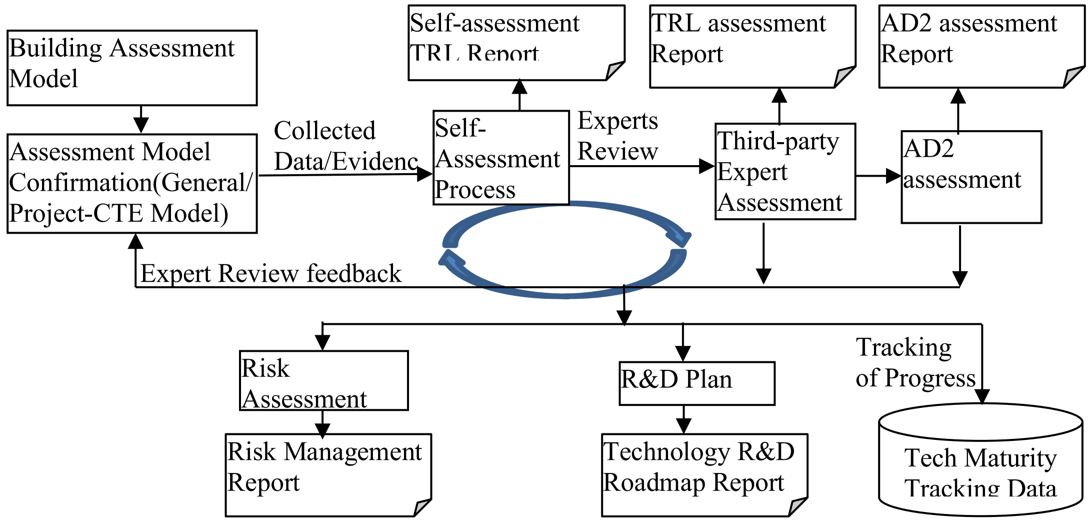

Figure 4-8: Information Flow of Assessment Process

More detail about the MSA approach based iteration process is presented in section 7.2 and Figure 7-2, and here we focus on the information and documents relations within the technology risk management involving TRL and AD2.

4.4 Assessment Supporting Information as Evidence Chain

Definition 4-1: Evidence of Technology Maturity: All the efforts have been taken and collected as evidence for the current status of the assessment criteria, in order to support the evaluation of a critical technology of maturity degree.

According to the assessment method of technology maturity, the very first thing is to decompose the system by WBS (or PBS) and build up a technical decomposing structure (namely Technology Breakdown Structure, TBS) to confirm the set of the Critical Technical Elements (CTE) needed to be evaluated. For each CTE, according to the specific technical field to refine assessment criteria in their "local" dialect of techniques area, and further to expand it to specific assessment items. Through collecting the evidence of the assessment details items, we can confirm the maturity degree of the technology (DoD, 2009), (Wu, 2012). The current evidence for all the rules that are evaluated and collected for all levels of the technology constitutes a collection.

If one establishes a formula to present that the CTE has reached the TRL level 1, all the efforts needed to be collected as evidence set, for short, Evidence of Technology Maturity or $ETM_{0\to1}$.

The $ETM_{0\to1}$ is expressed as the following:

$$ETM_{0\to1} = \{E_1^1, E_2^1, E_3^1, \cdots, E_{n_1}^1\}$$

$where\ E_1^1, \cdots, E_{n_1}^1$ are Evidences of different assessment criteria related to this CTE, for example, E_1^1 may stand for the papers reporting that

"*discovery reports on fundamentals of thrust chamber*" of "*the hydrogen and oxygen are mixed at a certain flow; the combustion may produce high-temperature vapour exhausting in the form of supersonic flow after treatment of Laval Nozzle and generates thrust*".

When we raise TRL from its first maturity level 1 to one higher level, its corresponding requested efforts is the working collection $ETM_{1\to2}$.

The $ETM_{1\to2}$ may be expressed as the following:

$$ETM_{1\to2} = \{E_1^2, E_2^2, E_3^2, \cdots, E_{n_2}^2\}$$

To raise the TRL from level 2 to a higher degree of level 3, its corresponding requested efforts is the working collection $ETM_{2\to3}$. Followed by this way, it forms 9 levels of collections of evidence. Ideally saying, when a technology reaches the TRL1, then all the maturity assessment items of TRL1 will be satisfied as "1". That is to say the elements from E_1^1 to $E_{n_1}^1$ in the evidence set will take the value "1", all others from$\{E_1^2, E_2^2, E_3^2, \cdots, E_{n_2}^2\}\ to\ \{E_1^9, E_2^9, E_3^9, \cdots, E_{n_9}^9\}$, all remain "0". Then it reached TRL2, the set will becomes a state that the elements from E_1^1 to $E_{n_2}^2$ in the evidence set will take the value "1", all others still remains "0". So as to all the following TRL scale, until on the TRL9, all the elements in the evidence set will take the value of "1".

So the Definition of "Evidence of Technology Maturity" could be expressed by the following:

$$\begin{aligned} ETM_{0\to9} &\equiv \{ETM_{0\to1}, ETM_{1\to2}, \cdots, ETM_{8\to9}\} \\ &\equiv \{E_1^1, E_2^1, E_3^1, \cdots, E_{n_1}^1\} \\ &\quad \cup \{E_1^2, E_2^2, E_3^2, \cdots, E_{n_2}^2\} \\ &\quad \cup \cdots \cup \{E_1^9, E_2^9, E_3^9, \cdots, E_{n_9}^9\} \end{aligned}$$

When technology develops to a certain degree of maturity, ideally, the technology should meet the target level and all the maturity assessment specific items of this maturity degree. This means it needs to reach the state value of "1" in all the characters of the maturity degree assessment criteria of the target maturity degree. Meanwhile, when the technology reaches the current maturity degree, it is considered to have met all the criteria of previous maturity degrees by default. Therefore, the technology should also meet all the previous maturity degree assessment criteria, which is to say the status values should be "1" in the set of the current and previous maturity degree assessment criteria.

In practice aspect, there is a possibility that the assessment of the maturity degree of the technology primarily (not entirely) meets the criteria of the maturity degree assessment. To limit some parts of the assessment criteria, one could determine a negotiated intermediate $\delta_i \in [0,1]$ value (which is the threshold of the state value in the TRL assessment criteria). When the assessment meets $S_i \geqslant \delta_i$, then it is concluded that the technology to be evaluated meets this assessment criteria. For example, the assessment feature is set as $\delta_i=0.8$ for some technology, then if the current state $S_i \geqslant 0.8$, which means the technology has met this specific criterion. This way of expression makes an assessment of technology maturity degree more flexible.

For an assessment feature, while collecting evidence to confirm the current value of this feature, it is possible to translate an index value from its growth laws of the assessment features.

For instance, one assessment feature is to see if the technology has involved in any systematic ambient temperature experiments.

Collected evidence is below.

(1) There is no need to take particular ambient temperature experiment below TRL level 4. So the efforts made on those rules are zero ("0").

(2) *On level 4 of the "Lab Environment" test, the ambient temperature is Lab room temperature (ranging from 0-35℃), the cost for the ambient temperature experiment in the lab of TRL4 is 50,000 currency units, and it may last for 5 working days (all the data in this part is for example purpose only).*

(3) On TRL5, a simulated environment experiment needs to be done. It is defined that the temperature of the simulation environment ranging from -20℃ to 55℃. The cost for the ambient temperature experiment in the lab of TRL5 is 250,000 currency units, and it takes ten working days.

(4) A simulated environment experiment needs to be done for TRL6 for the integration of the technology into the system prototype. The defined temperature of this simulation experiment is the same as TRL5. However, the ambient temperature experiment needs to be repeatedly done. Due to the change of the experiment subject, the cost for the ambient temperature experiment of this level

is 250,000 currency units. Moreover, it takes ten days.

(5) TRL 7 needs a wider temperature range for the typical application environment, like from -45~70℃. Moreover, the cost is 450,000 currency units. It takes 25 days.

(6) TRL8 and TRL9 do not need the ambient temperature experiment. Cost and time expenses are zero ("0").

So it is calculated that the most efforts for this assessment feature are 1,000,000 currency units and 50 working days. If we use the cost as the numerical basis, the technology-specific criteria would be "0, 0, 0, 50000, 250000, 250000, 450000, 0, 0" and in proportion of the total 1000000 is "0, 0, 0, 0.05, 0.30, 0.55, 1, 1, 1" of this assessment feature on levels of TRL1-9，the differences between the levels are "0, 0, 0, 0.05, 0.25, 0.25, 0.45, 0, 0". It shows a density function of difficulty distribution, which is a piecewise function like below:

$$Y = f(x) = \begin{cases} 0, & x \in \{TRL_1, TRL_2, TRL_3\} \\ 0.05, & x \in \{TRL_4\} \\ 0.25, & x \in \{TRL_5, TRL_6\} \\ 0.45, & x \in \{TRL_7\} \\ 0, & x \in \{TRL_8, TRL_9\} \end{cases}$$

This growing collection consists of an evidence chain to support the assessment features to grow from low to high levels.

4.5 SUMMARY

This chapter presents a modified qualitative TRL assessment method based on the traditional TRL assessment process and Chinese System Engineering Management procedure. The technology maturity attributes based assessment method is proposed to ensure the accuracy of the assessment.

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Chapter 5 Computational Method of Quantitative AD2 Assessment

This chapter presents a method for calculating AD2 in order to not only overcome the subjectivity of the existing evaluation methods but also achieve objective and comprehensive evaluation results of technology during its development. The method is based on the modified TRL assessment method by taking its all assessment information as the input to build an integral calculation formula of AD2. Using the formula and the numerical integration method, one can obtain a numerical result of AD2, to guide their technology management by using the quantitative assessment output as preliminary R&D plan. The quantitative assessment method could serve the NGLV Programme office as their basic management support. It reveals the internal link between technology risk and task involved within a project scope simultaneously.

Firstly in this chapter, the definition of AD2 is given, followed by a detailed analysis and discussion of its conception and attributes. Secondly, a procedure to build the assessment elements of technical maturity degree is established and using unified evidence chain built previously to support the procedure. It represents a numeric integration method; embody the parameter optimisation process with an optimisation algorithm. Finally, it gives a complete procedure to fulfil the quantitative assessment.

5.1 DEFINITION OF AD2 AND ITS ATTRIBUTES

> ***Definition 5-1*** *AD2 (Advancement Degree of Difficulty): The degree of difficulty for the Critical Technology Elements(CTE) of the given project developing from one degree of maturity to a higher degree of maturity (Bilbro, 2007b). That could be refined and expressed as the following:*
>
> ✓ *The sum of all the efforts required (these can be normalised as cost, or time needed, etc.);*
>
> ✓ *The relative proportion of the efforts in the whole process of Technology Development (Ratio or grade).*

The efforts above include new designation, developing new experiments, purchasing and installing equipment, merging new material, technical review and analysis, modelling and simulation, new staff training, or certification audit, etc. so that the weight of those efforts could give an index within all the efforts that this technology should be experienced to the success of the application.

When AD2 is expressed as relative grade, it takes ordinal "1" to "9" performance scales. Level 1 means the lowest difficulty degree, and level 9 means the highest difficulty degree, or it is expressed as the decimals ratio between 0 and 1 to express the relative proportion. When it is shown as a set of efforts, AD2 can be expressed as a collection of a series of activities, which can be reflected as forms of cost or time to express its numerical characteristic. Regarding AD2, it has its inherent attributes.

Property 5-1: *For the same technology, if the current maturity level is the same, the higher the target maturity level, the harder (higher) of AD2 of the technology difficulty. Otherwise, the lower the target maturity level, the easier of AD2 of the technology.*

Let's take optical mouse sensor development as an example (case study numbered Case-1). The mouse is a hand-held pointing device of computer hardware. It detects the two-dimensional movement on a surface, which allow smooth control of the graphical user interface of a computer system. The earlier mouse is the mechanical mouse that uses a boll contacted on the surface (called mouse pad) to capture the user movement of all directions and drives two rollers (X and Y, according to the left of following figure 5-1). The movement will be coded and transferred to a computer system as the pointing input information. The optical mouse sensor will replace the tacking boll with an optical emitter and an imaging array of photodiodes to detect movement relative to the underlying surface (the central and right figures of following figure 5-1). The new technology of optical mouse movement sensor will increase the mouse reliability for it has no moving mechanical parts (besides buttons and up-and-down scroll wheels) so that it does not require maintenance such as removing debris that the rolling boll collected. The optical mouse sensor need to be developed with a laboratory demonstration stage (TRL 4), then it will be tested in a relevant environment (TRL 5), at last, the sensor will be installed in an optical mouse to have an alpha test (TRL 7) before the mouse sales to the users.

Figure 5-1: Operating a Mechanical Mouse and Optical Mouse Example

So the property 5-1 of AD2 means that, if the mouse sensor is on its TRL 4 currently, then the AD2 of this technology from TRL4 to TRL7 is higher than the AD2 from TRL4 to TRL5. For some extra efforts such as integration of the optical sensor and the mouse, testing in an office working environment should be conducted to achieve the TRL7, obviously much higher than the AD2 of TRL4 to TRL5.

Property 5-2: *For the same technology, if the target maturity level is the same, the higher of the current maturity level, the lower of the AD2. Otherwise, the lower of the current maturity level, the higher the AD2.*

From the above example that if one would set the target maturity of the optical mouse sensor to TRL7, so the AD2 would be lower if the current TRL of this technology is on its TRL5 compared to the current TRL on its TRL4.

Property 5-3: *In the general case, for different technologies, even if the current level of maturity and the target maturity level are all the same, the intentions of their AD2 are usually different.*

Also, we could take the optical mouse sensor technology for illustration that they are designed to a different surface of opaque surface or glossy/transparent surface (newer design), for the later design would encounter with much weaker signal reflected. It is easy to understand that the later design requires more testing surface configuration to show that it works on all kinds of those. So the AD2 of later sensor design should have higher efforts from TRL5 to TRL7 compared to the traditional opaque surface design sensor.

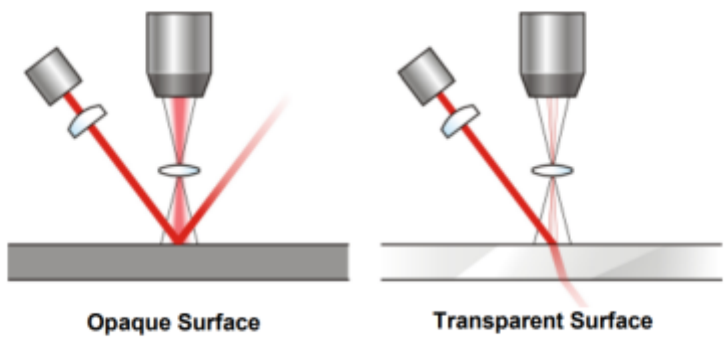

Figure 5-2: Different Technologies Result in Different AD2 within same TRL span

5.2 RECONSIDERATIONS OF ASSESSMENT METHOD OF AD2

By AD2 assessment, risks are confronted by technology development to offer guidance to relevant decisions from administrators. They are capable of capturing the technology development status in an accurate and precise way and preserve details in such an assessment.

Firstly, the definition of AD2 is a concept of "degree" which can convey such a concept through proportional relationships. During technology development, the status value of an entire development process ranges from "0" to "1"; from the perspective of technology, the variation from a status value of "0" to "1" has the largest difficulty; while the numerical value of difficulty for other development processes is a part of the numerical value of this largest difficulty. In other words, AD2 expresses all the efforts between the status from its existing status to the target status of maturity, and the span required by technology from status without any basis to that of fully matured. Using such methods can be acquired for AD2 (denoted by V_{AD2}) by " $V_{AD2} \in [0,1]$".

Meanwhile, during the development of TRL, it is assumed that the current state is $\boldsymbol{S_1}$, while the target state $\boldsymbol{O_1}$, change-of-state numerical value which is needed by technology development from $\boldsymbol{S_1}$ to $\boldsymbol{O_1}$ is $\boldsymbol{C_1}$; in addition, another target state $\boldsymbol{O_2}$ also exists, and the ranking of TRL that corresponds to $\boldsymbol{O_2}$ is higher than the ranking of it corresponding to $\boldsymbol{O_1}$. In the case that the technology develops from "0" to $\boldsymbol{O_1}$, the overall span of TRL required by it is $\boldsymbol{Z_1}$, AD2 which is needed by technology development from $\boldsymbol{S_1}$ to $\boldsymbol{O_1}$ can be expressed as:

$V_{1AD2} = C_1 / Z_1$.

If the span of technology maturity between $\boldsymbol{O_1}$ and $\boldsymbol{O_2}$ is δ, AD2 which is required by technology development from the current state $\boldsymbol{S_1}$ to the target state $\boldsymbol{O_2}$ can be denoted as $V_{2AD2} = (C_1+\delta)/(Z_1+\delta)$.

Furthermore, the relation between V_{1AD2} and V_{2AD2} need to be proved.

Prove:

$$V_{1AD2} - V_{2AD2} = \frac{C_1}{Z_1} - \frac{(C_1+\delta)}{(Z_1+\delta)} = \frac{C_1(Z_1+\delta) - Z_1(C_1+\delta)}{Z_1(Z_1+\delta)}$$

$$= \frac{C_1 Z_1 + C_1\delta - Z_1 C_1 - Z_1\delta}{Z_1(Z_1+\delta)} = \frac{\delta(C_1 - Z_1)}{Z_1(Z_1+\delta)}$$

because of $Z_1 > 0$，$(Z_1+\delta) > 0$，$\delta > 0$，$(C_1-Z_1) < 0$,

$\frac{\delta(C_1-Z_1)}{Z_1(Z_1+\delta)} < 0$，that is $V_{1AD2} - V_{2AD2} < 0$，as a result, $V_{1AD2} < V_{2AD2}$。

Proving Completed.

The above proof indicates, during the gradual increase in ranking of TRL at a target state, the numerical value of AD2 increases too. This is provided in an expression approach of proportion, which is in conformity with the basic concept of AD2 and explains that such an integration based expression approach of AD2 is mathematically rational.

In this thesis, AD2 is classified into nine levels, and definition thresholds have been set for AD2 at each level, as well as Bilbro suggested(Bilbro, 2010). Then, in line with the magnitude of all thresholds, a ranking of AD2 can be determined for technologies under assessment to fulfil the process.

The formula of integration can be adapted to achieve numerical values of AD2 during technology development in a more accurate manner. In this part, with an aim to establish a formula of integration for AD2 computation, the setup procedure of a basic integral formula with the decision-making procedure of weight parameters and state density functions in the formula is discussed respectively.

The assessment form of AD2 used by Bilbro (Bilbro, 2008) need to discuss in detail, and the refinement and localisation of assessment are formed during TRL assessment. The reason is that the assessment purpose may vary significantly during different phases of TRL and AD2. For example, the purpose is to identify whether there is a significant technical risk which influences whether the project could proceed to the next phase. This can be concluded as long as there is a major immature technique which is enough to influence the system acceptance during the technology assessment of critical decision point. Namely, the judgment of the problem can end up with "No". As long as there is a counterexample belonging to "$\neg$**B** → $\neg$**A** ", and condition **B** is ***necessary*** condition of **A**. What AD2 has to answer is what activities can be carried out to improve the technique to the needed maturity level, and it has to complete all the "efforts" to improve the technique maturity status to support the technical factor in order to improve the TRL level, so **B** is the ***sufficient*** condition of **A**.

If it further extends supplements and completes necessary conditions and makes them sufficient during the assessment of TRL and AD2, the following equivalent conditions shall be set up:

*"The system satisfies acceptance standard" ≡ (**necessary and sufficient**) equals to*

*(**Either**: "All the basic components of the subsystem included in the system have met the needed TRL"*

***Or**: "CTEs which have not reached technical maturity level have already set up technical measures fully guaranteeing its maturity via AD2")*

According to the above equivalent conditions, extended TRL and AD2 assessments are both admitted a set of complete unified evidence chain:

(1): the evidence assembly of success system (smoothly passes the acceptance) ≡ evidence assembly technical maturity of the basic components of various subsystems and bottom parts: (completed via full decomposition of PBS or WBS, make sure the purpose of system's technical assessment is equivalent)

(2): evidence assembly of various TRL assessments ≡ fulfil the necessary conditions and sufficient conditions: (supplement evidence related to "sufficiency" after the localisation of TRL assessment is completed, namely "as long as these efforts and evidence is satisfied, the TRL of CTE is improved")

(3): evidence assembly of assessment of AD2 of CTEs whose current condition do not satisfy the demand of system ≡ difference between technical conditions (evidence assembly of equivalence of maturity state of target technique-evidence assembly of equivalence of maturity state of current technique)

Based on the above evidence assembly and equivalent relation, assessment on AD2 can be completed by integration of evidence assembly among TRL assessment information.

If we establish AD2 for its reach the first maturity level-1 marked up as $AD^2_{0\to1}$, all the efforts needed to be collected as evidence set $ETM_{0\to1}$. In such a situation, the advancement degree of difficulty from TRL1 to TRL2 will be treated as the difference set of ($ETM_{0\to2}$ - $ETM_{0\to1}$), that is specific assessment items(and evidences) to TRL2.

During analysis of the unified evidence chain defined above, take all the efforts as the "member" of a "set". Take the definition of chapter 4 as an example:

$$ETM_{0\to9} \equiv \{ETM_{0\to1}, ETM_{1\to2}, \cdots, ETM_{8\to9}\}$$
$$\equiv \{E^1_1, E^1_2, E^1_3, \cdots, E^1_{n_1}\} \cup \{E^2_1, E^2_2, E^2_3, \cdots, E^2_{n_2}\} \cup \cdots \cup \{E^9_1, E^9_2, E^9_3, \cdots, E^9_{n_9}\}$$

Under normal circumstance, the efforts belong to different TRL level should be distinct, so if all the efforts combine a set with its elements of each distinct effort of $ETM_{0\to9}$, with all the

E_x^y, *while* $x \in (1, \ldots, n_1, 1, \ldots, n_2, \ldots, 1, \ldots, n_9), y \in (1, \ldots, 9)$ as the member of the set, the AD2 from a specified TRL to a higher one become a "true partitioning" of the whole set. There might be the condition where evidence of one CTE in different technical maturity levels is not "true sub-set" (integration of all the efforts SET needed to complete to represent this level), for example, there is a substitutional relation or duplicate relation between a certain technical measure in low-level M and one in high-level N, all the above need "de-couple" to a simple set:

- ✓ For duplicate relation: respectively submit as evidence in different basic assessment and distinguish each;
- ✓ For substitutional relation: adopt the evidence in high-level assessment, take the supplement of "difference value" as evidence, for example, assembly of (A1, A2, A3) turns into ((A1'+A1"), A2, A3), in which A1' is equivalent to the low-level evidence in cost aspect or certain aspect, and A1" is the different part of A1', acts as higher level evidence.

Also, we could conclude that: $TRL_1 \cup AD_{1\to9}^2 \equiv TRL_2 \cup AD_{2\to9}^2 \equiv \cdots \equiv TRL_8 \cup AD_{8\to9}^2$ Let take the TRL3 as an example that $TRL_3 \equiv \{ETM_{0\to1}, ETM_{1\to2}, ETM_{2\to3}\}$, while the $AD_{3\to9}^2 \equiv \{ETM_{3\to4}, ETM_{4\to5}, \cdots, ETM_{8\to9}\}$. The $AD_{3\to9}^2$ is the complementary set of TRL_3 is we define the $ETM_{0\to9}$ as the universal set (see figure 5-3).

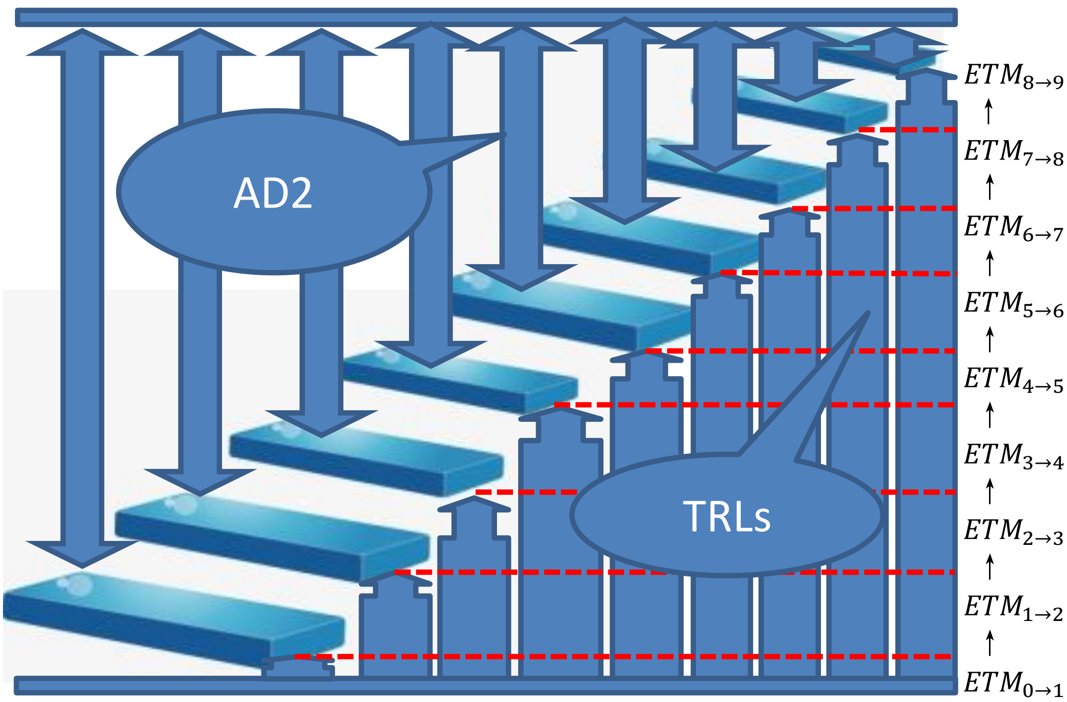

Figure 5-3: Assessment Evidence of TRL and AD2

The above figure demonstrates that the close relation of AD2 and TRL, within any TRL level, such as TRL 5 as another example, the evidence set has the all the elements from $ETM_{0\to1}$, $ETM_{1\to2}$, $ETM_{2\to3}$, $ETM_{3\to4}$, $ETM_{4\to5}$, so the complementary set of the universal set is $AD2_{5\to9}$ is the AD2 from TRL 5 to TRL 9.

Apart from the general condition in the mentioned technical development, there is also a particular condition of technical development. For example, during technical development, based on TRL assessment information, there might be a repetition of status value in different TRL level when the status value of maturity is "vibrating", explicitly, the score of a certain assessment level is lower than the previous level during the high-level assessment. This similar condition might be that the evidence offered during formal low-level assessment leads to "fake maturity" At this time, it shall "restore" the assessing result of the previous level according to the real historical phenomenon of the technique to reflect the exact situation of this technical risk.

For the similar assessment situation that same efforts exist in a different level, there are many alternative solutions of the adoptable technical solution to guarantee its maturity and "parallel to sequential" solutions of tackling, for this time, it is regarded as a "sequential" process while decomposed the efforts to more fundamental tasks.

Based on the above assumptions and analyses, it can still conduct integration based on unified evidence of AD2 after de-couple the internal relations among the efforts in the assessment set so that the set become a basic set.

5.3 COMPUTATIONAL METHOD OF AD2 ASSESSMENT

In this part, the calculation method is built based on AD2 property analysis. Among the calculation methods for AD2, the establishment of calculation flow and the integral computation are included.

From section 4.1, the assessment of TRL of a CTE starts with decomposed the level definition to several assessment features, then locate some assessment items needed an answer to each assessment feature. After collecting corresponding evidence information answering the assessment item, all the item answers belong to one assessment feature will be synthesised to get an outcome of this assessment feature. In this step, the input is all the evidence information of every assessment items. The output is an indicator to show whether (or how much) this assessment feature is satisfied. As discussed in section 4.4 and 5.2, the indicator could be normalised to $\delta_i \in [0,1]$. The mapping from input to the output could be treated as a function $\delta_i = f(\varepsilon_{j1}, \varepsilon_{j2}, \dots, \varepsilon_{jn})$, where $\varepsilon_{j1}, \varepsilon_{j2}, \dots, \varepsilon_{jn}$ are the evidences of the assessment items. Since all the items are closely related to one feature, this function could be called ***Maturity State Density Function***, means it aims to capture the maturity state of this assessment feature distributed to the efforts span related to this TRL level. The density function with all the variables is called Maturity Evidence Information Model.

Consequently, all the assessment features with the answer could put together to determine whether or how much this CTE achieved to this TRL level span. This composition also could be treated as another function which transforms all the assessment features the answer to one output, the final AD2. In practice, this function is usually a Weighted Summation. So the ***Weight Factors*** to each assessment features are significant to determine.

To come up together, the former further contains the establishment of a state density function, the weight factor selection for assessment feature as well as the integral formula setting up. A module chart for the calculation method is shown in Figure 5-4.

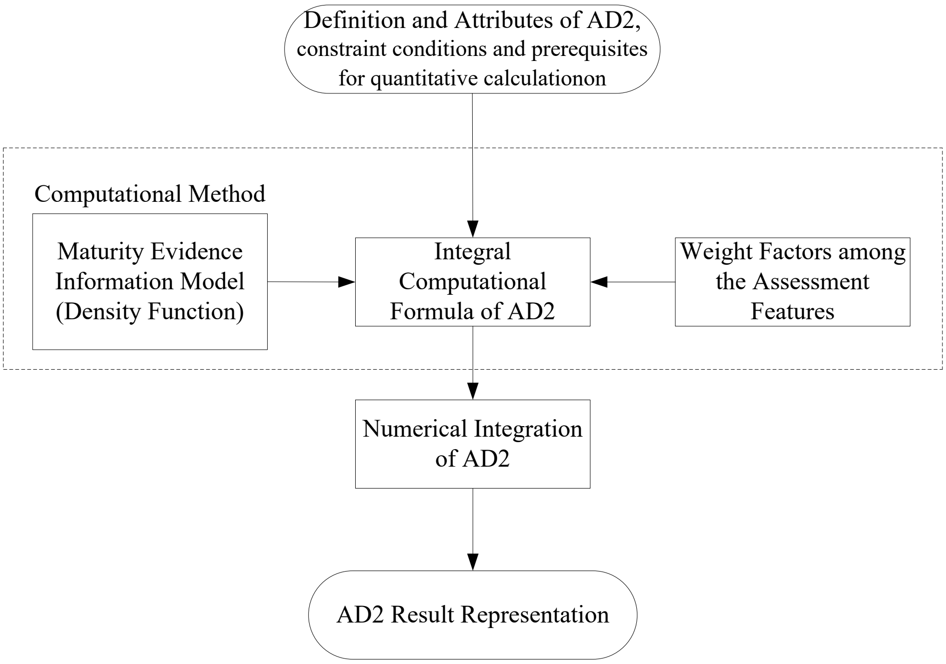

Figure 5-4: Computational Process Diagram for AD2

During the establishment of a state density function to capture the mature difficulty distribution, specific weight factors could be determined as a different priority, and its range can be determined according to fundamental properties of AD2. In comparison, during weight factor selection for maturity assessment features, optimisation selection is carried out by an optimisation algorithm to obtain weight factors of all assessment features to summarise the final assessment result. By acquiring both the state density function and the weight factors of assessment features, the computational formula of AD2 is set up by the formula of integration; specific to which, the numerical integration process is performed to acquire the value of AD2 and express the relevant results.

Table 5-1: Input / Output Relations of Quantitative Assessment Method of AD2

<table>
<tr><td colspan="2">Maturity State Density Function</td><td colspan="2">Weighted Summation</td></tr>
<tr><td>Input</td><td>Output
(input for the next step)</td><td>input
(weight factors)</td><td>Output
(Final AD2)</td></tr>
<tr><td>Assessment item$_1$ value</td><td rowspan="3">Assessment feature$_1$ value</td><td rowspan="3">Weight factor$_1$</td><td rowspan="11">$\sum Feature_i * Weight_i$</td></tr>
<tr><td>……</td></tr>
<tr><td>Assessment item$_{n_1}$ value</td></tr>
<tr><td>Assessment item$_2$ value</td><td rowspan="3">Assessment feature$_2$ value</td><td rowspan="3">Weight factor$_2$</td></tr>
<tr><td>……</td></tr>
<tr><td>Assessment item$_{n_2}$ value</td></tr>
<tr><td>……</td><td>……</td><td>……</td></tr>
<tr><td>Assessment item$_i$ value</td><td rowspan="3">Assessment feature$_i$ value</td><td rowspan="3">Weight factor$_i$</td></tr>
<tr><td>……</td></tr>
<tr><td>Assessment item$_{n_i}$ value</td></tr>
</table>

During the calculation of AD2, greater weight factor should be allocated to stress the corresponding maturity assessment features to reflect that the managers should paid more attention to the relevant maturity development procedure. Hence, the corresponding weight values should be assigned to various assessment features directed at diverse assessment features with different importance during maturity assessment.

In the TRL assessment evident chains built in chapter 4, the set-theoretic difference set of a two-level TRL corresponding evidence, including the basic assessment elements in the evidence chains between the corresponding state span ratios. It is to be the expected evaluation efforts developing from a maturity state to another higher maturity state. When a technology has reached a specific higher maturity state, that is, the technology manages to achieve the degree of maturity in each evaluation features. The state span between the current maturity state and target maturity state became an essential factor in the expression of AD2, called mature technology difficult span. (D_{AD2})

Due to the uneven distribution of the state density, the integral formula of the difficult span of technical maturity needs to be performed in the state density dimension, which is the definite integral from the current TRL level to the higher target level.

$$D_{AD2} = \int f(density)d(density) = \int f(y)d(y) \qquad (5\text{-}1)$$

Among them, $f(y)$ as the state density function, there is different state density in each assessment feature. In the same TRL assessment, the state value of the technology maturity gradually increased. Therefore, the piecewise function could give a vivid description of

$f(y)$ in this situation. Such state density gradient process will further reflect the calculation of the AD2 in engineering technology growth.

The TRL assessment items can be expressed in each of the assessment features for the technology to achieve, and the set of state values shows the set of the technology mature state at that time. The difference between the two maturities statuses can calculate the span accurately through an integral that the AD2 corresponds to the span, the integral formula is as follows,

$$D_{AD2} = \int \alpha_{feature}(TRL_m - TRL_n)d(feature) = \int \alpha_x(f(x)_m - f(x)_n)d(x) \quad (5\text{-}2)$$

Among them, $\alpha_{feature}$ as the weight factor (coefficient) of technology assessment dimension, namely the weight value in the mature degree of evaluation features, belongs to empirical data and can be determined by the experienced experts, and also can be chosen through an optimisation algorithm. Meanwhile, the weight value of every assessment feature numerical exist as follows,

$$\sum \alpha_{feature} = 1 \quad (5\text{-}3)$$

Based on the TRL assessment method of TRL, the weighted summary of the various rules of all level is 1, for example, in the TRL5 of one technology, its maturity assessment features have 16 rules, then $\sum_{i=1}^{16} \alpha_{feature} = 1$.

In (5-2), TRL_m means the mature state of the technology at the level of m and it is determined by the state value of the level m in the details assessment features; TRL_n means the mature state of the technology at the level of n ($n \leq m$) and it is the output of the level n among the details assessment features; One can get the sum of the state S_m at the level of m and the state S_n at the level of m by numerical integration, see as following,

$$S_m = \int \alpha_{feature} TRL_m d(feature) = \int \alpha_x f(x)_m d(x) \quad (5\text{-}4)$$

$$S_n = \int \alpha_{feature} TRL_n d(feature) = \int \alpha_x f(x)_n d(x) \quad (5\text{-}5)$$

On the above calculation, the AD2 means the technology difference between the state S_m and the state S_n, that is changing the formula (5-2) to the following,

$$D_{AD2} = S_m - S_n \quad (5\text{-}6)$$

According to the state distribution of TRL can be derived that assessment features are corresponding to the state value, and the calculation of AD2 belongs to piecewise integration process from the assessment features dimension consideration, it is concluded that one can get the overall number of the AD2 span by the sum of all the numerical integration.

From the integral theory, the assessment features are corresponding to the maturity density function to describe the growth within this assessment feature. On could determine the assessment feature value uniquely if only one could gather the assessment information wholly and correctly. Therefore, the AD2 could be obtained by $\sum Feature_i * Weight_i$ if each feature was uniquely determined. After the analysis, the weight factors are unknown value, it requires the expert experience or to establish the appropriate optimisation algorithm to obtain the weight value.

To sum up, the AD2 could be getting by two-step integration: (1) using definite integral of the maturity density function from the current TRL to the target TRL. It is doing integral to the direction of the assessment feature to capture the efforts stimulating the feature growth; (2) weighted summation of multiple assessment features. It is integrated into the direction to cross all assessment features. Ultimately the formation of the integral formula for complete computing AD2 span as follows,

$$D_{AD2} = \sum_{i=1;j=1}^{i=N_9;j=9} Weight_{ij} * f\left(density_{ij}\right) d\left(density_{ij}\right) = \sum_{\Omega} \alpha_{ij} * f(y)dy \qquad (5\text{-}7)$$

Among them, $f(y)$ is the state density function, α_{ij} as the assessment feature weight factor value. Ω is the integral domain for the computation of the AD2, and is expressed as the difference between the two maturity parts in the AD2 span, see the following,

$$\Omega\text{:} \begin{cases} 0 \le i \le N_9 & (each\ assessment\ feature\ in\ 9\ TRL\ levels) \\ 0 \le j \le 9 & (TRL\ level\ from\ 1\ to\ 9) \end{cases} \qquad (5\text{-}8)$$

After getting D_{AD2}, the technical maturity of the difficult span value, V_{AD2} is:

$$V_{AD2} = D_{AD2}/D \qquad (5\text{-}9)$$

Among them, D is the value of the technology matures difficult span that the state value develops from all "0" to all "1" as the technology on all assessment features in the whole process of the development, the specific formula as follows,

$$D = \sum_{\Omega} \alpha_{ij} * [\int_0^1 f(y)dy] \qquad (5\text{-}10)$$

The state value develops from "0" to "1" belongs to the whole process of the development in the TRL assessment features, as for the same technique, D is the same value as the same calculation of the evaluation rules. Therefore, D is a relatively fixed value and we will focus on the D_{AD2} in the following discussion.

5.4 WEIGHTING PARAMETERS OF THE CALCULATION EQUATION

Equation (5-7) shows in the integral formula of AD2 in which the weight factors among the assessment features play a vital role in the final calculated results of TRL. Considering the values of the weighting factors are distinct during the assessment, it is necessary to determine the specific value of weight factors for their corresponding assessment characteristic. Besides, the weighting factors need optimising to reveal the most appropriate weighting values.

When determining weighting factors, traditional researchers suggested assigning value by the experts' experience, and expertise are relatively subjective and can hardly get objective and accurate values for the weighting factors. It also increases the workload of experts and is not beneficial to improving work efficiency.

The selection of the values of weighting factors belongs to the domain of optimisation field, with the characters of discretization, non-linearity and complexity. In different applications, some optimisation algorithms could be referenced. For relatively simple continuous and linear questions analysis, standard optimisation algorithms such as Lagrange multiplier(Tamura et al., 2005), simplex methods (Tuzikov et al., 2003), the gradient descent method(Jenssen et al., 2007) can be employed. Recently, researchers have studied the use of swarm optimisation approaches(Barbosa et al., 2015) and evolutionary algorithms(Borangiu et al., 2015).

For TRL and AD2, some of the intelligent optimization algorithms should be considered, including Genetic Algorithm(Mou et al., 2005, Al-Rawi and Karajeh, 2007, Lu et al., 2008, Jun and Yong, 2011), Ants Colony (Ma et al., 2009), Simulated Annealing(Fung and Chan, 2006, Jenssen et al., 2007), particle swarm algorithm(Tseng et al., 2008, Ma et al., 2009) and so on. Many of them have their advantages and limitations. From the practical point of view, the optimisation theory could only be accessed by the user (especially the manager of a project) via a software tool integrated into the working network, rather than doing the optimisation themselves. Genetic algorithms (GAs) are evolutionary algorithms of searching in the elements space of binary strings or arrays of other types. The research and application of GA dated back to 1950s, and now it is formalised finally became widely recognised and popular for solving inequalities, function optimisation, and determining the weights in neural networks, etc. This thesis employed GA to gradually obtain a more accurate value of the weighting factor through the evolutionary process. Another reason to choose GA as a suitable one is that GA was well-developed and ever-ready to implement. There are many easy accessible programing toolboxes so that they could embed in the assessment supporting software.

To be more specific, GA is suitable to the nature of the current optimisation which is seeking the solution of weighting parameters, for GA is using unified chromosomes to represent the internal mechanism of mapping the input to the output. Although the configuration of parameters of each technology being assessed varies from one to another, GA has been proved effective and efficient to find the comparatively accuracy solution.

GA is a matured computational method that uses in the optimisation process. A genetic algorithm is an iterative search process based on **natural selection** and **genetic evolution**. It selects excellent **chromosomes** for reproduction via **selection**, **crossover** and **mutation** operators in the populations built by initialisation. The primary cycle of the process could be described as the following figure:

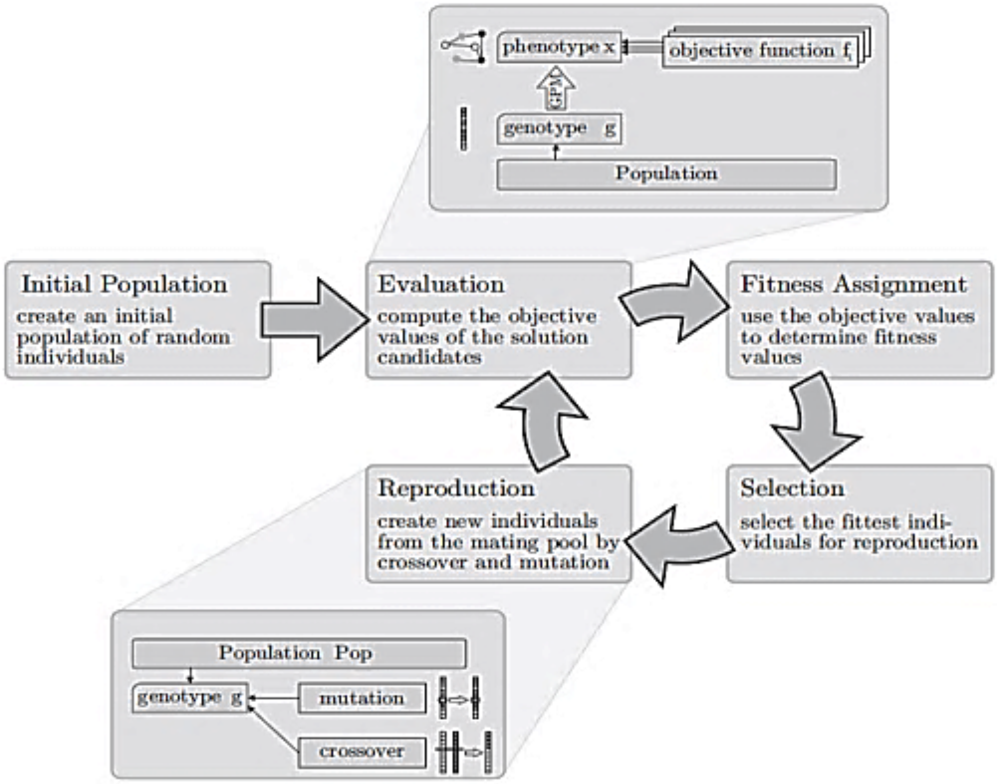

Figure 5-5: The Basic Cycle of GA in Optimisation Searching

After coding the chromosome to represent the weight factor, random initialisation of the population is performed. The evaluation of the generation is based on the objective values to determine fitness, to select the best (in a mathematical way, called “fitness”) individuals. Then, the population will produce the next generation using the operators such as selection, crossover and mutation. By this way from genetic processes and the natural evolution and selection, one could get optimised population after certain cycles occurred.

As for the calculation process of AD2 in this thesis, it is possible to find the optimal global solution via a multi-step iterative process. The particular type of objective function is used to summarise how close each with this population is to achieving the optimisation aims (which is the best practice by the leading edge experts). It has the name of "Fitness function", and is used in genetic programming and genetic algorithms to guide simulations towards optimal design solutions. In brief, the GA achieves an iterative process of individual reconstruction within the population through implementing genetic manipulation on individuals of the group, by the guard of "Fitness Function". Compared with other optimisation methods, GA uses simple encoding techniques and reproduction mechanism to represent and characterise some complex phenomena.

In the process of establishing fitness function, it is necessary to adopt form-based AD2 evaluation results from the best experts group, that is AD_0^2. Firstly, calculate the value of AD2, V_{AD2}, via Equation (5-9); then grading V_{AD2} with a designated threshold value to derive different AD2 levels, When the difference between the current AD2's value AD_c^2 and predetermined AD_0^2 is larger, it indicates that the value of the current combination of weighting factors has a more significant deviation with the target situation. So the Fitness Function should get a lower value for the chromosome; otherwise, it indicates the value of fitness for the chromosome is higher. The fitness function established could be expressed as follows,

$$fit = \frac{1}{| AD_c^2 - AD_0^2 |} \tag{5-11}$$

The fitness value could, therefore, be calculated via Equation (5-11) and the chromosomes with a higher degree of fitness will be retained and kept for the next step of the operation.

The detailed calculation process of genetic algorithm includes chromosome encoding, selection, crossover and mutation. A chromosome encoding process encodes the corresponding weighting values for each assessment feature. The selection process is to select chromosomes of higher fitness in a variety of populations, that is to say, selection of suitable combinations of weighting values assessment features of which give better values AD2. The aim of crossover and mutation processes is to ensure genetic algorithm not fall into the locally optimal solution but able to get the best combination of weighting values within the overall portfolios. The following has the detail of the steps.

(1) Chromosome encoding

Suppose each weighting factor's value of assessment feature could be represented by ***h*** genes at consecutive positions, $(g_i, g_{i+1}, g_{i+2}, ..., g_{i+h})$. After transferring the values of these ***h*** genes from binary to decimal, the maximum decimal value represented by ***h*** bits of the binary value is "2^h-1", that is to say,

$MaxGene_{binary\_to\_decimal}(g_i, g_{i+1}, g_{i+2}, ..., g_{i+h}) = 2^h - 1$. If one takes the ratio of the decimal value represented by ***h*** bits of binary value to "2^h-1" as the corresponding weighting factor of assessment features, then this ratio could be expressed as follows:

$$\alpha = Gene_{binary\_to\_decimal}(g_i, g_{i+1}, g_{i+2}, ..., g_{i+h}) / 2^h - 1 \quad (5\text{-}12)$$

Suppose there are "$M_{feature}$" detailed assessment features of AD2, then the chromosome will contain "$M_{feature} \times 2^h$-1" genes, and the encoding for the chromosome could be expressed as follows:

$$R_{weight} = (g_1, g_2, g_3, ...g_{2^h-1}, ..., g_{M_{feature} \times (2^h-1)}) \quad (5\text{-}13)$$

This kind of chromosome encoding is not only in line with the selection process of the weighting factor's values of assessment features but also with simple encoding format that facilitates the operation of genetic operators.

(2) Initialisation of population

Once the encoding process is finished, proper GA operations will be carried out on chromosome encoding to obtain the optimal solution in the population and complete the selection of the weighting factor's value. The initialisation of this process is also the initialisation process of the whole population.

Individuals in the initialised population by GA are mostly randomly generated to avoid fall in the local optimisation point. In the selection process of weighting factors, the sum of each weighting factor's value equals to 1. In the process of randomly generating initialised population, the weighting factor's values are also randomly generated, and their sum surely equals to 1. After generating the weighting factor's values, if each value is multiplied by "2^h-1", the product is expressed with the h-bit binary number and assume ***h*** = 4 in this research (which means it is expressed by 4-bit binary number), then the initialisation of chromosomes could be composed by binary values. In the process of initialising the population, another variable needs to set is population size, i.e. the number of chromosomes.

After chromosome encoding the weighting factor's value of assessment features and initialising the corresponding population, the genetic algorithm enters into its main process - genetic operation. The genetic operation is a kind of simulation of how bio-genes inherit. It makes use of its associated genetic operators (selection, crossover and mutation) and its adaptation to the environment to manipulate and control the evolution operations of chromosomes in the population.

(3) Selection operators

The evolution of creatures follows the principle of "survival of the fittest". Individuals with a stronger ability to adapt to the environment will have a greater chance of survival, and then reproduction of the next generation. According to the normal genetic algorithm, chromosomes of a larger fitness value will have a higher probability being selected; there are more opportunities for subsequent genetic operation, which is known as genetic algorithms "**selection**" process and completed by the sub-selection operators. The purpose of selection is to inherit the optimised individuals to the next generation directly or to generate a new optimised individual by crossover for the next generation; the whole process of selection is based on the calculation of the individual fitness in the initialised population using fitness function. Chromosomes of higher fitness can replicate more copies in their next generation; while chromosomes of lower fitness present with little or even no chance in the next generation. To calculate the degree of fitness, fitness function establishment is the key to the operational process of selecting operators. This thesis uses a traditional **roulette wheel** selection method. In this method, each chromosome occupies a sector in the virtual roulette, and the area of the sector occupied by the chromosome is proportional to the value of its fitness. A higher fitness value not only means larger sector area occupied by the chromosome, but also means the stronger chromosome adaptability and more suitable weighting combination of chromosome for the calculation of AD2; while a smaller fitness value means smaller sector area occupied by the chromosome and indicates that weighting combination of chromosome is less suitable to calculate AD2.

(4) Crossover operator

Most of the existing genetic algorithms use a fixed crossover probability (namely p_{cross}) and a fixed mutation probability (namely $p_{variate}$). However, both of them usually could not maximize the genetic algorithm converge to the optimal global solution. It is found that the two main factors affecting p_{cross} and $p_{variate}$ are fitness function and current generation. When the value of generation is small or when the values of fitness function are dispersed, it is taken as the early stage of evolution and needs larger p_{cross} and $p_{variate}$ to avoid genetic algorithm falling into a locally optimal solution. The simultaneously genetic algorithm needs smaller p_{cross} and $p_{variate}$ to achieve faster convergence during the late stage of evolution.

Based on this, adaptive crossover probability p_{cross}, mutation probability $p_{variate}$, crossover location in the gene (namely l_{cross}) and mutation location in the gene (namely $l_{variate}$) are established.

The **crossover** operator produces a new generation of chromosomes by replacing or restructuring operations in different parts of the gene. Determining crossover probability and intersection points are the two keys to construct the crossover operator.

A. for the earlier stage of evolution

If the current number of the reproduction generation (namely $n_{generation} \le \phi$, where ϕ is the predefined threshold value of generation) and at the time, the individuals in the population has significant difference of fitness function, such as $(fit_{\max} - fit_{avg}) / fit_{avg} \ge \varphi$ (where $fit_{\max}$ is the maximum fitness function of all individuals and fit_{avg} is the average fitness function, where φ is another predefined threshold value of difference), it is actually in the early stage of evolution and requires typically larger p_{cross}, that is to say, it needs predetermined crossover probability (namely p_{cross0}) to multiply a larger factor, and it also needs l_{cross} to be set closer to the comparatively sensitive location (namely l_{cross0}, predetermined of sensitive location of gene) of the assessment feature in the existing TRL state. This will help to broaden the search and avoid falling into a locally optimal solution. The corresponding p_{cross} and l_{cross} at this early stage could be expressed as follows:

$$p_{cross} = p_{cross0} \times e^{(\frac{n_{end} - n_{generation}}{n_{end}}) \times (\frac{fit_{\max} - fit_{avg}}{fit_{avg}} - \varphi) / (\frac{fit_{\max} - fit_{avg}}{fit_{avg}})} \tag{5-14}$$

$$l_{cross} = l_{cross0} \times e^{(\frac{n_{generation}}{n_{end}}) \times (\varphi - \frac{fit_{\max} - fit_{avg}}{fit_{avg}}) / \varphi} \tag{5-15}$$

In which, n_{end} is the predetermined termination generation, means when the evolution reached this maximum generation, the GA process will stop; $n_{generation}$ is the current generation.

B. for the later stage of evolution

When $n_{generation} > \phi$ or $(fit_{\max} - fit_{avg}) / fit_{avg} < \varphi$, it is actually in the late stage of evolution and requires typically smaller p_{cross}; it also needs l_{cross} to be set more away from the sensitive location l_{cross0} of the assessment feature. This will help to control the magnitude of change in each generation and improve the convergence rate. The corresponding p_{cross} and l_{cross} at this late stage could be expressed as follows:

$$p_{cross} = p_{cross0} \times e^{(\frac{n_{generation}}{n_{end}})\times(\frac{fit_{\max}-fit_{avg}}{fit_{avg}}-\varphi)/\varphi} \tag{5-16}$$

$$l_{cross} = l_{cross0} \times e^{(\frac{n_{end}-n_{generation}}{n_{end}})\times(\frac{fit_{\max}-fit_{avg}}{fit_{avg}}-\varphi)/(\frac{fit_{\max}-fit_{avg}}{fit_{avg}})} \tag{5-17}$$

Exchanging the $p_{cross} \times n_{gen}$ genes before the location l_{cross} with those $p_{cross} \times n_{gen}$ genes after the location l_{cross}; n_{gen} is the number of genes in the chromosome.

(5) Mutation operator

The **mutation** operator of the GA aims to maintain the diversity of individuals in the population and avoid GA neglecting the data which is far away from ideal characteristics and only operating the data which is close to the ideal characteristics. This will avoid the situation that GA falls into a locally optimal solution prematurely.

A. for the earlier stage of evolution

If $n_{generation} \le \phi$ and $(fit_{\max} - fit_{avg}) / fit_{avg} \ge \varphi$, it is actually in the early stage of evolution and requires typically larger $p_{variate}$ and it also needs $l_{variate}$ to be set closer to the comparatively difficult-to-complete location $l_{variate0}$ of the assessment features in the existing TRL state. This will help to maintain the diversity of individual chromosomes in the population. The corresponding $p_{variate}$ and $l_{variate}$ at this early stage could be expressed as follows:

$$p_{variate} = p_{variate0} \times e^{(\frac{n_{end}-n_{generation}}{n_{end}})\times(\frac{fit_{\max}-fit_{avg}}{fit_{avg}}-\varphi)/(\frac{fit_{\max}-fit_{avg}}{fit_{avg}})} \tag{5-18}$$

$$l_{variate} = l_{variate0} \times e^{(\frac{n_{generation}}{n_{end}})\times(\varphi-\frac{fit_{\max}-fit_{avg}}{fit_{avg}})/\varphi} \tag{5-19}$$

B. for the later stage of evolution

When $n_{generation} > \phi$ or $(fit_{\max} - fit_{avg}) / fit_{avg} < \varphi$, it is actually in the late stage of evolution and requires typically smaller $p_{variate}$; it also needs $l_{variate}$ to be set more away from the sensitive location $l_{variate0}$ of the assessment features in the existing TRL state. This will help to improve the convergence rate. The corresponding p_{cross} and l_{cross} at this late stage could be expressed as follows:

$$p_{variate} = p_{variate0} \times e^{(\frac{n_{generation}}{n_{end}}) \times (\frac{fit_{\max} - fit_{avg}}{fit_{avg}} - \varphi) / \varphi} \tag{5-20}$$

$$l_{variate} = l_{variate0} \times e^{(\frac{n_{end} - n_{generation}}{n_{end}}) \times (\frac{fit_{\max} - fit_{avg}}{fit_{avg}} - \varphi) / (\frac{fit_{\max} - fit_{avg}}{fit_{avg}})} \tag{5-21}$$

In which, n_{end} is the termination generation of GA. Mutation is operated to the $p_{cross} \times n_{gen}$ genes after the location $l_{variate}$.

The adaptive crossover probability p_{cross} and mutation probability $p_{variate}$ established with the algorithm mentioned above is reasonable and feasible due to their mutual complementation and consistency with the proposed chromosome encoding method.

(6) Termination condition of the genetic cycle

After selection, crossover and mutation operation to the encoded chromosome, a population with the new composition of the chromosome was obtained.

GA will terminate its execution based on the stable genetic termination condition after carrying out some GA operations.

When selecting the values of the weighting factors for AD2, it is suggested to terminate the evolution once it exceeds a specific value of generations; and in the corresponding new population obtained, it will select the chromosomes of highest fitness values, in which the values of weighting factors expressed in each gene are the values of weighting factors required in the AD2 calculation.

5.5 STATE DENSITY FUNCTION IN THE AD2 CALCULATION

According to the AD2 calculation equation (5-7), the state density function $f(y)$ is to be determined, which is used to express the values of TRL state density corresponding to different values of TRL state when in the same magnitude of state value change during the process of technology development.

The density of the state is a process of non-continuous change, and it would typically be expressed with a piecewise function. In the same interval of state, the state density may vary with different evaluated techniques; its change may be very complicated, e.g., there may be several sub-ranges of state in one interval of state and the change of state density in each sub-range of the state are different.

In this thesis, one can take the linear function relationship as an example, which means the difficulty of all the efforts distributed according to a linear during the entire TRL span. The efforts distribution will climb up, reaching a peak at its middle age. The distribution of density of state both in the "0 to 0.5" state interval and "0.5 to 1" state interval is assumed; the state density function established accordingly could be expressed as follows:

$$f(y) = b - ky \tag{5-22}$$

In which, b is the intercept of state density function; k means the slope of the state density function. In the two intervals of state, their intercepts of two state density functions are the same, and their absolute slopes of state density function are the same, though $k < 0$ in the "0 to 0.5" interval of state and $k > 0$ in the "0.5 to 1" interval of state. These two parameters are empirically-base; once they are determined, the state density function $f(y)$ could be obtained and then substituted into Equation (5-7) for AD2 calculation.

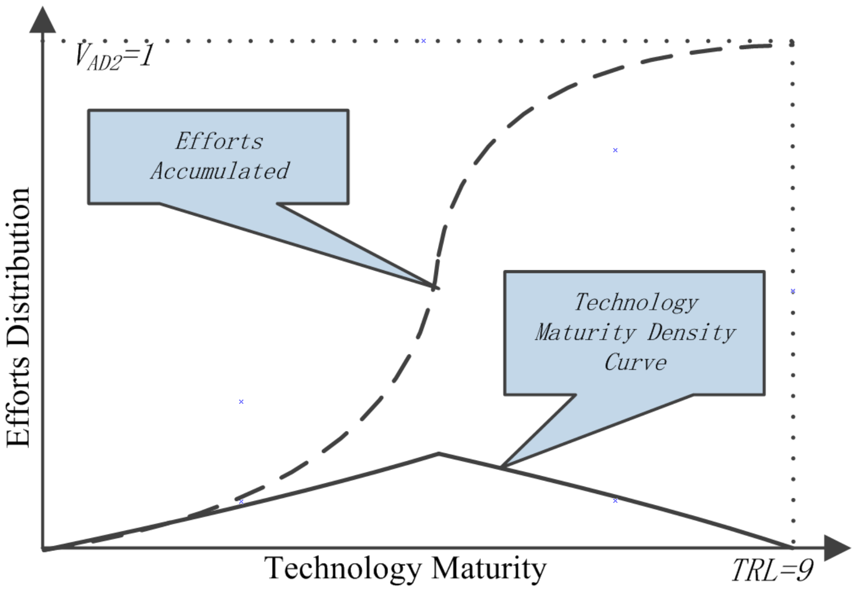

Figure 5-6: The Example Linear Density Function

Although b and k are empirical, there are still constraints in the process of determining these two parameters; and these constraints have to be selected when the basics of AD2 are satisfied. In the established integral formula for calculating the AD2, it is necessary to verify if the selection of main parameters will make the calculated AD2 value meet the basic concepts and properties of TRL and AD2.

Equation (5-7) is an original formula to calculate the AD2. It is necessary to carry out the expansion of equation and assignment of coefficients based on this equation to obtain final numerical results of AD2. Considering D in the Equation (5-10) denotes the span of advancement of difficulties degree from the state "0" to the state "1", it is taken as an AD2 span value covering the whole process of technology development. It is a relatively fixed value regarding each assessment feature of technology readiness. To give a concise process, the justification is mostly based on the expansion of D_{AD2} derived from Equation (5-7).

The calculated AD2 needs to meet some requirements, that is to say, in a variety of specific conditions, the requirements of degree and magnitude for the technology to be evaluated need to be satisfied. Before discussing the fundamental properties of AD2, there is a prerequisite for all types of properties: when assessing whether technology has reached a level of readiness, it needs all of the state values of the assessment features equal to "1". However, in some specific situation, to exactly equal to "1" is unrealistic; so once the state value is greater than a recognized threshold value (such as "0.8"), it could be regarded that the rules of detailed assessment are satisfied; otherwise, it should be regarded that the rules of detailed assessment are not met, and this technology is not ready for this level of readiness. Typically, if the existing state value is higher than the targeted state value, then assume the existing state value equals the targeted state value.

By analysing the concept for AD2, the following rules need to be obtained.

Rule 5-1: For a technology to be evaluated having the same state values of targeted technology readiness and aiming for the same assessment features, the smaller of the existing state values, the higher value of AD2, notes more difficulty for this technology to develop from the existing state to the targeted state of TRL.

Considering it is a technology to be evaluated, D's values will keep the same as a positive number. This makes the denominators for calculation the same, and the sign of results will not be affected. So, only the absolute of D_{AD2} will be discussed here (that is $AD_j^2 = D_{AD2}$). The discussion of the Rule should be completed via the following and AD_j^2 for a certain assessment features could be expressed as follows (according to the integral calculus of $f(y) = b - ky$):

$$AD_j^2 = \int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha[bf_{nj}(x) - \frac{1}{2}kf_{nj}^2(x)]dx - \int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha[bf_{mj}(x) - \frac{1}{2}kf_{mj}^2(x)]dx \quad (5\text{-}23)$$

The discussion should be demonstrated by:

When $f_{1nj}(x) = f_{2nj}(x)$, if $f_{1mj}(x) < f_{2mj}(x)$, then $AD_{1j}^2 > AD_{2j}^2$

Proving:

When $f_{1nj}(x) = f_{2nj}(x)$ and $f_{1mj}(x) < f_{2mj}(x)$, the difference between the two values of AD2 is as follows:

$$AD_{1j}^2 - AD_{2j}^2 = \{\int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha[bf_{1nj}(x) - \frac{1}{2}kf_{1nj}^2(x)]dx - \int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha[bf_{1mj}(x) - \frac{1}{2}kf_{1mj}^2(x)]dx\}$$

$$-\{\int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha[bf_{2nj}(x) - \frac{1}{2}kf_{2nj}^2(x)]dx - \int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha[bf_{2mj}(x) - \frac{1}{2}kf_{2mj}^2(x)]dx\}$$

By combining the *n*-th level of readiness state with the *m*-th level of readiness state equation parts together, the equation mentioned above could be expanded as follows,

$$AD_{1j}^2 - AD_{2j}^2 = \{\int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha[bf_{1nj}(x) - \frac{1}{2}kf_{1nj}^2(x)]dx - \int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha[bf_{2nj}(x) - \frac{1}{2}kf_{2nj}^2(x)]dx\}$$

$$-\{\int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha[bf_{1mj}(x) - \frac{1}{2}kf_{1mj}^2(x)]dx - \int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha[bf_{2mj}(x) - \frac{1}{2}kf_{2mj}^2(x)]dx\}$$

Considering $f_{1nj}(x) = f_{2nj}(x)$, which means

$$\int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha[bf_{1nj}(x) - \frac{1}{2}kf_{1nj}^2(x)]dx = \int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha[bf_{2nj}(x) - \frac{1}{2}kf_{2nj}^2(x)]dx$$

So, the difference between these two levels of AD2 could be expressed regarding the difference between the states of the two levels of technology readiness as follows:

$$AD_{1j}^2 - AD_{2j}^2 = -\{\int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha[bf_{1mj}(x) - \frac{1}{2}kf_{1mj}^2(x)]dx - \int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha[bf_{2mj}(x) - \frac{1}{2}kf_{2mj}^2(x)]dx\}$$

To obtain the relationship between the AD2 of the two levels, the equation mentioned above could be further expressed as follows:

$$AD_{1j}^2 - AD_{2j}^2 = \int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha[bf_{2mj}(x) - \frac{1}{2}kf_{2mj}^2(x)]dx - \int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha[bf_{1mj}(x) - \frac{1}{2}kf_{1mj}^2(x)]dx$$

$$= \int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha[bf_{2mj}(x) - bf_{1mj}(x)]dx + \int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha[\frac{1}{2}kf_{1mj}^2(x) - \frac{1}{2}kf_{2mj}^2(x)]dx$$

$$=\alpha b\int_{N_{feature\_j-1}}^{N_{feature\_j}}[f_{2mj}(x)-f_{1mj}(x)]dx+\frac{1}{2}\alpha k\int_{N_{feature\_j-1}}^{N_{feature\_j}}[f_{1mj}^2(x)-f_{2mj}^2(x)]dx$$

$$=\alpha\int_{N_{feature\_j-1}}^{N_{feature\_j}}\{b[f_{2mj}(x)-f_{1mj}(x)]-\frac{1}{2}k[f_{2mj}(x)-f_{1mj}(x)][f_{2mj}(x)+f_{1mj}(x)]\}dx$$

$$=\alpha\int_{N_{feature\_j-1}}^{N_{feature\_j}}[f_{2mj}(x)-f_{1mj}(x)]\{b-\frac{1}{2}k[f_{2mj}(x)+f_{1mj}(x)]\}dx$$

Due to the values of weighting factors for assessment features of TRL are greater than 0 ($\alpha>0$), to keep $AD_{1j}^2-AD_{2j}^2>0$, the following has to be permanently guaranteed:

$$\int_{N_{feature\_j-1}}^{N_{feature\_j}}[f_{2mj}(x)-f_{1mj}(x)]\{b-\frac{1}{2}k[f_{2mj}(x)+f_{1mj}(x)]\}dx>0$$

In order to make integration results constantly positive, the integral function requires to be consistently positive, which means $[f_{2mj}(x)-f_{1mj}(x)]\{b-\frac{1}{2}k[f_{2mj}(x)+f_{1mj}(x)]\}>0$ is always established.

Due to $f_{1mj}(x)<f_{2mj}(x)$, so $f_{2mj}(x)-f_{1mj}(x)>0$

To establish the corresponding constraint condition for the parameters in the equations mentioned above,

Make $b-\frac{1}{2}k[f_{2mj}(x)+f_{1mj}(x)]>0$, that is $b>\frac{1}{2}k[f_{2mj}(x)+f_{1mj}(x)]$

Due to $0\le f_{mj1}(x),f_{mj2}(x)\le 1$,

then, $0\le\frac{f_{2mj}(x)+f_{1mj}(x)}{2}\le 1$

There are two situations as follows:

① when $k>0$, to guarantee $\frac{b}{k}>\frac{1}{2}[f_{2mj}(x)+f_{1mj}(x)]$ always established, it needs $\frac{b}{k}>1$, i.e. $b>k$;

② when $k<0$, to guarantee $\frac{b}{k}<\frac{1}{2}[f_{2mj}(x)+f_{1mj}(x)]$ always established, it needs $\frac{b}{k}<0$, i.e. $b>0$.

So, when $\begin{cases}k>0\\b>k\end{cases}$, or $\begin{cases}k<0\\b>0\end{cases}$, the equation (5-7) established will meet the Rule (5-1).

End

By justifying the Rule 5-1, it is evident that the two essential parameters in the state density function must meet the conditions: $\begin{cases} k>0 \\ b>k \end{cases}$ or $\begin{cases} k<0 \\ b>0 \end{cases}$.

Rule 5-2: For a technology to be evaluated that having the same state density and the identical difference in state values of targeted technology readiness, the higher of the value of the weighting factors of the assessment features, the more significant value of AD2 for this technology.

Considering it is a technology to be evaluated, D's values will keep the same as a positive number. This makes the denominators for calculation are the same, and the sign of results will not be affected. So, only the absolute of D_{AD2} will be discussed here (that is $AD_j^2 = D_{AD2}$). According to Rule 5-2, it is needed to prove the following situation is established:

When $f_{1nj}(x) = f_{2nj}(x)$, $f_{1mj}(x) = f_{2mj}(x)$, and $k_1 = k_2$, $b_1 = b_2$, if $\alpha_1 > \alpha_2$, then $AD_{j1}^2 > AD_{j2}^2$.

Proving

$$AD_{j1}^2 - AD_{j2}^2 = \{\int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha_1[b_1 f_{1nj}(x) - \frac{1}{2}k_1 f_{1nj}^2(x)]dx - \int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha_1[b_1 f_{1mj}(x) - \frac{1}{2}k_1 f_{1mj}^2(x)]dx\}$$

$$-\{\int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha_2[b_2 f_{2nj}(x) - \frac{1}{2}k_2 f_{2nj}^2(x)]dx - \int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha_2[b_2 f_{2mj}(x) - \frac{1}{2}k_2 f_{2mj}^2(x)]dx\}$$

Given the identical density state and the identical difference of stage values, the equation mentioned above can be further expressed as:

$$AD_{j1}^2 - AD_{j2}^2 = \int_{N_{feature\_j-1}}^{N_{feature\_j}} (\alpha_1 - \alpha_2)[bf_{nj1}(x) - \frac{1}{2}kf_{nj1}^2(x)]dx - \int_{N_{feature\_j-1}}^{N_{feature\_j}} (\alpha_1 - \alpha_2)[bf_{mj1}(x) - \frac{1}{2}kf_{mj1}^2(x)]dx$$

$$= (\alpha_1 - \alpha_2)\{\int_{N_{feature\_j-1}}^{N_{feature\_j}} [bf_{nj1}(x) - \frac{1}{2}kf_{nj1}^2(x)]dx - \int_{N_{feature\_j-1}}^{N_{feature\_j}} [bf_{mj1}(x) - \frac{1}{2}kf_{mj1}^2(x)]dx\}$$

$$= (\alpha_1 - \alpha_2)AD_{j1}^2$$

Considering $AD_{j1}^2 \geq 0$ and $\alpha_1 - \alpha_2 > 0$, so $AD_{j1}^2 - AD_{j2}^2 > 0$, that is $AD_{j1}^2 > AD_{j2}^2$

End

Through the justification mentioned above, it is found that the Rule 5-2 surely applies, despite any values for the parameters ***b*** and ***k*** and the weighting factors, that is to say, the

AD2 calculated by Equation (5-7) will meet the requirement in Rule 5-2.

Justification of these rules is based on the assumption that the state density function is set as an integrable function, that is to say, the value of AD2 could be find out by the integral process. It is also a commonly-used means to set a linear state density function in the process of AD2 calculation, as the linear function is a typical distribution of all the efforts involved to mature a technology. In this case, the linear function is selected for the management demonstration purpose. If the state density function is set as a quadratic function or other forms of function, the two rules could still be justified as the process mentioned above.

In this thesis, we take the linear function as an analysis example. Although there might be the difference in state density function expression for different technologies to be evaluated, it is unnecessary to establish the corresponding expressions of the state density function for each technology to be evaluated in this thesis, for the AD2 assessment process has a universal meaning, it does not depend on the density function.

5.6 Calculation and Implementation Process of AD2 Assessment

As mentioned above, the integral formula used to calculate AD2 is obtained. Based on the established integral formulas, it is possible to carry out numerical integration calculations which could be programmed and realised by using computer languages.

5.7 Mathematical Calculation Process of AD2

Equation (5-7) is used for computing the value of AD2. It could be implemented by expanding Equation (5-23) as follows:

$$D_{AD2} = \int_0^{N_{feature}} \alpha dx \int_{f_m(x)}^{f_n(x)} f(y)dy = \int_0^{N_{feature}} \alpha dx \int_{f_m(x)}^{f_n(x)} (b-ky)dy$$

$$= \int_0^{N_{feature}} \alpha dx[(by - \frac{1}{2}ky^2)\Big|_{f_m(x)}^{f_n(x)}] = \int_0^{N_{feature}} \alpha[(by - \frac{1}{2}ky^2)\Big|_{f_m(x)}^{f_n(x)}]dx$$

$$= \int_0^{N_{feature}} \alpha\{b[f_n(x) - f_m(x)] - \frac{1}{2}k[f_n^2(x) - f_m^2(x)]\}dx \quad (5\text{-}24)$$

By observing the State Distribution of AD2, it is found that distribution curve of TRL is a piecewise distribution function from the perspective of function analysis; in the different intervals, the state function of the distribution curve of TRL is different. Therefore, the

Equation (5-13) could be transferred into a form of piecewise sum up:

$$D_{AD2} = \sum_{j=1}^{j=M} \int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha\{b[f_{nj}(x) - f_{mj}(x)] - \frac{1}{2}k[f_{nj}^2(x) - f_{mj}^2(x)]\}dx \quad (5\text{-}25)$$

in which, M is the number of piecewise distribution function within AD2 range to be calculated, and are the targeted and existing functions of technology readiness level; $N_{feature\_j}$ are the numbering of assessment feature of corresponding intervals.

For concise and convenience, the Equation (5-25) can be converted to

$$D_{AD2} = \sum_{j=1}^{j=M} \{\int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha[bf_{nj}(x) - \frac{1}{2}kf_{nj}^2(x)]dx$$

$$-\int_{N_{feature\_j-1}}^{N_{feature\_j}} [bf_{mj}(x) - \frac{1}{2}kf_{mj}^2(x)]dx\} \quad (5\text{-}26)$$

The purpose of the separation of two integral terms is to separate the m*-th* level with the n*-th* level of technology readiness. In each level of technology readiness, the distribution curve of TRL is expressed as a plotline, that is to say, this function is as piecewise:

$$S_n = \sum_{j=1}^{j=M} S_{nj} \quad (5\text{-}27)$$

$$S_{nj} = \int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha[bf_{nj}(x) - \frac{1}{2}kf_{nj}^2(x)]dx \quad (5\text{-}28)$$

In which, S_n is the targeted level of technology readiness for this specific technology. It is expressed by the area occupied by the n*-th* level of technology readiness.

Similarly, the existing level of technology readiness for this specific technology, namely the state value of the m*-th* level of technology readiness, S_m, could be expressed as the sum of S_{mj} in all ***M*** domains as follows:

$$S_m = \sum_{j=1}^{j=M} S_{mj} \quad (5\text{-}29)$$

$$S_{mj} = \int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha[bf_{mj}(x) - \frac{1}{2}kf_{mj}^2(x)]dx \tag{5-30}$$

Through the conversion mentioned above, the process of calculating D_{AD2} with Equation (5-30) could be achieved by calculating S_{nj} and S_{mj}, which means the calculation of AD2 could be converted into the sum of the span of state values of technology readiness regarding the assessment feature of each TRL. Considering the principles and processes for calculating S_{nj} and S_{mj} are the same, only the calculation process of S_{nj} will be discussed here.

When calculating S_{nj}, it is needed to further analyse S_{nj} in each segmentation of the piecewise function,

$$S_{nj} = \int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha[bf_{nj}(x) - \frac{1}{2}kf_{nj}^2(x)]dx \tag{5-31}$$

Assumes the integrand in Equation (5-31) is defined as follows,

$$F(x) = \alpha[bf_{nj}(x) - \frac{1}{2}kf_{nj}^2(x)] \tag{5-32}$$

Then Equation (5-31) could be converted to

$$S_{nj} = \int_{N_{feature\_j-1}}^{N_{feature\_j}} F(x)dx \tag{5-33}$$

in which $F(x)$ is the integrand, namely the state function of the j-th particular evaluation characteristic of technology.

Within the location of each curve, $f_{nj}(x)$ could be calculated according to the closed interval which are state distribution point values corresponding to the two adjacent assessment feature. $F(x)$ is then obtained according to Equation (5-32), and the final integration result will be obtained by substituting $F(x)$ in to (5-33).

With handling and decomposition of the Equations mentioned above, the detailed calculation processes for AD2 are obtained; the integrand $F(x)$ in each interval could be determined regarding the parameters α, b, k and the state distribution curve function $f(x)$; $f(x)$ could be determined according to the state values of assessment feature of TRL. Once all of the parameters and state values of assessment feature of TRL are fixed, the integrand $F(x)$

is known, and the integration result of AD2 is also consequently obtained.

5.8 IMPLEMENTATION OF AD2

Once gathering all the information needed, it is possible to calculate AD2 according to the numerical integrations of AD2. Here the maturity function $f(y) = b - ky$ is chosen as the example.

Step1: assign initial values to the parameters in the calculation equation of AD2, including weighting factor of assessment features $\alpha_{feature}$, the coefficients of the state density function, k and b; establishment of the AD2 equation;

Step2: Acquire the input data for AD2 calculation from the information above assessment items of AD2, that is to say, to obtain the state values for each detailed assessment questions at the current state and predefined target state for the technology to be evaluated;

Step 3: Prepare the input data obtained from step 2 and determine the relationship between the existing state values and targeted state value of technology;

Step 4: According to the established AD2 equation, calculate the change of the AD2 value that needed to have the technology develop from an existing state of technology readiness to the targeted one;

Step 5: Calculate the change of the state value of technology readiness for each assessment feature when it varies from "0" to "1". The ratio of the value obtained from Step 4 to the value obtained from Step 5 is the AD2.

Step 6: Output of AD2 value and the corresponding level value of AD2

It is noted in **Step 3** that there might be the case when the existing state value is higher than the targeted state value of technology readiness for some reasons. When this happens, it is required to tackle by assessors and designers.

The programmatic flowchart is summarised and drawn as the following:

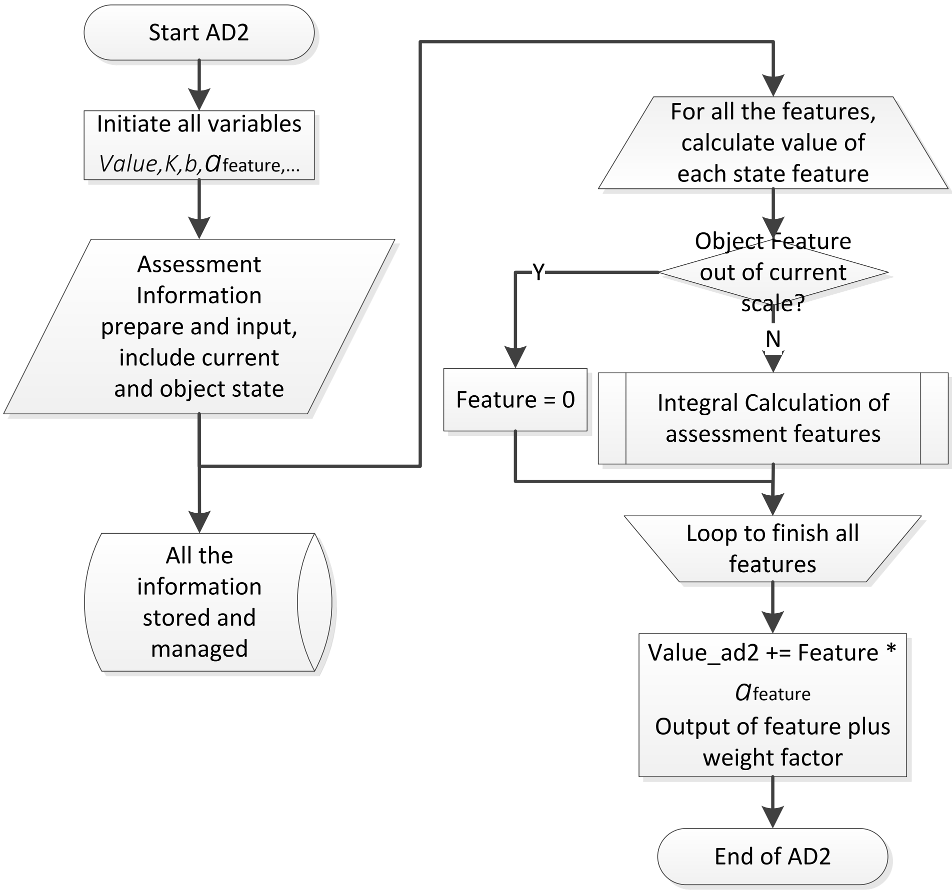

Figure 5-7: Procedure Flow Chart of AD2 calculation

According to the process mentioned above of algorithm implementation, it is easy to derive pseudo-code for AD2 calculation as follows, (the notes between "/*" and "*/" are non-executable descriptions of the algorithm procedure):

Procedure AD2Computation

{ **Initiate** k, b; /* initialization of parameters for state density function */

Initiate $Value_{AD2} = 0$; /* Initialization of value of AD2 */

For $(i = 1, i \le N_{feature}, i++)$

Initiate $\alpha_{feature\_i}$; /* Initialization the values of weighting factors for each assessment feature */

For $(i = 1, i \le N_{feature}, i++)$

{ **Input** $PresentStatusValue_{feature\_i}$;

/* Enter the state value of each assessment feature at current TRL */

Input $ObjectStatusValue_{feature\_i}$;

/* Enter the state value of each assessment feature at targeted TRL
Input target state of maturity of the technical details of each assessment feature value corresponding state */

}

/* According to the Equation of AD2, Calculate the value of AD2 */

For ($i = 1, i \le N_{feature}, i++$) {

If ($ObjectStatusValue_{feature\_i} < PresentStatusValue_{feature\_i}$)

/* analyse the relationship between the existing state value and targeted state values of the technology readiness on each assessment feature */

$Distance_{AD2\_i}$= 0;

/* If the targeted state value is less than the existing state value, the efforts span of AD2 on this assessment feature is 0 */

Else { $Distance_{AD2\_i}$=

$$\text{Integration}\{\alpha[bf_{Object\_feature\_i}(ObjectStatusValue_{feature\_i}) - \frac{1}{2}kf^2_{Object\_feature\_i}(ObjectStatusValue_{feature\_i})]\}$$

$$\text{-Integration}\{\alpha[bf_{Present\_feature\_i}(PresentStatusValue_{feature\_i}) - \frac{1}{2}kf^2_{Present\_feature\_i}(PresentStatusValue_{feature\_i})]\}$$

/* Obtain the change of value of TRL on each feature by integration */

}

$Distance_{AD2} += Distance_{AD2\_i} * \alpha_{feature\_i}$;

/* Sum of the values on each assessment feature to obtain the change of state */

}

$Value_{AD2\_i} = Distance_{AD2} / Distance_{all}$

/* Obtain the value of AD2 via the change portion of all related maturity state of two TRL */

}

/* end of AD2 calculation. */

In this procedure, one could confirm that the essential steps of TRL assessment are embodied as a sub-procedure of the "Integration()". One could sum up all related assessment features belong to certain levels of TRL. It is a new quantitative method of TRL assessment, and it can reveal the internal linkage between TRL and AD2.

5.9 SUMMARY

The definition of AD2 and its attributes are presented at the beginning of this chapter. These are used to build up the assessment process of AD2. Based on corresponding assumptions and restrictions, a numerical integration method is proposed for AD2 assessment. This chapter illustrates the method based on the evidence information collected from the TRL assessment process to provide input for computation. The integral calculation is used as the primary method to establish the AD2 calculation formula to get the assessment values. The critical steps of the mathematical calculation process for AD2 are illustrated; this includes determining the weight factors of integration, the integrand and the algorithm description of numerical processing.

Chapter 6 Visualisation of TRL/AD2 for Decision-Making

6.1 THE DEFINITION OF VISUALISATION

The goal of technology development is to upgrade the maturity of technology gradually, so that it will be successfully applied to corresponding products or services within the project scope. Therefore, project managers are more concerned about the current state in the process of technology development, as well as the necessary progression for it to achieve targeted readiness levels, the most difficult parts among R&D efforts, and how to ensure the success. When the managers perform their decision-making, surely a "whole picture" of technology maturity would be very useful to guide them.

This chapter introduces one typical two-dimensional method of the TRL and the AD2 information visualisation, taking the form of a two-dimensional coordinate diagram, with the TRL state displaying the current status of technology maturity and the AD2 represents the status of the difficulty in technology development estimated from its current status to the desired one. Visualisation aims to establish a distribution map of the various statuses related to the maturity level of technologies to show the potential risks may conceal. The relevant definitions and fundamental properties of the visualisation of technology readiness and technology maturity difficulty should be specified ahead of further detailed discussions.

Definition 6-1 Status Distribution Diagram of Technology Readiness: A two-dimensional coordinate diagram enabled to represent the whole status of technology maturity is termed as a status distribution diagram of technology readiness.

Definition 6-2 Status Distribution Point of Technology Readiness: A point employed to stand for the status value of a technology to be assessed determined by a specific detailed feature of readiness assessment element is termed as a status distribution point.

Definition 6-3 Status Distribution Curve of Technology Readiness: In a Status Distribution Diagram of Technology Readiness, the curve that connects every status distribution point of technology readiness of a technology to be assessed is termed as a status distribution curve of technology readiness.

Definition 6-4 Status Distribution Diagram of Technology Maturity Difficulty: Based on the status distribution diagram of technology readiness, a diagram describing the degree of the difficulty in the development of the technology to be assessed from its current status and the goal status of readiness is termed as status distribution diagram of technology maturity difficulty.

The readiness state of technology could be well-determined by all the efforts have done, and the assessment of technology readiness is achieved by the standard set by every detailed feature of technology maturity, with only one status value for each detailed feature of readiness assessment. Therefore, in a certain status, a technology is pinned with a unique and fixed status value on each detailed feature of readiness assessment, and the status distribution point of technology readiness attained in the two-dimensional coordinate diagram should be unique and fixed as well.

Consequently, there is one and only one status distribution point of technology readiness of technology for each detailed feature of technology maturity assessment. The unique of all status distribution points of technology readiness guarantees the uniqueness of the assemblage of status distribution points, which is unique of the status distribution curve.

In the two-dimensional coordinate diagram displaying the maturity status of technology, all information related to the coordinate has been determined. For there is one and only one status distribution curve of technology readiness of technology, the status distribution diagram of technology readiness should also be unique, so as to status distribution diagram of technology maturity difficulty, inherited from its unique of current status and targeted status.

The process of technology assessment demands human participation, inviting subjective factor of the assessors into the information obtained about technology maturity. For the same status of a specific technology, the results may vary due to the subjective of assessors. When assessors make different assessments of the same technology, a meta-synthesis or similar method could be adopted to reach the agreement step by step. This situation may occur more frequently when we do the AD2 assessment for its predictive prospect.

Since TRL is a fundamental constituent of AD2, it needs to be visualised before the presentation of AD2. With the major constituents of both the TRL diagram and the AD2 diagram, a relation chart of the visualisation of technology maturity information is drawn as in Figure 6-1.

The visualisation process of technology maturity difficulty contains three major components, respectively the construction of the **current** status distribution diagram of TRL, the **target** status distribution diagram of AD2 and the two-dimensional coordinate diagram of technology status.

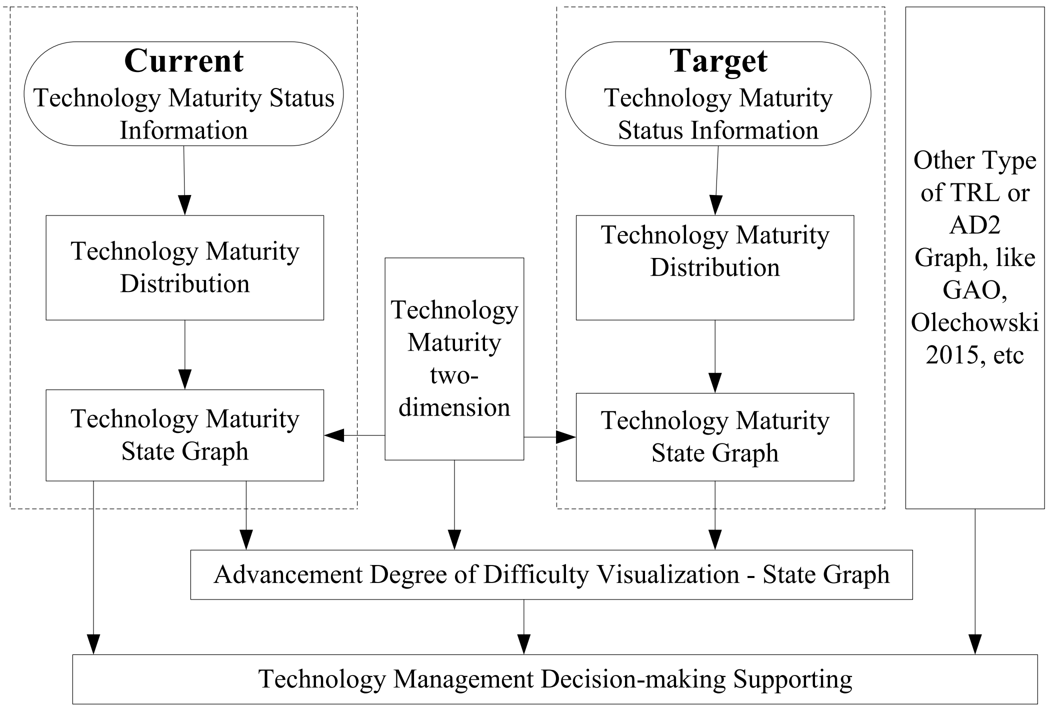

Figure 6-1: The visualisation method of technology maturity state

A two-dimensional coordinate diagram is constituted of a horizontal ordinate, a vertical coordinate and the background information of the coordinate. The current status distribution diagram of TRL and the target status distribution diagram of AD2 are constructed in the same way through the obtainment information about technology readiness assessment feature, the arrangement of the status distribution points of technology readiness and the layout of a status distribution diagram of technology readiness.

6.1 VISUALISATION OF TECHNOLOGY MATURITY

The status of technology maturity varies with the development of technologies, with the status value of technology maturity changing correspondingly. During the process, degrees of difficulty also vary. In order to capture the whole picture of the status of technology maturity difficulty, information of "easy or not easy to change status values" of technology readiness is indispensable in a status distribution diagram of technology readiness. Therefore, there are shared and distinctive key compositional attributes in technology readiness and technology maturity difficulty, as shown in Figure 6-2.

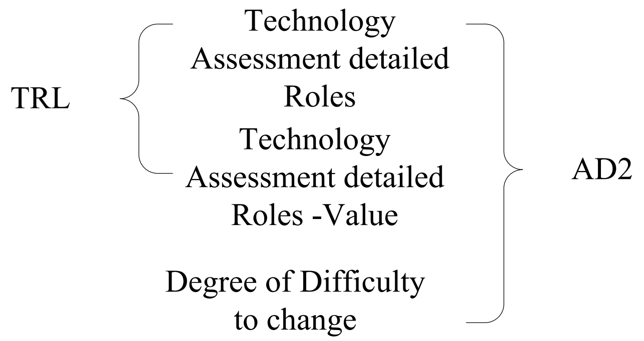

Figure 6-2: Distribution diagram of key compositional attributes

In the process of presenting technology readiness by a two-dimensional coordinate diagram, background information of the diagram is required besides the horizontal and vertical coordinates. All necessary information about the technology maturity status could be covered, making it feasible to take a two-dimensional coordinate diagram as the form of visualisation. In the meantime, a technology status distribution diagram taking the form of a two-dimensional diagram could maintain a good consistency between the visualisation of technology readiness and that of maturity difficulty.

In the two-dimensional coordinate diagram, the horizontal ordinate stands for the detailed features of technology readiness assessment, the vertical coordinate stands for the satisfaction (status values) of the technology corresponding to each detailed feature of assessment, and the background of the coordinate stands for the degree of difficulty during the changing process of technology maturity status.

(1) The horizontal ordinate information in a two-dimensional coordinate diagram

In the process of technology readiness assessment, the primary standard is determined by detailed features of technology readiness assessment. The assessment should decide whether the technology meets these rules, and the current readiness level is estimated by synthesising every feature assessments. Thus, detailed features of technology readiness are designed as the horizontal ordinate of the status distribution diagram of technology readiness in the visualising process.

The detailed features of technology readiness are formulated by refining the assessment standards of all levels of technology readiness. Correspondingly in the process of configuring the status distribution diagram of technology readiness, the horizontal ordinate reads the detailed features of assessment as the standard of technology readiness. For instance, the horizontal ordinate may exhibit all the detailed features of readiness Level 5 with each one detailed feature mapped to one position on the horizontal axis. The horizontal ordinate consists of dispersed symbols, represented in readiness Level 5 as respectively F_{501},

F_{502}, …… F_{522}. Furthermore, these detailed features of technology maturity assessment generate a common type of description.

In a status distribution diagram of technology readiness, the horizontal ordinate includes all detailed features of technology readiness assessment for TRL1-TRL9. In practice, the detailed feature of a certain readiness level usually is more related to ***adjacent*** levels than to the "further" ones. For instance, when TRL5 is in the process of rating, the detailed features to pinpoint the technology on Level 5 would normally show larger variations in the scores obtained in TRL4 and TRL6, while the scores of detailed features (TRL2 or TRL 3, for example) would remain relatively invariant over TRL7, 8 or 9 (their status value might all be 0). Therefore, attention should be focused on the changing pattern for closer TRL in visualisation, whereas irrelevant detailed features should be ignored or even excluded from the status distribution diagram.

(2)The vertical coordinate information in a two-dimensional coordinate diagram

To accurately exhibit the readiness status of the technology for each detailed feature of assessment, the vertical coordinate reads the current status of the technology for each detailed feature of assessment. For a more preservation of the readiness status of the technology and a more lucid demonstration of the technology readiness situation for each detailed feature of assessment, the traditional "yes/no" criterion for assessment should be ameliorated or replaced by $S_i \in [0,1]$ to mark the degree of satisfaction of the detailed features, with S_i indicates the satisfaction degree of detailed feature Number i of TRL assessment feature by the current status of the technology to be assessed. "0" Means totally unsatisfied, "1" means fully satisfied, and any $0 < S_i < 1$ indicates the degree the technology has achieved for a certain detailed feature of readiness assessment. The closer S_i gets to "1", the closer the status of this technology assessment feature gets to meet the detailed feature criteria, and vice versa.

Take the third detailed feature F_{503} ("compare the consistency between the demonstration results of function and performance and the designed/anticipated function and performance") for the TRL5 assessment feature for example, the assessors evaluate the current status of the technology, collate the demonstration results of function and performance, and compare them with the anticipated performance in the design of the technology. If the values match perfectly, the ideal situation will be considered reached, i.e. $S_i = 1$. On the contrary, if there is a considerable gap between the demonstrated results and designated target of either function or performance, the large discrepancy from the ideal value will draw a proximate conclusion as $S_i = 0$. And if the discrepancy is partly acceptable, it could be marked by a value chosen between the range of $0 < S_i < 1$. For instance, $S_i = 0.8$ indicates a relatively small discrepancy between the demonstration and the design. When multiple functions and performances are concerned for one particular technology assessment feature and the significance of these functions to the technology should be granted with the corresponding weight factor for a priority synthesis.

Given the status value of a technology to be assessed for each detailed feature, the status distribution points of technology readiness can find their positions, which connect each other to form the current status distribution curve of readiness of the technology.

(3)The background information of a two-dimensional coordinate diagram

The installation of the status distribution diagram lays the ground for the status distribution diagram of technology maturity difficulty. Thus, preparation for displaying the developing difficulty of the technology starts when drawing the status distribution diagram of technology readiness.

In the progression of technology development, the AD2 varies at each stage of the advancement of maturity. This thesis adds information about the AD2 in the progression of technology development by putting background information into the original two-dimensional coordinate diagram. According to the general laws of technology development, the efforts may not (in substantial probability) equally requested during the whole development process. So, the background is not evenly distributed within the rows (assessment feature) in the status distribution figure (as in Figure 6-5). One can define that the lighter area is more difficult to span across the same interval of status values, suggesting a higher degree of difficulty in technology development, which means harder to tackle, that requires more efforts of all resources, and vice versa. The concept of the density of the changing difficulty in technology status embodies the unevenly changing character of these statuses.

Definition 6-6 Density of the Difficulty in Technology Status: In the developing process of technology maturity, the technology maturity difficulty value corresponding $0 < S_i < 1$ of the change in technology assessment features is termed the density of the difficulty in technology status, and called status density for short.

According to the study of the technology innovation, the efforts of the technology to new product could be treated as S-style curve, and there are TRIZ theory based on the statistics of the innovation to guide the forecast of new technology (Mann, 1999), so that an S-curve of typical new product coming to the market. The following diagram (figure 6-3) is showing that the four recommended metrics to help the process of determining where a product advances along its evolutionary s-curve, including R&D output performance, Number of Inventions, Level of Invention and Profitability curve.

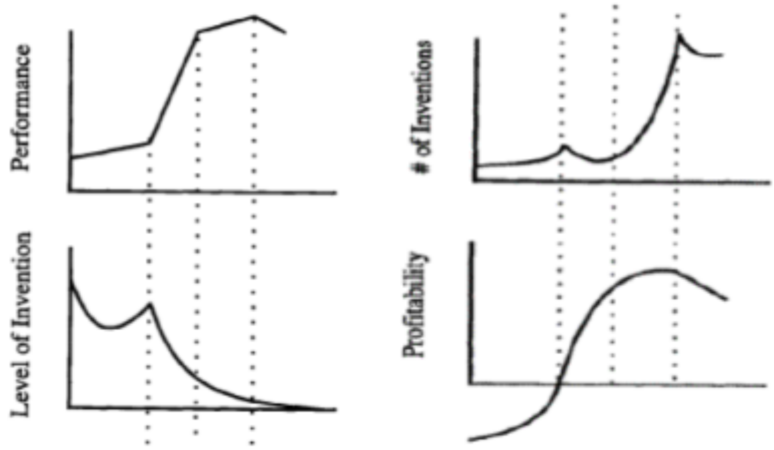

Figure 6-3: Altshuller's "Lifelines" of Technological Systems (Mann, 1999)

From this thesis point of view, the main efforts to a new product could be classified as the following diagram, which shows the growth "direction" of the R&D path as the figure 6-4.

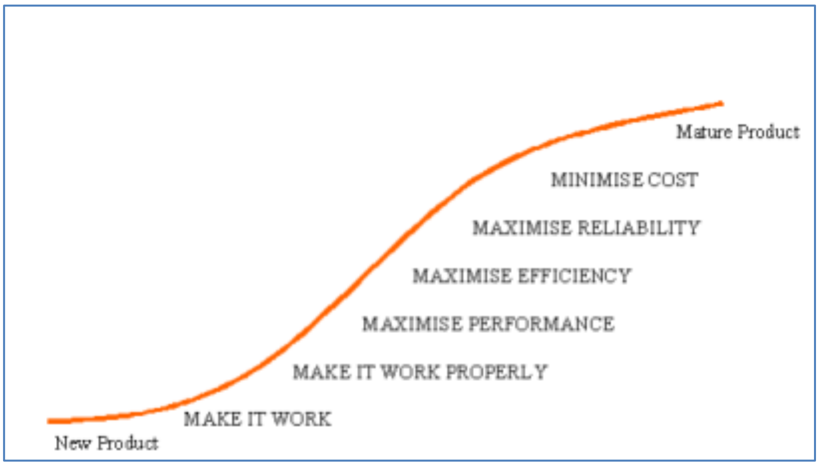

Figure 6-4: The Typical Invention-Focus S-curve

With reference to the S-curve of TRIZ(He et al., 2010), the background of the status distribution diagram of technology readiness shows that the status values corresponding to detailed features of technology readiness assessment vary within the range from 0 to 1, starting from the darker area to the brighter area then changing gradually back. With the horizontal coordinate, vertical coordinate and the background of the status distribution diagram combined, the status distribution diagram of technology readiness appears as in Figure 6-5.

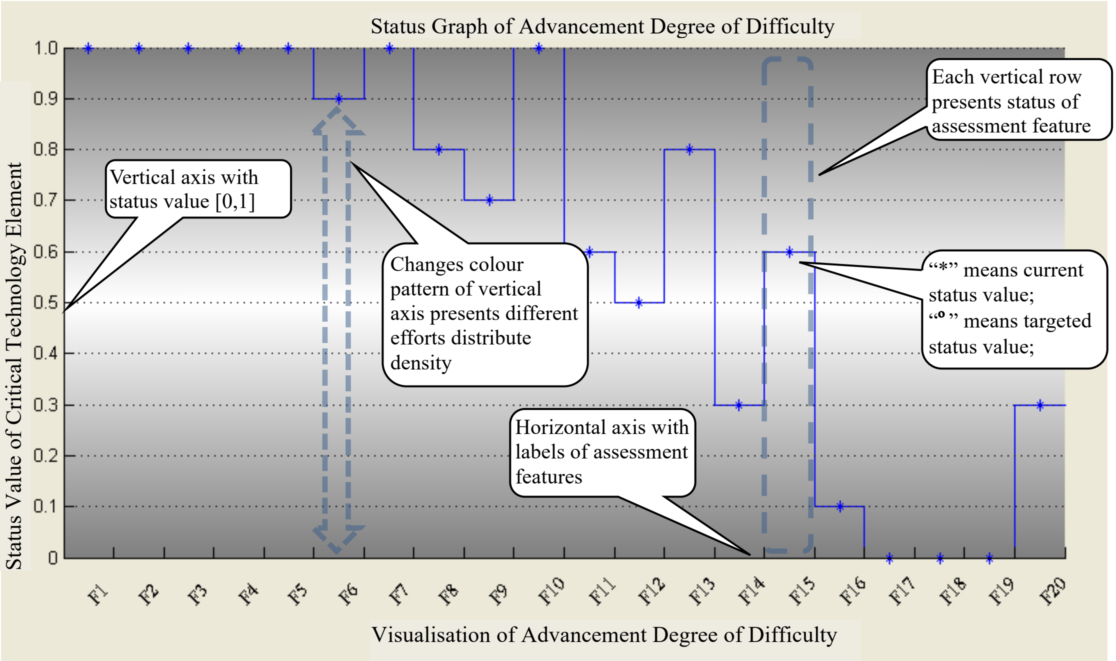

Figure 6-5: The status distribution diagram of technology readiness

The notations in the figure show the meanings of each part of the diagram, as discussed above, the status distribution diagram of technology readiness could display the status values of the technology to be assessed for each detailed feature of assessment on each readiness level distinctly to research staff and managers of the project, which exhibits the whole picture of the current readiness status of the technology and lays the ground for further visualisation and decision-making of the technology management in the process of development.

6.2 VISUALISATION OF TECHNOLOGY MATURITY DIFFICULTY

The AD2 expresses the degree of the difficulty of the technology to develop from its current status to the higher goal, i.e. the discrepancy across two readiness levels in the process of technology development. On the basis of the established of the current status distribution diagram, the next step is to construct the target status distribution diagram, that is, besides the current status distribution curve of technology readiness, a target status distribution curve is further needed.

Each status corresponds to a unique status distribution curve, and there are two different status distribution curves for each of the two statuses. The difference shown in the diagram of two curves is the part that requires a change in the technology status. A more considerable difference between the two status distribution curves indicates a more substantial proportion of efforts that need improvement and more significant difficulty standing in the way of technology ripening and vice versa.

The discrepancy between the current status distribution curve of technology readiness and the goal status distribution curve is an assemblage of the differences in status values of all relatively detailed features of assessment, representing the AD2. When a technology reaches a certain readiness level, it is ideally supposed to meet all detailed features of readiness assessment for the targeted readiness level, i.e. to obtain a status value of "1" for each corresponding detailed feature of TRL. In the meantime, since it is by default that the technology should meet all maturity criteria of every lower level before it reaches the current one, it should also meet all detailed features of readiness assessment for every previous TRL level, represented by the status values of "1". However, pragmatically speaking, in the process of assessing the readiness level of a technology, when the technology to be assessed meet almost every detailed feature of assessment for a certain readiness level, flexible criteria shall be applied to certain detailed features by setting a negotiable intermediate value $\delta_i \in [0,1]$ (as the threshold status value for the number i of detailed feature of TRL). As long as $S_i \geq \delta_i$, the technology to be assessed will be accepted as meeting the detailed feature. For instance, suppose a specific detailed feature is given $\delta_i = 0.8$, the technology will be considered having met the detailed feature when $S_i \geq 0.8$. Such an adjustment makes it more flexible, and for different technologies to be assessed and different detailed features, this kind of strategy shows more adaptability.

When technology is required to reach TRL n with the readiness status demanded by this readiness level, it is idealistically supposed to meet all detailed features of readiness assessment for every readiness level from TRL 1 to TRL n, i.e. to obtain a status value $S_i = 1$ for each corresponding assessment feature. The status distribution diagram of TRL with the target readiness as TRL n is shown in Figure 6-6.

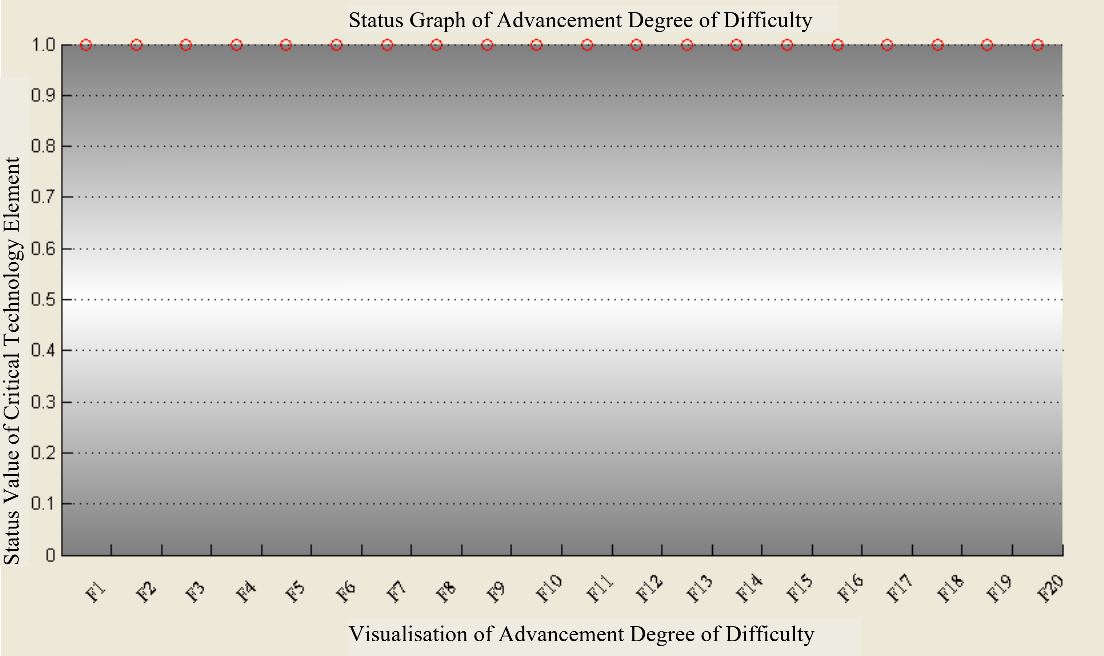

Figure 6-6: A specific goal status distribution diagram of readiness (meet all criteria)

In the development from the readiness level in Figure 6-5 to the readiness level in Figure 6-6, the technology maturity difficulty should be displayed by integrating the two status distribution curves from the two diagrams in one diagram as shown in Figure 6-7.

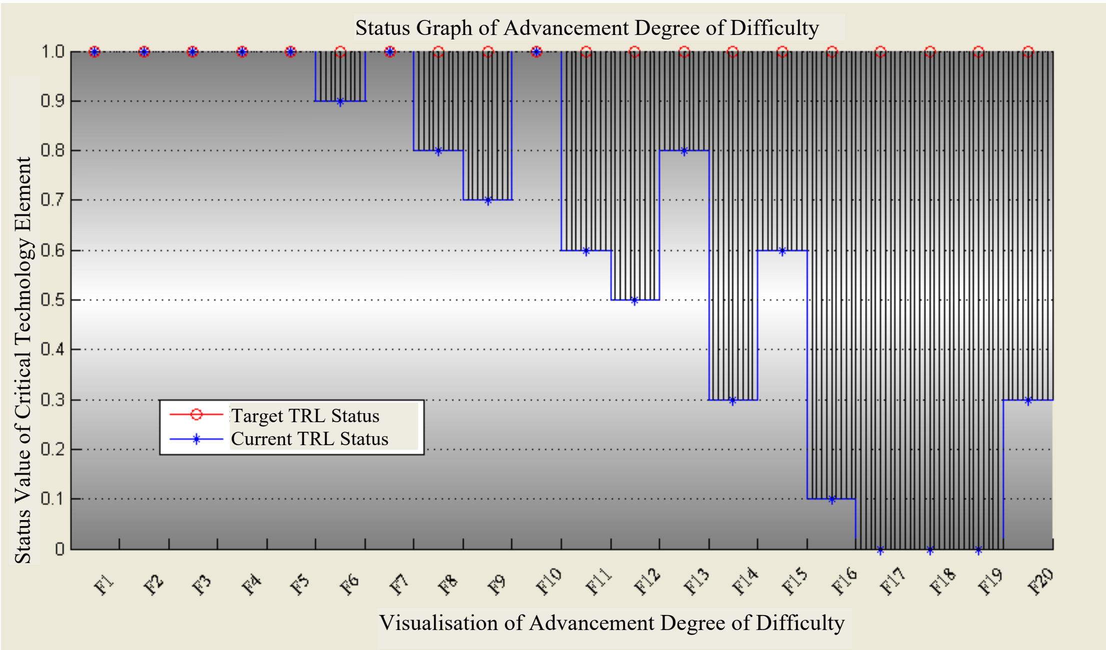

Figure 6-7: A schematic diagram of the status distribution curves of AD2

If $S_i = 1$ is only required of the technology for the majority of detailed features of technology maturity assessment from Level 1 to Level n and the threshold δ_i of status value

S_i is subjected to adjustment according to the practical application of the technology, thus $\delta_i \leq 1$ is allowed. The target status distribution diagram of readiness at TRL n after adjustment is shown in Figure 6-8.

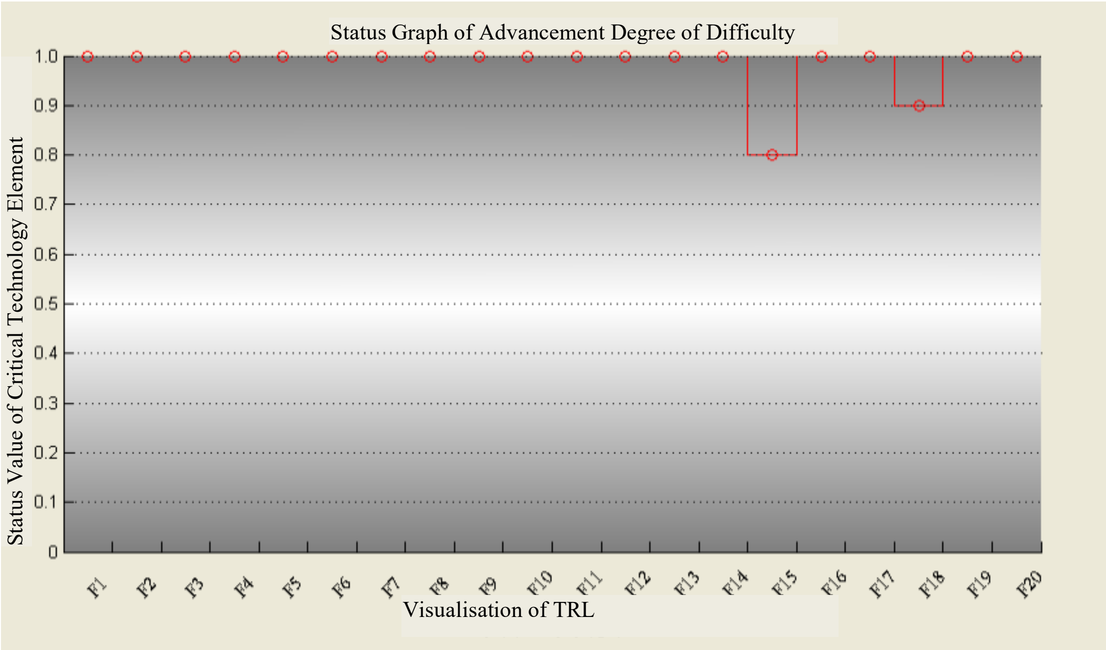

Figure 6-8: A specific goal status distribution diagram of readiness

In the development from the readiness level in Figure 6-5 to the TRL n in Figure 6-8, the technology maturity difficulty should be displayed by integrating the two status distribution curves from the two diagrams in one diagram as shown in Figure 6-9.

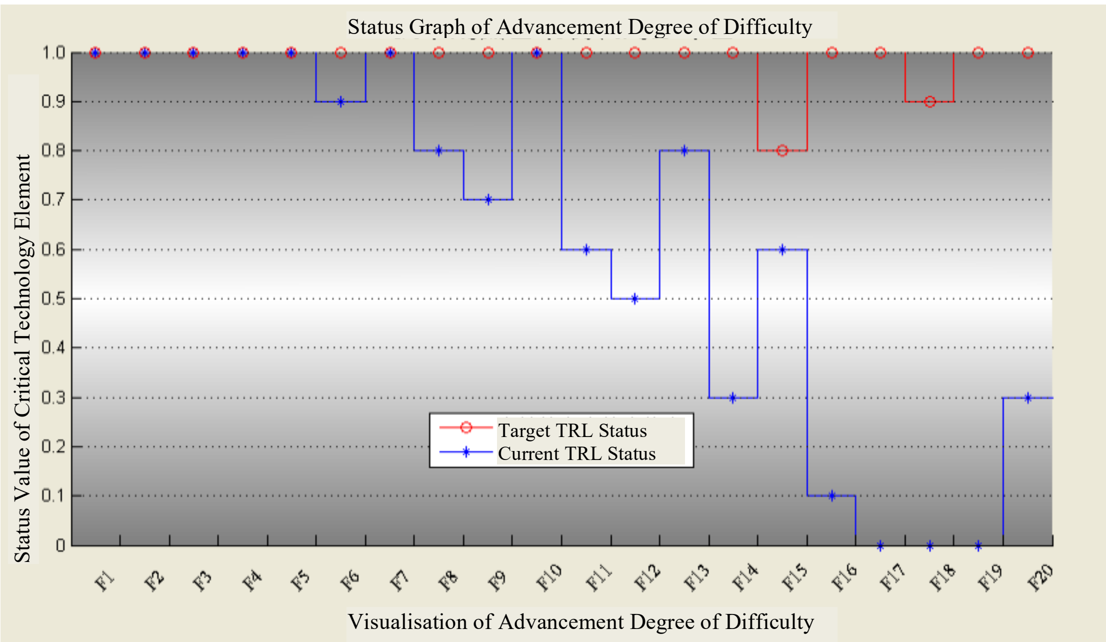

Figure 6-9: A schematic diagram of the status distribution curves of AD2

Since the change of technology maturity status reflected in Figure 6-9 has more universality, the discussion and illustration below will focus on Figure 6-9.

In Figure 6-9, a discrepancy area appears between the two status distribution curves, which are the area of status to be crossed in the course of developing from the current maturity status to the target maturity status. The density varies in this area. The area to be crossed indicates the degree of difficulty for the technology to improve and adjust itself when developing from the current status to the target status, which is represented in the form of shades as shown in Figure 6-10.

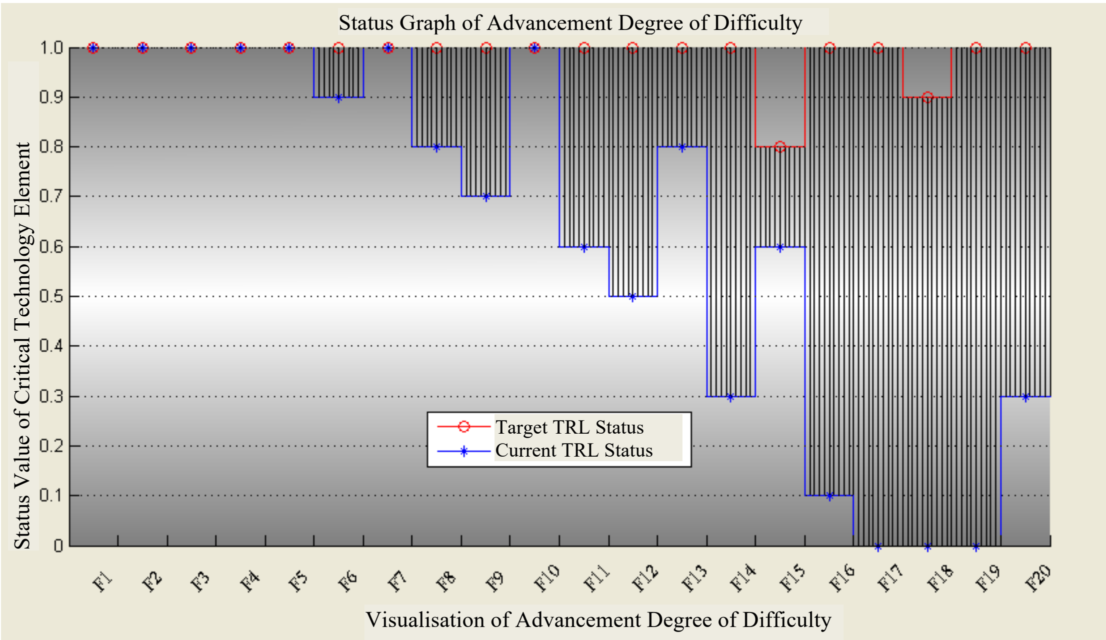

Figure 6-10: The status distribution diagram of technology maturity difficulty

In Figure 6-10 the area between the two status curves, i.e. the shadowed portion in the diagram, stands for the AD2 for the technology to develop from the status in Figure 6-5 to Figure 6-8.

The diagram drawn above is the complete visualisation of the current status of TRL and the target readiness status. It enables R&D team and manager to capture the whole status of the technology as well as its future dynamics trends more clearly and accurately.

To grant more universality to the discussions and illustrations of the visualisation of technology readiness, most detailed features of technology and readiness assessment will be interpreted in the process of the discussion and establishment of the status distribution diagrams of technology readiness constructed above.

The horizontal coordinate, vertical coordinate as while as the background information in the diagrams are all changeable according to specific application situation, while most of the essential adjustments happen for the background information of the two-dimensional diagram, i.e. the density of the change in technology status.

While those discussed above are general phenomena happening in the course of development for most technologies, there exist other situations where technologies follow an evenly changing pattern from the beginning of developing to final proved successful in the project. When the different density patterns are displayed in the status distribution diagram of technology readiness, the background should take different patterns, leading to a more accurate demonstration of the variation of difficulty distributions of the technology development, as shown in Figure 6-11(where each vertical row has a unique colour pattern to identify their different density functions).

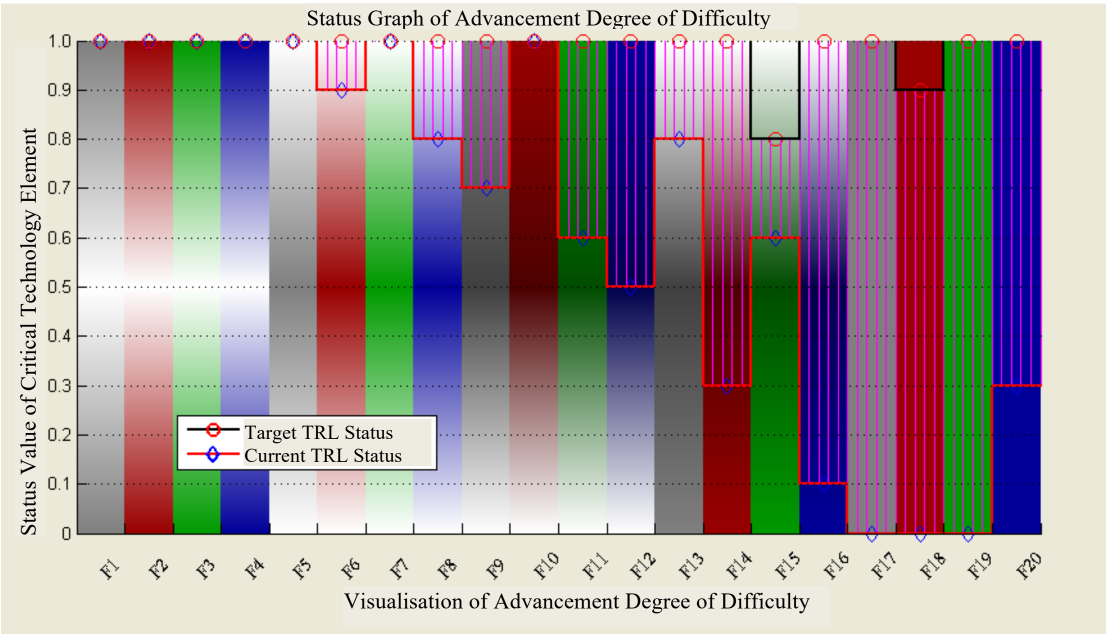

Figure 6-11: Expanded status distribution diagram of technology maturity difficulty

The status distribution diagram of technology readiness and status distribution diagram of technology maturity difficulty constructed based on such an approach will facilitate and support the decision making in management.

6.3 Suggestions for Decision Making based on TRL/AD2 Diagram

Since the decision support based on the features of information from the diagram established above, one can analyse the difficulty issues within the project. It is closely related to the system under developing; the present thesis will select some representative sample cases to make a brief explanation.

(1) In general, the assessment features are sequentially distributed over the nine levels from left to right on the status distribution profile; they are also arranged according to the order of classification of elements such as R&D, testing, validation, production, deploy, flight, retirement or management, so the diagram should have a growing pattern from the left to the right. If there is a technology assessment feature on the left side of status distribution profile keeping at the status of a lower order, then the administrative level should pay attention to this assessment feature and identify if its corresponding job, in reality, has a long-term difficulty of growth.

(2) If there is still abnormal "low-high-low" circumstance for certain assessment feature at different levels of TRL even after excluding unreasonable evaluation thresholds, then it indicates that there is "vortex circulation" growth during the maturation process of the technology assessment feature. The reasons for this may be diverse, e.g. specific experiment needs to be repeated multi times at different TRL which means there could be a workflow refinement opportunity on those waste of resources.

(3) In an ideal situation, different TRL curves are roughly uniformly distributed along the direction of growth; if one of the curves has unusually large space and the possibility to increase, then the administrative level should pay attention to this type of assessment feature and identify if too much difficulty is allocated to this level.

Above patterns of status distribution diagram are only some samples from the real sophisticated circumstance. Further study indicates decision-making models building and verifying, etc.

6.4 SUMMARY

Visualisation of TRL and AD2 was presented in this chapter; this can be used to support decision-making process management. The visualisation includes the technology maturity level and the technology maturity difficulty. The choice of the form of visualisation was discussed, and visual status distribution and visual status determination of the related data were established.

Chapter 7 Risk Management based on TRL/AD2 and MSA

7.1 MSA APPROACH OF RISK MANAGEMENT USING TRL/AD2

This thesis focuses on grasping the critical technology development risk which decides the success or failure of a project and is clearly very important for the project management. In the previous chapters, the identification of TRL and AD2, and the visualising technics have been discussed. In the development of technology, the developers and managers should have an overall cognition and mastery of the technology development process including the current maturity state, the target maturity state, the advancement for a technology to be developed from the current TRL to a target TRL, and the risks in the development process. The TRL and AD2 assessment results will be used for the evaluation of a technology development risk. Based on the risk, the management team could adjust technology development plan, resources and time, which is to facilitate the technology risk management using the assessment result.

Due to the technical complexity of the system, the assessment of AD2 is that the future maturity of the technology needs to be predicted, which is a judgment of its future development difficulty. In practical work, we can refer to the existing knowledge and experience. However, the unique nature of the project decides that we cannot guarantee that the technology experience would be applicable to other technologies. At this time, we need to take the MSA-based, multiple iterative spiral upward cognition process to gain insight into the problem.

Based on the literature review about the Meta-Synthesis Approach, Gu (Gu,2004)and Yu, etc (Yu and Zhou, 2005) have proposed a generic framework of MSA, consist of expert system and machine system. In the aiming of using MSA to tackle the technology risk management problem, one needs to “localise” the common MSA to a domain specified working procedure. In this thesis, the combination of MSA framework and the TRL/AD2 assessment methods are inevitable.

Firstly, an expert group pre-judges the current condition to find out the primary development direction and give a preliminary route map. This process needs as many technology experts as possible from different technical fields composing the knowledge and experience of their fields. This is a qualitative Meta-synthesis System Approach based on traditional experiences. The experts usually are invited from the technical fields which could present the leading edge.

Moreover, then, with the support of the quantitative modelling and analysing computer software tool, the working group perform the preliminary quantitative assessment by the quantitative AD2 approach. They can make basic assumptions based on the experts' suggestions to deal with any unpredictable technical problems in the assessment. For example, the regularity (growth curve or function) of evaluation characteristic of some assessment field and some vital target judgment principles like the relative weight factors of the synthetic assessment, etc. The modelling and analysing could be performed by the technical engineers who are familiar with computer simulation software. They have mathematical foundations and quantitative modelling and analysis ability. At the same time, they need the assistance of experts group of the technology-related fields to get the meaningful analysis done.

These assumptions and the quantitative calculation results will be submitted to the expert group together. With the help of the knowledge system (tools of knowledge search engine, historical database, data mining, literature quantitative analysis, technology trend analysis, etc.), the expert group will do the comprehensive analysis (comprehensive integration of qualitative and quantitative analysis) on the quantitative calculation results (a quantitative analysis formed under "if-then" scenarios) of the first round.

In general, quantitative evaluation statistics will produce the "inspiration" and "enlighten" from the expert group. Through this, experts group bring up more "what-if" scenarios, judgment basis for the current and new understanding of the project technology connotation as the input criterion of next round quantitative analysis to achieve a spiral rise. Then the modelling and analysis staff develop the second round quantitative assessment, which results will be submitted to the expert group for the second round comprehensive synthesis of qualitative and quantitative analysis.

Referring to a Meta-synthesis System Approach of combining qualitative and quantitative information, we need to facilitate the linkage between the experts' experience of deep understanding of the problem, and quantitative analysing data of the computer software tools, utilizing the insight of the problem and merits of quantitative evaluation, to achieve a qualitative and quantitative Meta-synthesis System Approach by multiple iterations and a step by step approach(Zhang, 2014).

The Meta-synthesis Approach based decision-making supporting system of the case study project is shown in Figure 7-1.

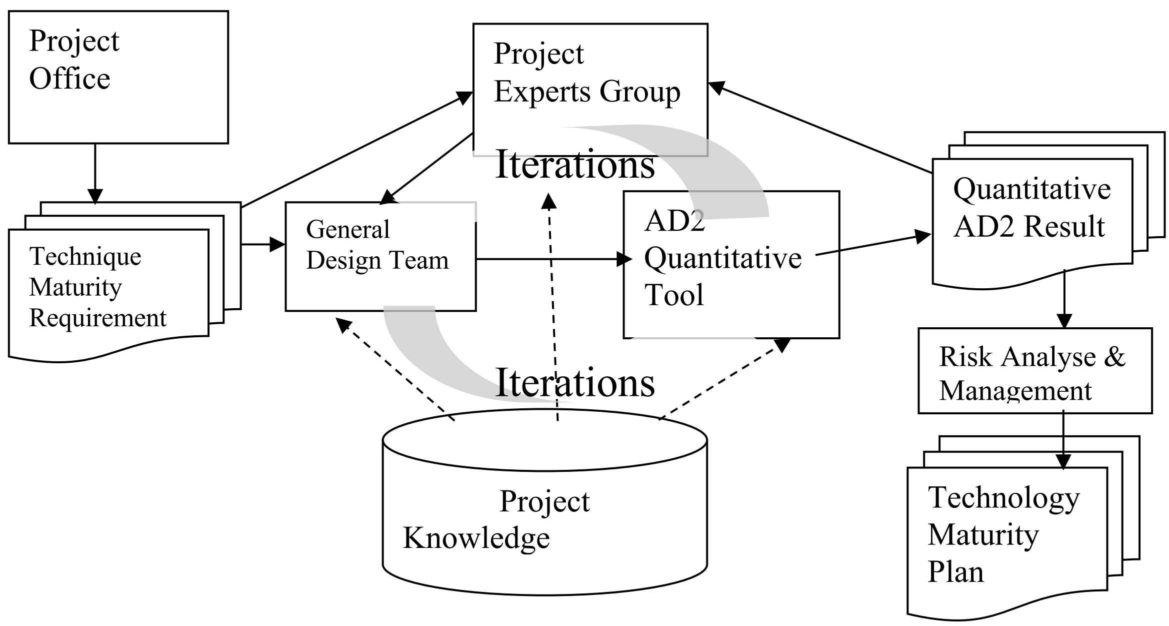

Figure 7-1: MSA approach used in risk management

As illustrated in Figure 7-1, the general technical design team takes the responsibility of innovation and production. They are under the supervision of the experts group. The TRL/AD2 quantitative assessment is used as the essential step of the quantitative synthetic method by software usage, although the TRL distribution density function and integral integrated weight coefficient among different AD2 are two key factors.

The Project Knowledge Database is established to both support the expert and designer team. Also, the knowledge is a reference source of the TRL/AD2 assessment tool. The database is the basic infrastructure of project supporting facilities.

The Knowledge Database contains the project related technical information, the know-how of the design process, product or service information, craft knowledge, etc. The structure of the database is using mapping technology to capture the network relations about the knowledge to form a hierarchical knowledge map. Also, there include some tools about knowledge acquisition, classification, structuring, fusion, representation, searching and reporting. All the knowledge will be identified, confirmed, archived using multimedia technology.

The project expert group and computer tool system connect the "Man-Machine combination with Man-based' principle with the support from related technical knowledge. Moreover, the AD2 quantitative assessment gives out the data as the element of the computer tool. For one aspect the input information of the quantitative calculation to the computer is from the expert group's deductions of development trends and similar experience. The first round of calculation is done, to judge according to the result before the revision, enriched with the recognition of the problem by the expert system and fulfilled by the content in the project knowledge base. Whether it needs a next round iteration, it should be decided by the expert system referring to the decisive information input, based on that to do the risk analysis and to make the plan for technology readiness(Zhang, 2014).

Through this method, the Chinese aerospace mission headquarter could reveal the "real nature" of technology risk and could monitor the progress of the degree of difficulty upgrading from one TRL level to a higher one, more objectively and comprehensively.

7.2 Meta-Synthesis System Approach Via Management Regulations

To illustrate the Meta-Synthesis System Approach, spiral iteration is frequently used in practice. For example, the annual research plan of this project usually goes through two rounds of this process.

At first, the project office commissions the headquarter experts to prepare the draft annual plan based on the overall project plan and implementation of the plan in the previous year (see figure 7-2, step 1), which will be sent to the subsystem/contract research organisations for refinement (see figure 7-2, step 2). The R&D organisations receive the draft plan and conduct an AD2 quantitative evaluation based on the current TRL of the technology (see figure 7-2, step 3). When the AD2 and GA algorithm are used, the quantitative evaluation should refer to technical parameters and indexes confirmed by experts.

Then the AD2 results from the organisations are submitted to the project management office and revision is initiated based on AD2 quantitative evaluations of each organisation. Adjustments may be made according to the quantitative evaluations. Adjustments on AD2 input parameters may be proposed.

Next, the second draft is distributed to all organisations for second-round AD2 evaluation. All organisations submit the quantitative evaluation data to the office (see figure 7-2, step 4). The headquarters summarise the advice and prepare the version for approval (see figure 7-2, step 5). The experts review the second version of the R&D document (see figure 7-2, step 6). If the draft plan is not ready for approval, then there could be another round of refinement (figure 7-2, step 7, 8, 9 and 10). Otherwise, the R&D plan will be implemented after being approved by the chief engineer.

In summary, the multi-spiral process can evaluate the technology risk, and AD2 values calculated more close to the leading experts' judgements. It shows that the algorithm is objective excluding the subjective judgment of individual assessment experts. Besides, AD2 can be obtained based on TRL data by the algorithm which avoids second-round expert evaluations.

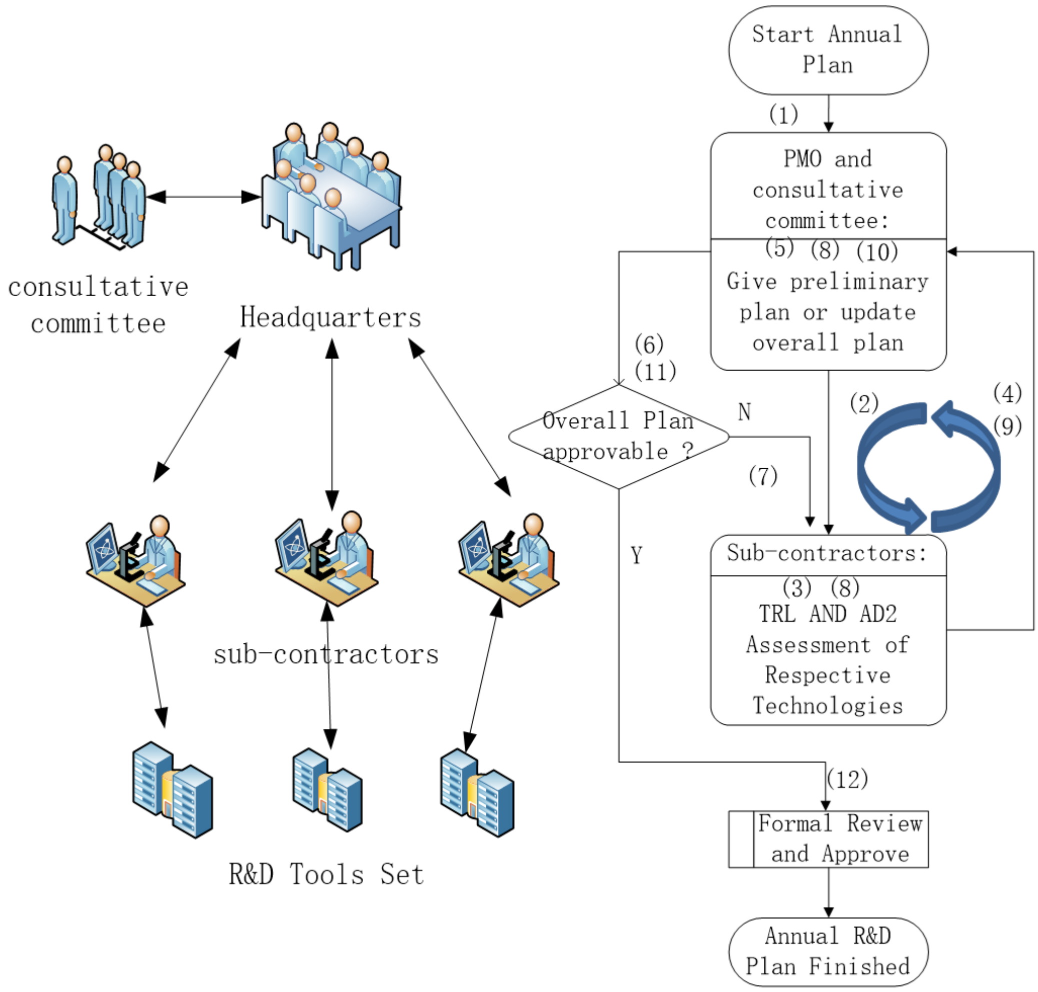

Figure 7-2: MSA Based Annual R&D Plan (two round spiral refinement)

However, AD2 values obtained may not be exactly the same as obtained from experts' evaluations. The reasons for the inconsistency mainly include:

(1) The inaccurate weighted value of each criterion.

(2) The inaccurate state density function parameters.

The two values above are determined by the experts according to numerous calculations following the nature of AD2. They have been confirmed in many practical cases.

7.3 TRL/AD2 Assessment Information Management Software

As stated in chapter 2, an assessment method could be assisted by a computer software tool and be given the detailed information management ability.

Computer Aided System Engineering is well-recognised by all means. The essential function of the software is to assist the risk management in data handling and process acceleration. The user of the software includes the PM Officer, research engineer, project quality manager, technology assessors and all other related staffs.

From the perspective of the project office, the whole picture of the assistance platform should include a set of management standards, a series of methods or tools, and an information management system, as shown in the following (Figure 7-3):

- ✓ Assess process or other standard procedure management: one can define and modify the process and information.
- ✓ Collect the assessment supporting information: gather the information according to the assessment steps, including the detailed definition of different levels of the TRL/AD2, features or the evidence chain supporting information, for an instance, research report, design scheme, test data, simulation report, design review, etc., and classify and store them within the Database system.
- ✓ Assessment procedural supporting: including self-assessment by the R&D institute, independent third-party assessment, assessment project confirmation, information collecting, report review, etc.
- ✓ Knowledge database manages: including the interfered technology knowledge map of the technologies, technology breakdown structure or CTE dictionary.

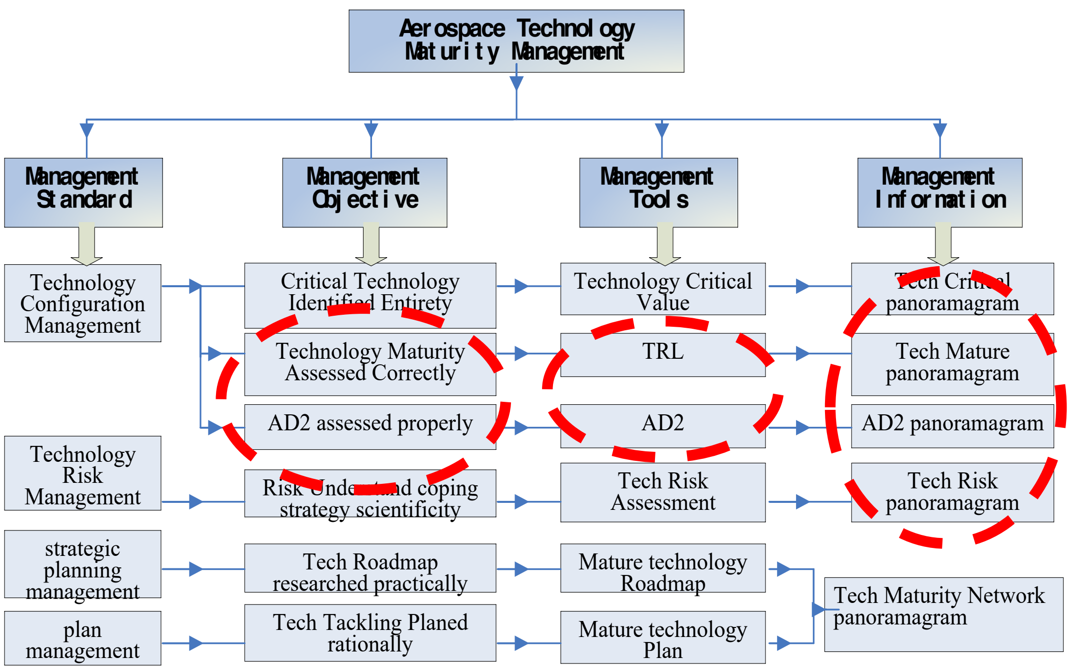

Figure 7-3: Information flow of Aerospace Technology Maturity Management

The information flow of the computer software tool could be demonstrated in several iterations with the Experts Group. The circled blocks are the primary information related to its main function. The objective information of the assessment was to maintain the assessment correctly and adequately. The TRL and AD2 tools will produce the assessment report containing the main information.

The software was designed for the management of the critical supporting technical information and technology maturity information. The main functions include the data model definition modular, maturity-model definition modular, assessment model definition modular of TRL and AD2, the visualisation modular, report document generation modular, and audit function modular, etc. It could use a Meta-Synthesis Approach to facilitating the integration of qualitative and quantitative method.

The Function Tree of the software is designed as the following diagram (Figure 7-4).

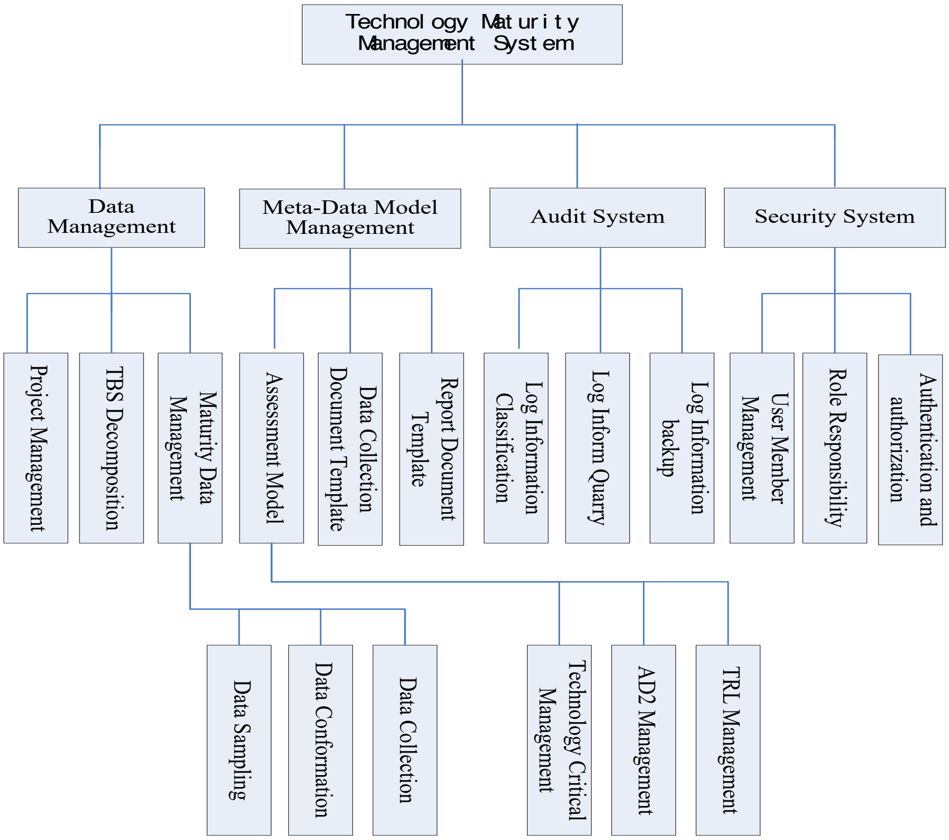

Figure 7-4: Function Decomposition Tree

The tool uses a Browser/Server software deploy model. The customer could log on the tool via the Internet Browser, even the system manager could use a browser to install and deploy the system. The typical runtime of the user interface is shown as the following:

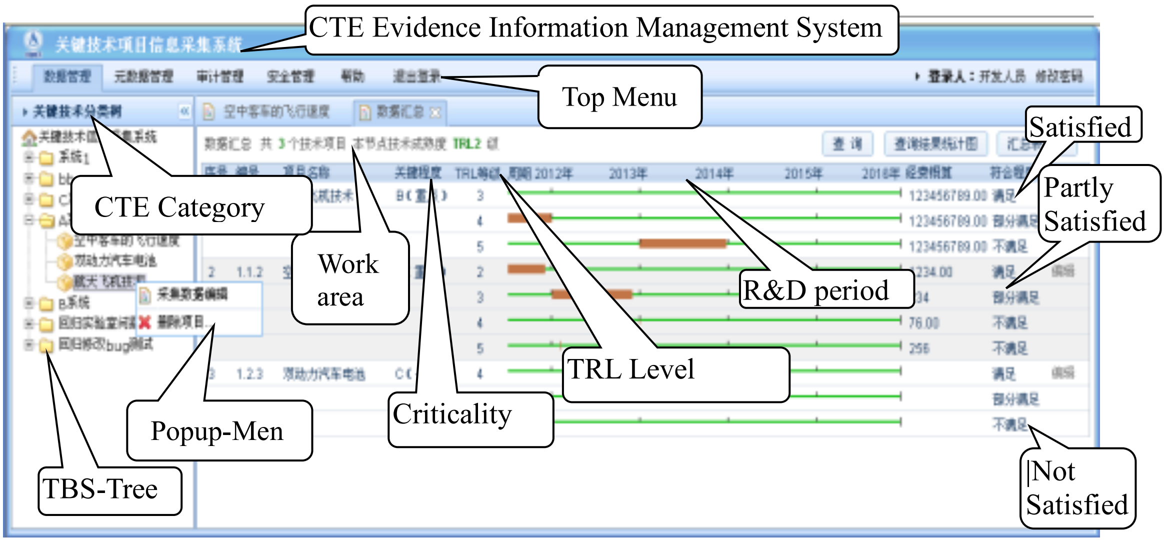

Figure 7-5: Typical User Interface Design (1)

The following diagram demonstrates the CTE under assessment supporting information well organised by the software tool, using Database editing facilities.

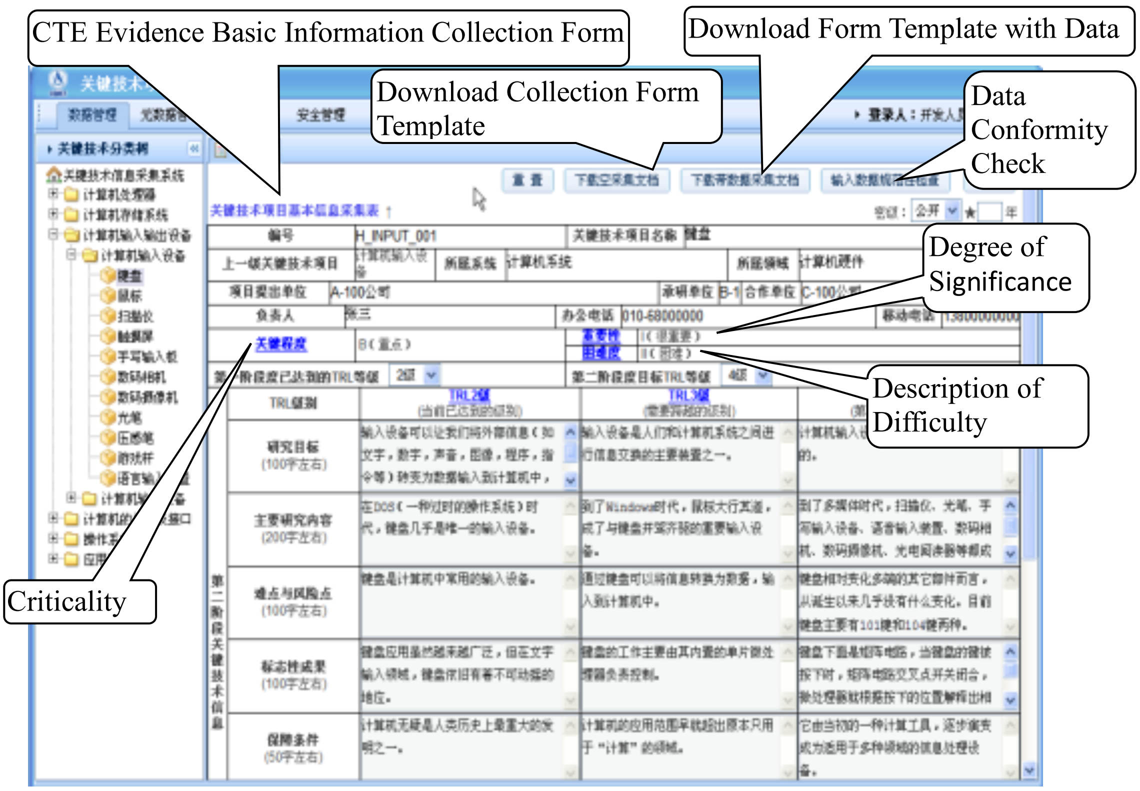

Figure 7-6: Typical User Interface Design (2)

The following diagram illustrates the critical statistics pie chart shows the distribution of the technologies' maturity.

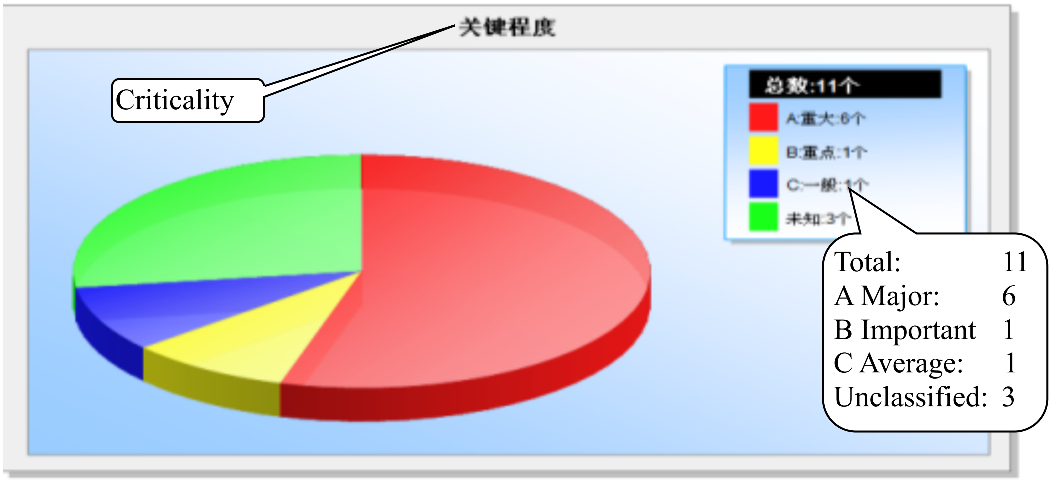

Figure 7-7: Typical User Interface Design (3)

The tool has the facilities of report documentation generation, which could generate different reports for managers, engineers and costumes. The reports have several types of diagram, chart and detailed descriptions. The following table concludes the functionalities comparison about the "CTE Evidence Information Management System" developed in this thesis and the Calculation Tool from ARFL laboratory.

Table 7-1: Functionality Comparison of the Software and Calculator

Functionality	Calculator (ARFL /US)	CTE Evidence Information Management System (NGLV)
Assist TRL and AD2 process	Assessment result collected/stored	Same to left one
Maturity Level suggestions	Give level suggestions	Same to left one
Documentation or report generation	Brief assessment form	Multi-template documentation support ✓
Data Set Management	No source data included	Enriched data set for assessing, contained or linked ✓
Future Validate support	Not support	could be validated anytime ✓
TRL-Feature-Item assessment set flexibility	Fixed assessment item set, selectable to include/exclude	Expendable assessment item set, different assessment configuration support ✓
Deploy Facility	Stand-alone computer systems with MS Office runtime installed	Web Server with PDS system integrated, Intranet within Company ✓

7.4 APPLICATION OF TRL/AD2 ASSESSMENT IN RISK MANAGEMENT

After the technology risk is confirmed, the framework of the specific technology risk management with TRL/AD2 integrated is shown in Figure 7-8.

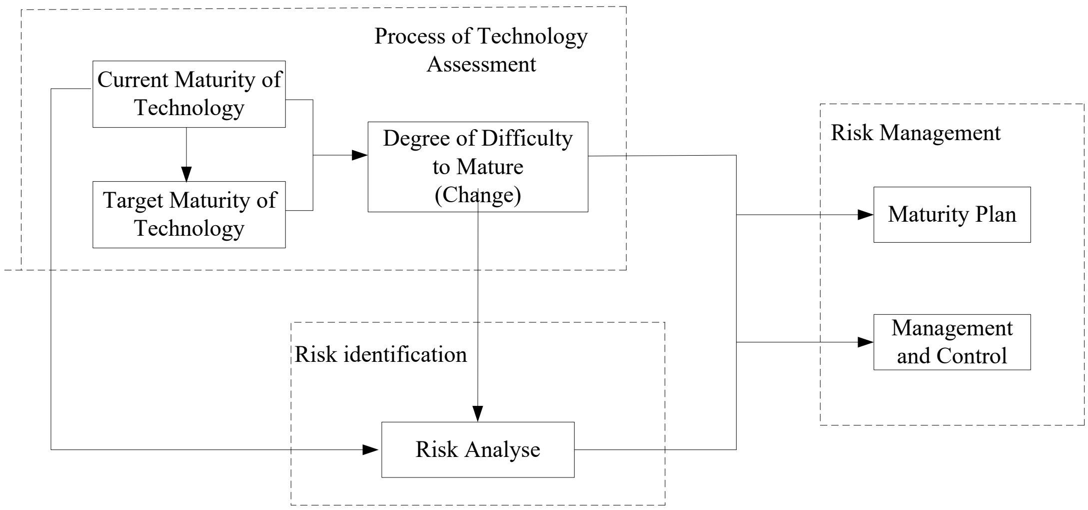

Figure 7-8: Risk Process and AD2 integrated

In Figure 7-8, through assessment the current TRL and TRL desired to get AD2, we get the assessment result which is related technology risk assessment to guide in making the technology research plan and management control plan. Based on this guiding principle to complement the key technology research plan, the Chinese aerospace mission command system can use it on every mission stage to identify and control the technology risk quantitatively so that it can assure the resources investment of the technology research plan confirmed by the designer.

In this thesis, qualitative TRL assessment and quantitative AD2 based MSA is used as a closed loop to identify and give guidance to technology advancement, as showed in Figure 7-8, TRL and AD2assessment is performed (in top-left corner of the figure) and result is used as input to Risk Analyse, also AD2 assessment information is transferred as reference to Maturity Plan procedure in Risk Management. Generally speaking, MSA could be a way of thinking to tackle the complex issue in many system engineering phases.

7.5 SUMMARY

The Meta-Synthesis Approach of combined qualitative and quantitative analysis is used with multiple iterations spiral to improve the accuracy of the insight of the technology risk. Computer-aided tools are designed to integrate TRL visualisation, AD2 visualisation, AD2 calculation and supporting information management in the MSA approach. All the above procedures are composed of the risk management process of the NGLV Programme and performed in the mission headquarter, which is also applicable for complex missions.

Although researchers at domestic and abroad have done a quantity of research on technology risk analysis, it is still comparatively challenging to have an accurate quantitative evaluation of technology risk for its dynamic content, sophisticated mechanism and predict of future.

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Chapter 8 Case Studies

The verification or validation of the new method is the necessity of this PhD study. From the research point of view, the methods proposed should be validated or verified to show its capacity or performance. As this research is focused on management with human's experiences involved in, a suitable way to validated or verified is case studies to be performed by assessment experts, designer, decision-makers or researchers.

As research on system engineering management, the most finding is not easy to show its improvement than traditional methods, so the cases chosen are dedicated to individual innovation first, then to the whole MSA approach. This chapter selects the typical parts of the whole case of technology evaluation, which focus on the TRL assessment, AD2 assessment calculation, visualisation method and the MSA approach. The cases are Ka-band Relaying Satellite transceiver, liquid oxygen and liquid hydrogen (Lox/LH2) rocket engine, questionnaire-based investigation and technology risk synthesis of X-Ray telescope satellite using MSA process.

8.1 CASE STUDY OF TRL ASSESSMENTS

8.1.1 Case-2: Ka-band Relaying Satellite Telecommunication

The chosen case to illustrate the modified method is "Ka-band Relaying Satellite Telecommunication technology" (Case study numbered Case-2, for the case study in chapter 5 is already numbered Case-1). The Ka-band is a portion of the microwave part of the electromagnetic spectrum defined as frequencies in the range 26.5–40 gigahertz (GHz).
The Following is the Satellite communication bands. (ChineseGovernment, 2016)

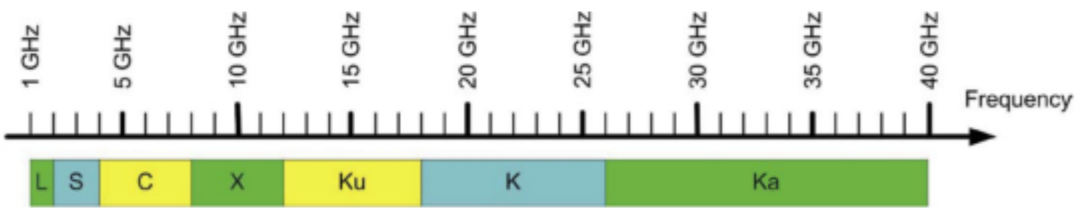

Figure 8-1: Satellite Communication Band Spectrum

The "Ka-band" could be the future of satellite communication because people continuously demand wider bandwidth signals and lower bands be getting full of K/Ku/C/X/S-band.

Ka-band surely can provide additional frequency ranges at satellite bands spectrum. It is also very suitable to the Satellite-to-Satellite relaying communications. Besides, the Ka-band has the advantage of lower attenuation, while the satellite to satellite communications almost happens in the outer space(Li et al., 2017).

The below (left) is the ground instrument developed by SkyWare Corp. for ESA. The right one is the Testbed named "SCaN". It is NASA's next space networking demonstration and will operate aboard the International Space Station. SCaN includes two S-bands and one Ka-band Software Defined Radios (SDR) processing unit.

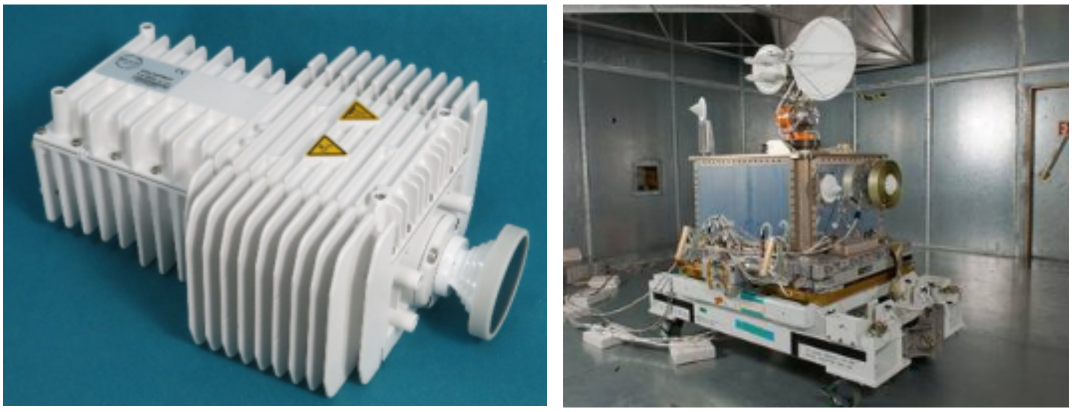

Figure 8-2: (L) ESA's Ka-band Transceiver and (R) NASA's Ka-band testbed

From the technology maturity assessment aspect, the following table illustrates the significant R&D efforts of the different levels and the map to technology maturity attributes. (taking TRL definition from NSAS as in this case study).

Table 8-1: Mapping of the technology maturity attributes and the R&D efforts

TRL	major R&D efforts at each level	**Technology** maturity attributes (each "question" in this row will derive an assessment feature)			
		technology state	integration state	Verified or Validated environment	performance indicator
1	Basic principles observed and reported, mainly included the Ka-band signal characteristic.	--	--	--	--
2	Discussion or reports documented description of the application using Ka-band in satellite communications, feasibility and benefit.	--	--	--	--
3	Setup the initial demonstration performance, implementation of the basic functions, Principle	Ka-band satellite relaying technology	Not integrated yet	Simplified laboratory environment for feasibility	Low transit power, low bit rate,

	verification				

TRL	major R&D efforts at each level	**Technology** maturity attributes (each "question" in this row will derive an assessment feature)			
		technology state	integration state	Verified or Validated environment	performance indicator
4	Ka-band satellite replaying transceiver finished principle prototype model building	Optimized Ka-band TTC performance (Satellite TTC relaying function included)	principle prototype (Ka-band satellite relaying transceiver, e -board)	the laboratory environment	Low transit power, low bit rate,
5	Demonstration prototype		Ka-band transceiver (microwave standard) and TTC system of satellite	Ka-band satellite to ground verification;	Middle transit power, middle bit rate,
6	Electric performance prototype	secondary payload launching prototype	Satellite relaying TTC system including Ka-band transceiver	Flying experiment	Middle transit power, full bit rate,
7	Typical application environment flight demonstration (Secondary Satellite Launching or secondary payload of the main satellite)	Ka-band satellite relaying transceiver		Secondary Satellite flight	full transit power, full bit rate,
8	Qualification for flight deployment, fully test	Ka-band satellite relaying transceiver	System level (relaying satellite)	Fully verification and validation environment	full transit power, full bit rate,
9	Technology product has deployed and relaying mission Operations completed.	Ka-band satellite relaying transceiver		Satellite to satellite, onboard space flight	full transit power, full bit rate

This case study shows the new assessment methods could facilitate the technology assessment more efficient, besides its usefulness. As recorded report, the overall technology assessment days needed similar to Ka-band relaying satellite telecommunication technology working group spent nearly 2 weeks to finish the technology TRL assessment, while this working group only use 3 days and a half to achieve the assessment result, including the assessment maturity matrix develop and allocate the answers to each attribute questions. After the assessment review, all the information collected was stored in Project Data Base, could be retrievable as needed.

8.1.2 Case-3: Thrust Chamber of Hydrogen-oxygen Rocket Engine

The case takes the first hydrogen-oxygen rocket engine of China developed by China Aerospace Science and Technology Corporation for New Generation Launch Vehicles project (NGLV), the case adopts the assessment method with equivalent evidence to establish the evidence chain of "hydrogen-oxygen rocket engine" from the elementary to the advanced product development and application processes, i.e. from the discovery of fundamental principles, proposition and simulation of application assumption, technical pre-research, principle prototype test and project presentation to the final successful application in flight missions. This case study will use the assessment attributes based TRL method to demonstrate the effective and efficient of the new method.

After work structure breakdown (WBS) decomposition, the thrust chamber will be selected as the Critical Technology Element (CTE). The full description of the case study will be Appendix B of this thesis and in this section will simply take TRL 5 as an example.

Table 8-2: Thrust Chamber TRL 5 Assessment features and Evidence

TRL 5: Component and/or breadboard validation in a relevant environment				
Assessment Attributes	**Passing Criteria of Assessment**	**Assessment Feature of CTE**	**Assessment Evidence from research institutes**	
			Supporting information on the assessment item	**Conformity**
Integration level of technology entity and system	Component level with the integration level enhancement	The thrust chamber is integrated with other components into a liquid hydrogen-oxygen engine.	A completely independent liquid hydrogen-oxygen engine demonstrate prototype with turbopump-fed gas-generator circulation. For such an engine, thrust chamber, turbo pump, fuel gas generator and actuator, etc. are integrated together primarily.	Meet the requirements
Fidelity of technology entity relative to final products	Principle prototype with a medium fidelity.	The thrust is close to that of an envisioned final product; in addition to a single thrust chamber, the liquid hydrogen-oxygen engine can be started at a time without any sway.	A single thrust chamber with a thrust of 4,000kg is developed, and the engine can be started at a time without any sway. Comparing with the preceding thrust chamber, the thrust is improved from 800kg to 4,000kg, while the chamber pressure is enhanced from 2.0MPa to 2.6 MPa.	Meet the requirements
Fidelity of demonstration environment relative to the operating environment	The corresponding environment with a low fidelity	Ground environment	Ground environment (engine test stand)	Meet the requirements
Conformity of demonstrated performance to the desired performance	Demonstrated performance conforms to the desired performance	The proper performance based on which engineering application feasibility can be verified is achieved. For example, while the thrust is 3500-4000Kg, the specific impulse > 4200 N·s/kg, chamber pressure > 2.0MPa. Design performance conforms to the desired performance, and the demonstrated performance accords to design performance.	Design performance: thrust=4000Kg; specific impulse≥4200 N·s/kg; chamber pressure=2.6MPa; combustion efficiency≥0.98; blending ratio of engine=5.0. Demonstrated performance: thrust=4000Kg; specific impulse=4200 N·s/kg; chamber pressure=2.6MPa; combustion efficiency=0.98; blending ratio of engine =5.0. Demonstrated performance conforms to design performance, and design performance accords with the desired performance of the assessment team.	Meet the requirements

8.2 INTEGRAL CALCULATION EXPERIMENTS

The development of an integral method of TRL and AD2 involves two key parameters — weight selection of each evaluation feature, and state density function establishment. The individual analysis must be performed on the two modules, and the detailed test must be done on the accuracy of the AD2 calculation method. 50 technologies to be evaluated are provided for the experiment within NGLV project, which is all under TRL6.

8.2.1 CASE-4: Parameter Selection Accuracy Analysis Experiment

The formula set up for computing AD2 involves two importance parameters: weight of each evaluation feature and relevant parameters in the state density function.

(1) State Density Function

In section 4.2.3, state density function is deemed to be a linear function which includes slope **k** and intercept **b** and discussion on parameters selection have been performed to determine parameter range. The parameter range ensures that the parameter selected conforms to the nature of AD2. Accurate parameter values should be determined by the experts.

Set the values of slope **k** and intercept **b**, if k=1, b=2, the AD2 formula can be converted to:

$$V_{AD2} = D_{AD2} / D$$

$$= \sum_{j=1}^{j=M} \int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha\{b[f_{nj}(x) - f_{mj}(x)] - \frac{1}{2}k[f_{nj}^2(x) - f_{mj}^2(x)]\}dx / D$$

$$= \sum_{j=1}^{j=M} \int_{N_{feature\_j-1}}^{N_{feature\_j}} \alpha\{2[f_{nj}(x) - f_{mj}(x)] - \frac{1}{2}[f_{nj}^2(x) - f_{mj}^2(x)]\}dx / D \qquad (8\text{-}1)$$

In the above formula, D represents the span value of difficulties when the state value of each evaluation feature develops from all on “0” to “1”. $f_{nj}(x)$ and $f_{mj}(x)$ can be determined by specific state values. Emphasis will not be put on weight α, which is taken to be equal for each feature. Equation 5-33 can be used to calculate the AD2 when developing from the current state (such as TRL3) to the target state (such as TRL4). For example, VAD2=0.237 means the AD2 is at level 8. Then experts will evaluate the results to determine whether the AD2 value is accurate.

The experiment results of AD2 calculation and evaluation (from TRL3 to TRL4) with the method mentioned above are shown in Table 8-3.

Table 8-3: State Density Function Parameter Selection and Comparison Table

CTE ID.	Target Readiness Level	k	b	AD2 Result	AD2 Score	AD2 Average of Experts Assessment	Within the score
CTE1	4	1	2	0.237	8	8	YES
CTE2	4	2	3	0.215	8	8	YES
CTE3	4	2	1	0.186	9	8	NO
CTE4	5	1	2	0.469	6	6	YES
CTE5	5	2	3	0.441	6	6	YES
CTE6	5	2	1	0.377	7	6	NO

Analysing the experiment data, we can find that the obtained value falls within the value range specified and conforms to the nature of AD2. In selecting a specific value, the calculated AD2 is the ratio between the span from current TRL to target TRL and that from state value "0" to state value "1".

From the comparison table, the ***k*** and ***b*** of the CTE1, CTE2, CTE4 and CTE5 are within the score, and the final result of AD2 is confirmed by the average assessment of the experts. While the CTE3 and CTE6 have got notable variation from the experts' assessments ("9 vs 8" and "7 vs 6"), but one could find the Identification method as the selection of ***k*** and ***b*** is out of the score, so it is practicable to avoid using such the result. So one could find that as the same state density function is used for calculating the two types of the span, the selection of a specific value does not affect the result as long as the selection agrees with the nature of AD2 (***k*** and ***b*** are chosen within the score).

(2) Weighted Factor

When selecting the weighted factor of each evaluation feature, genetic algorithm replaces expert discussion. The experiment compares the weighted values obtained from the genetic algorithm with those from the expert group decision. In the experiment, ten experts are asked to assign weighted factor values to each TRL evaluation feature. Then the weighted values of one technology and 5 weight factors are calculated with a genetic algorithm.

The GA initial configurations are randomised selected from the range$[0,1]$. The Gene would be not less than 4 times of the weight factors, which means 5 * 4 = 20 segments. In this experiment, we used $(g_1, g_2, g_3, \ldots g_{2^h-1}, \ldots, g_{20})$. Then the experts would use a Delphi method to group vote the final result. More information about the experiment could refer to the paper published titled "Computation of Advancement Degree of Difficulty Based on Genetic Algorithm".

The results are compared in table 8-4.

Table 8-4: Weight Factors Selection and Comparison Table

Weight ID	Experience-based assignment										Average of GA
	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10	
1	0.24	0.45	0.34	0.20	0.30	0.58	0.31	0.43	0.33	0.41	0.36
2	0.36	0.30	0.37	0.57	0.22	0.29	0.35	0.39	0.71	0.34	0.37
3	0.58	0.51	0.40	0.53	0.81	0.37	0.66	0.47	0.40	0.37	0.48
4	0.33	0.19	0.21	0.45	0.27	0.30	0.56	0.31	0.21	0.26	0.29
5	0.08	0.07	0.10	0.05	0.02	0.04	0.03	0.01	0.03	0.11	0.04

To give a visual display of the weighted value comparison, one could take one criterion (take Weight ID 2) for example, as illustrated in Figure 8-3.

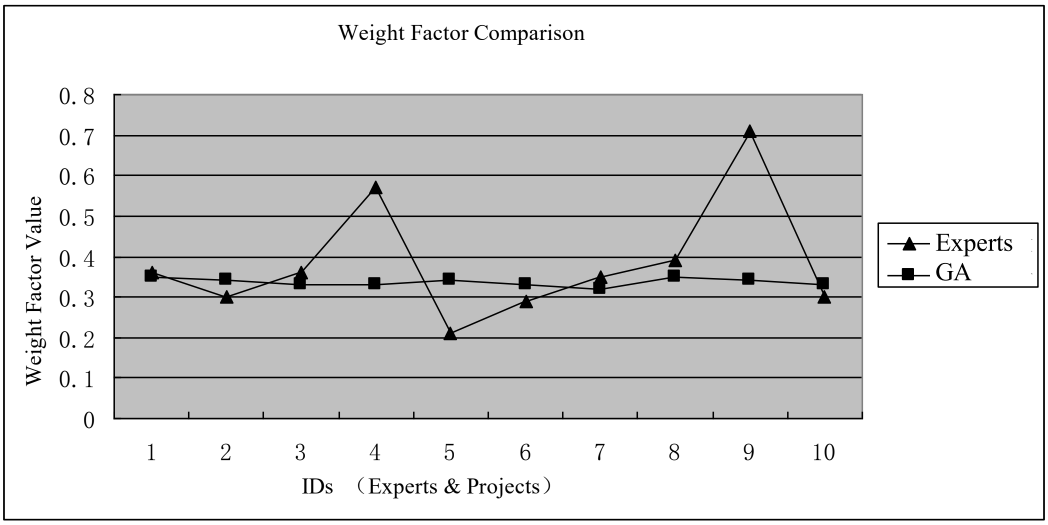

Figure 8-3: The Weight Factor Comparison

Analysing the experiment data, it could be demonstrated that the values obtained from the expert group discussion are relatively dispersed; while those from the genetic algorithm are closer to the average value of expert discussion, which performs better in computing AD2.

8.2.2 CASE-5: AD2 Accuracy Analysis Experiment

To analyse the accuracy of AD2 calculation method, we compare it with the Bilbro's checklist form. At first, give 10 experts with the Bilbro's forms to evaluate AD2 of a technology. The experts assign values to AD2 when developing from one state of TRL to a high one. Then use the method proposed in this thesis to calculate AD2. Pre-define threshold valves to 9 degrees.

Then compare the results. Invite 10 experts to evaluate 5 CTEs' AD2 from current TRL to

TRL6. Part of the evaluation and results are listed in Table 8-5.

Table 8-5: AD2 Assessment Result

CTE ID	Bilbro's Checklist Method										Computational Method
	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10	
1	3	2	4	2	3	5	1	3	3	3	3
2	6	3	6	6	7	6	5	7	6	5	6
3	3	5	4	4	4	4	6	5	4	4	4
4	2	1	1	1	1	3	1	1	2	1	1
5	3	5	3	3	2	3	3	4	3	3	3

The experiment results show that the experts' evaluations are subjective due to the experts' personal preference, as well as their understanding and judgement on the items. The data are relatively discrete though with a well-recognised value, which embodies the evaluation of most experts. Other values are dispersed above or below it. The value obtained by the GA algorithm proposed in this thesis is the closest to the well-recognised value, thereby demonstrating that the algorithm is more objective and comprehensive.

8.3 VISUALISATION OF TRL/AD2 EXPERIMENTS

Visualisation method is intended to show TRL and AD2 in different cases and present, in a direct way, the panorama of technical development to R&D personnel and project managers. The goal of the experiment is to illustrate that this method can be used for TRL visualisation and AD2 visualisation of critical technologies of various projects.

In TRL-based technical evaluation criteria, TRL consists of 9 levels, falling into 3 categories:

- ✓ Low-level readiness (TRL1, 2, 3)
- ✓ Middle-level readiness (TRL4, 5, 6)
- ✓ High-level readiness (TRL7, 8, 9).

This section will present a Visualisation of corresponding technologies in 3 TRL categories and analyse the resulting TRL and AD2 distribution patterns.

8.3.1 CASE-6: Fabricating Membrane Thermopile Sensors (low TRLs)

Take the technology for **fabricating membrane thermopile sensors** for example. The ISO standards call this a heat flux meter. Hukseflux Corp. has developed a reliable sensor (Hukseflux, 2016) and Chinese aerospace institutes also take this kind of sensor as a critical technology in the NGLV project. The sensor has rapidly become the ideal of choice for fire testing and has mainly used to test reaction to fire and fire resistance. It is also used as a calibration reference standard for test equipment, for example, inflammability and smoke chamber tests.

As the example is chosen with the CASC of China, all the assessment information are provided and collected from the research institutes within China mainland.

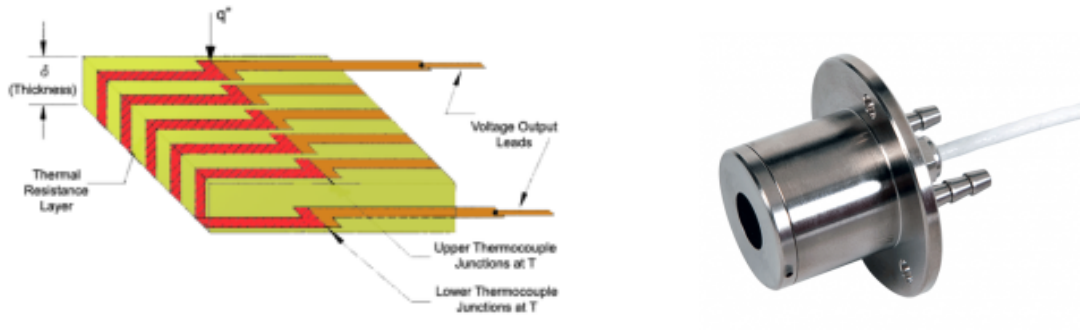

Figure 8-4: Principle and product of fabricating membrane thermopile sensors

When at TRL1-TRL3, the technology is at the early stage of development, thus satisfying more evaluation criteria of low-level readiness than those of middle and high-level readiness. In this case, the curve of TRL is on the very left of the origin.

This technology is selected for this experiment for the following reasons:

(1) Significance to the Mission: The fabricating technology of sensors determines their operating temperature, sensitivity and stability, thereby affecting the temperature resistance of the sensor and the overall performance of the system. The complex fabricating technology for membrane sensors entails optimisation of technological parameters depending on the device, membrane material composition, and specific requirements.

(2) The severity of Failure: There is no mature technique for fabricating membrane thermopile heat flux sensors in China, which is the most significant risk. The immaturity directly affects the microstructure, binding force and thermal stress of the membrane, thereby posing a threat to the high-temperature resistance performance and lifetime of the membrane and the overall device performance.

The evaluation of this fabricating technology shows that it is above TRL1 and currently at TRL2 with some aspects reaching TRL3. All the state values of this technology are “0” from TRL4 to TRL9. Therefore, it is more worthwhile to plot the state distribution from TRL1 to TRL4, as illustrated in Figure 8-5.

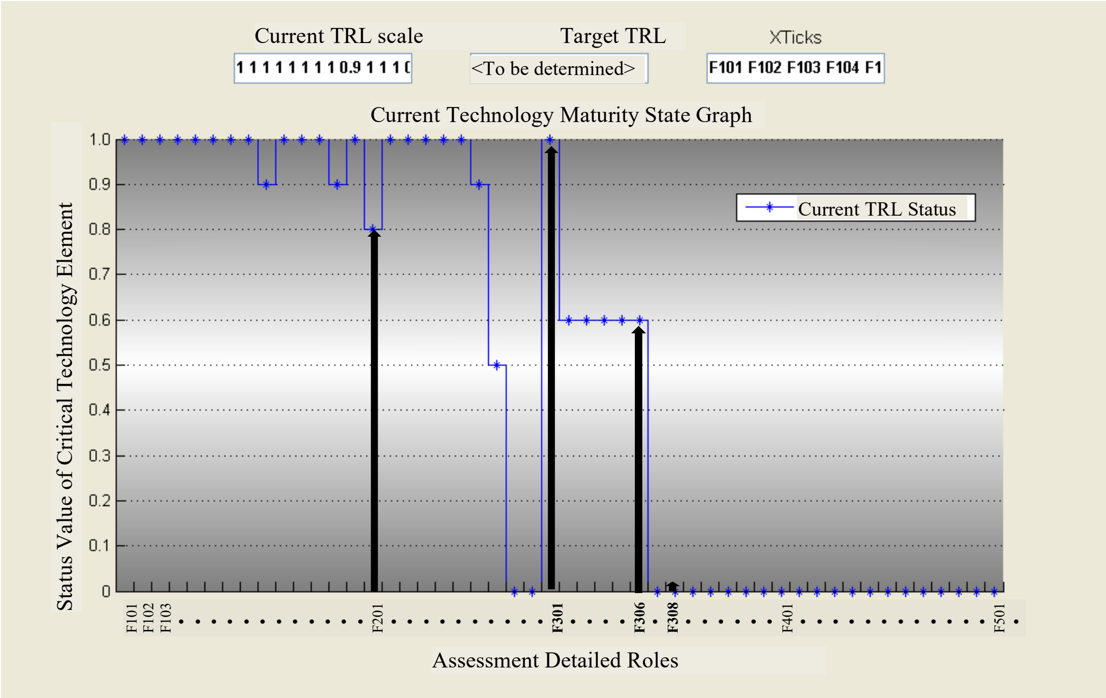

Figure 8-5: The state distribution diagram of technology readiness (1)

The TRL state distribution clearly shows that this technology is at TRL2 with some aspects reaching TRL3. Quantifying the state values corresponding to each criterion will give the TRL state distribution pattern. For example, item F301 of TRL3, "to present the technical competence estimation of this expected CTE product", is satisfied, thus, its state value is 1; item F308 "to briefly describe the simulated environment and its parameters in this model and compare them with those of the predicted product so as to analyse whether the model includes the most important environment parameters" is not satisfied so the state value is 0 since the technology has not been modelled and simulated of its sensor have been set; item F306 is to "describe the main functions and performance of the CTE test equipment and compare with those of the expected CTE product" is partially satisfied, so the state value is set to 0.6 since the target melting temperature is “>1200℃(at 3000 seconds)” and the current operating temperature is “ 660 ℃(at 180seconds)”.

The readiness objective of the technology is level 4. Figure 8-6 illustrates AD2 distribution from the current state to level 4 readiness state. The shadow shows where the AD2 level is when developing from the current TRL to ideal level 4. Since the aim is ideal level 4, all state values corresponding to the evaluation criteria of this level should be 1, including part of those of level 2 that have been satisfied. Take assessment item F201 for example, the current state value is 0.8, but the requirement of technical development at TRL2 has been satisfied. During the technical development towards an ideal state, if the target is the ideal state, the state values corresponding to the targeted TRL evaluation rule features should be set to “1” here.

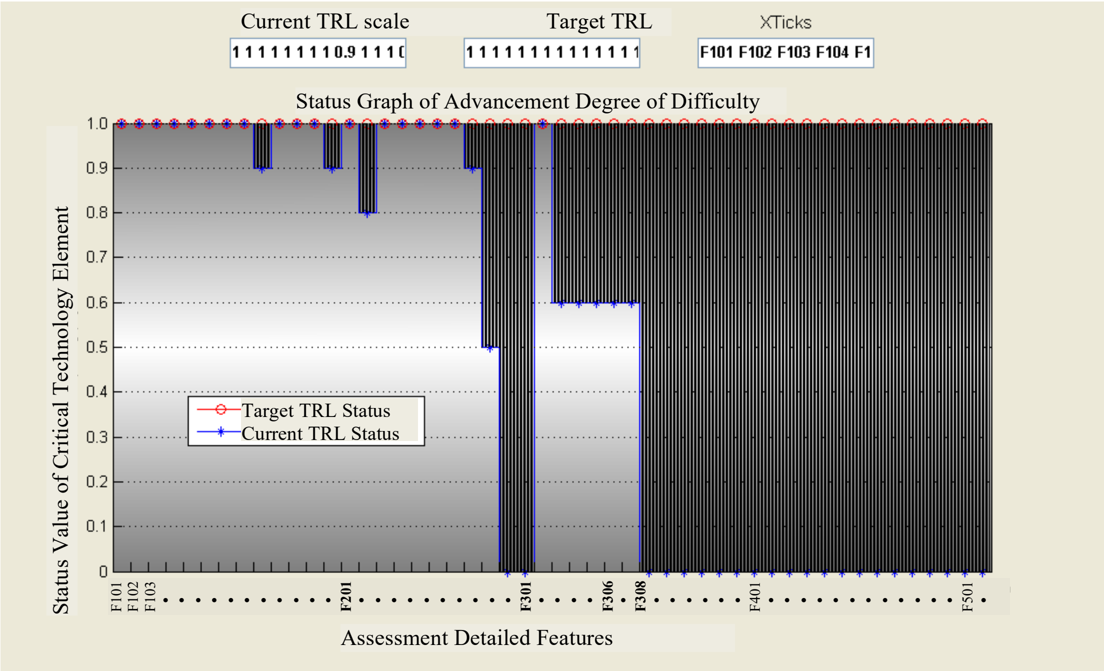

Figure 8-6: The state distribution diagram of technology readiness (2)

8.3.2 CASE-7: Designing High-Velocity Thrust Chamber (middle TRLs)

Take the technology for designing a thrust chamber under high-velocity rarefied flow disturbance for example. The high-velocity thrust chamber is the most critical part of the rocket engine. When at TRL4-TRL6, the technology is at the middle stage of development, thus satisfying far more evaluation criteria of low- and middle-level readiness than those of high-level readiness.

The technology deems it is the right choice for this experiment from the following points:

(1) **Significance to the Mission**: The operating environment of the thrust chamber under high-velocity rarefied flow disturbance is entirely different from the attitude control thrust chamber under a vacuum environment. Since the injector jet is directly affected by the external environment, it is necessary to verify whether the injection unit can ensure reliable ignition and stable combustion and to measure the temperature margin under aerodynamic heating. It has excellent effects on structural reliability; therefore, it is the key to project success.

(2) **The severity of Failure**: The turbulence generated in the combustion chamber and the nozzle under conditions of high-velocity rarefied flow poses a direct threat to ignition reliability and combustion stability. There is a significant technical risk.

The evaluation of this technology shows that it is at TRL4 after meeting all requirements of TRL1-TRL3, with some aspects reaching TRL5. Figure 8-7 shows its TRL pattern plotted according to the evaluation data.

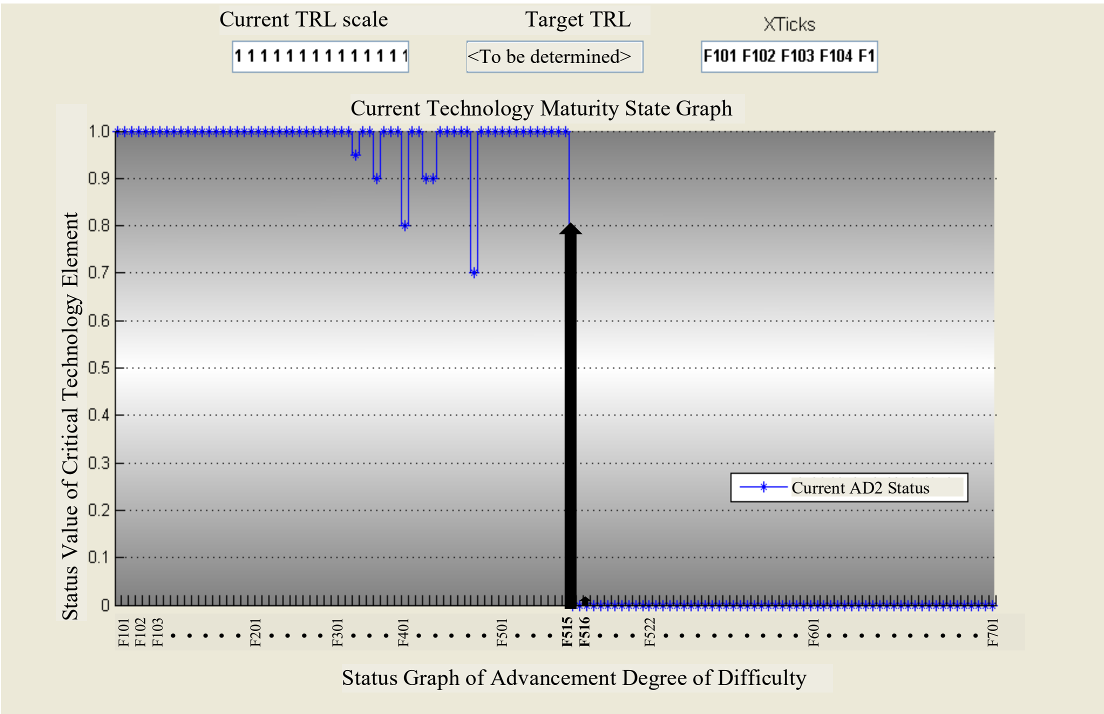

Figure 8-7: The state distribution diagram of technology readiness (3)

All the state values of this technology are “0” from TRL6 to TRL9. Therefore, it is more worthwhile to plot the state distribution from TRL1 to TRL6. Regarding the technology itself without considering the environmental factors, it is matured. Its application in projects, however, is subject to the environment that entails an environment platform for demonstration. At present, an environment test has not been done yet due to incomplete preparation. Thus a clear boundary occurs at F516. All state values corresponding to evaluation criteria before F516 are mostly 0.8 and above, while that of F516 to F522 are 0.

This technology is currently at TRL4. All state values of TRL6 and beyond are 0, making no sense to the evaluation. The readiness target of the technology is TRL5. The below, Figure 8-5 clearly shows that effective evaluation of AD2 from the current TRL to TRL6. The shadow shows where all effort is when developing from the current TRL to TRL6.

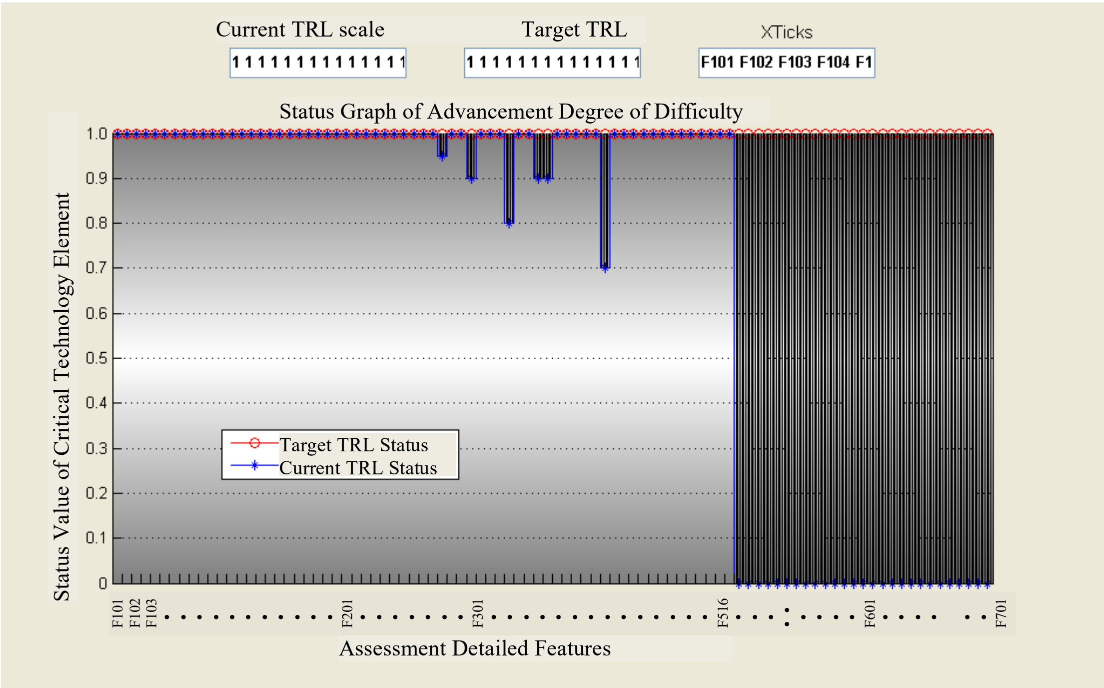

Figure 8-8: The state distribution diagram of technology readiness (4)

8.3.3 CASE-8: Liquid Hydrogen/Oxygen Thrust Chamber (high TRLs)

Take the technology for thrust chamber of liquid hydrogen/LOX rocket engine for example.

When at TRL7-TRL9, the technology is at the advanced stage of development, thus basically satisfying all evaluation criteria for low- and middle-level readiness. In this case, the curve of TRL covers most area of the diagram, as the technology for the thrust chamber of liquid hydrogen/LOX rocket engine. The pump-up gas generator cycle liquid hydrogen/LOX rocket engine (namely YF-73) is a Chinese developed rocket power system consisting of thrust chamber, turbo pump, gas generator, various valves regulators, racks and pipelines. It serves as the main engine for NGLV 3rd stage. The thrust chamber, consisting of a head (injector and porous metal panel) and body, mainly converts propellant energy and produces thrust. It is core components of hydrogen/LOX rocket engine.

The main tasks for developing a thrust chamber includes the development of an injector, head structure of the part where the injector situates, heat transfer structure of the body, Laval Nozzle shape and structure. The injector must ensure efficient energy conversion and combustion reliability and tackle possible unstable combustion. Nozzle placement, propellant tracing, static structural strength and thermal intensity must be considered when developing the head structure. Heat transfer and thermal structure must be considered when developing the body. The injection efficiency must be considered when designing the nozzle shape.

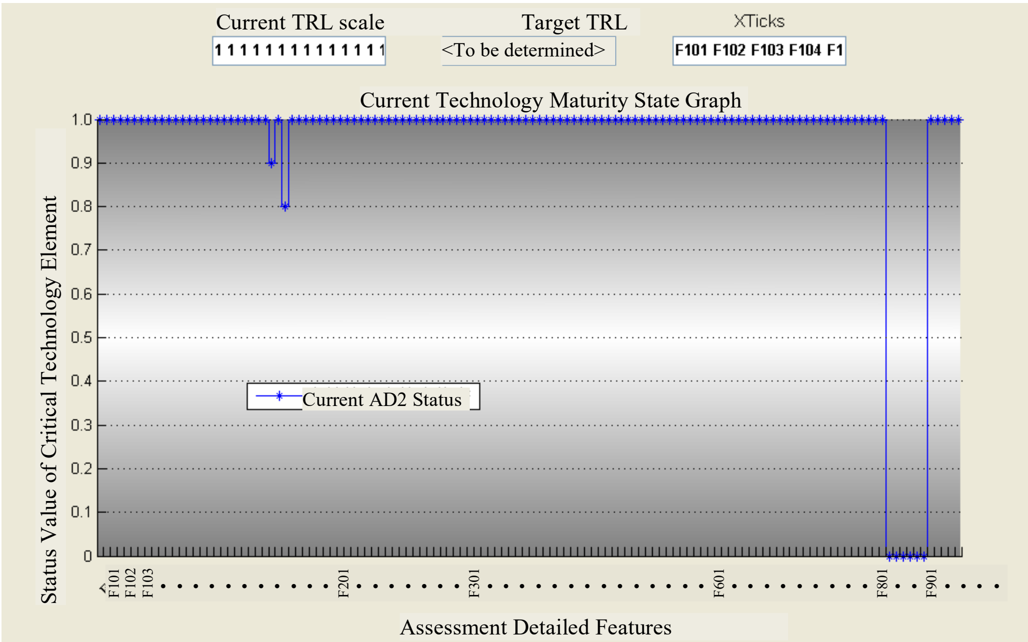

Figure 8-9: The state distribution diagram of technology readiness (5)

It should be noted that the main tasks at TRL8 are to perform various tests and evaluations during the flight model phase, such as qualification and acceptance tests. Since there is no flight model phase in rocket development (because rocket carrier capacity varies in different tasks, it is mission-dependent), qualification and acceptance tests have been done before the test flight, that is, at TRL7. There is no TRL8 for this technology. TRL7 is followed directly by TRL9. Since this technology has reached TRL9, the AD2 assessment could finish.

The visualisations mentioned above make it impossible to present the current readiness state and AD2 required to the target readiness state in the state distribution diagram to vividly illustrate the current state and dynamic development of the technology to the management and technical personnel. Information conveyed through visualisation is far more detailed, objective and accurate than presenting TRL and AD2 only.

8.4 MSA QUESTIONNAIRE AND EXAMPLE OF SPIRAL INSIGHT OF TECHNICAL RISK

8.4.1 MSA Approach Questionnaire

The AD2 is calculated to provide management with a clear and vivid picture of technology development. The risk assessment of technology development, following AD2 calculation, is necessary for the management to make decisions on fund and workforce investment. It is also the application of AD2 in risk assessment.

During the development of technology, research organiser, funds and the environment are indispensable and inter-connected factors. They are all critical to technological development. Risk assessment is essential for technological development and also interconnects with the above factors. Therefore, risk assessment should be performed with the application of AD2 values that have been obtained for further risk analysis. Based on the risk assessment process mentioned above, use a risk analysis module in the software tool to perform technological risk analysis for CTEs. Then $P_{failure}$ is given by:

$$P_{failure} = f_{failure}(V_{AD2}, TRL) = V_{AD2} / TRL \quad (8\text{-}1)$$

Given the values of AD2 and current TRL, $P_{failure}$ can be found. Then the risk level of technology development can be obtained with the risk analysis matrix.

In this thesis, a questionnaire based example of the MSA approach was demonstrated for the insight of technical risk. The MSA approach embodied within the software platform was put into its first on-line experiment around 2011. The author prepared a questionnaire of the MSA approach during the training course of the software and TR/AD2 methods at the end of July 2011.

The questionnaire included three parts, which were background information about the MSA software, satisfaction about the training, and selection of technology CTE to put into software as the first experiment within the NGLV project. The first part was related to this thesis so it is a list here. The MSA and TRL/AD2 related questions are the following:

Question 1*: your team's working duty in NGLV project, choose from the flowing:*

☐*Technology manager;*☐*Risk Assessor;*☐*Technology researcher;*☐*Supporting*

Question 2*: Rule of technical Risk in NGLV project for the success of the project: (5 grade of importance)*

☐*Major Factor;*☐*Most Important;*☐*Average Impact;*

☐*Less Impact;* ☐*Nothing Impact;*

Question 3*: In your practice, which method is your first choice for controlling technology risks?*

☐*Technology Review;* ☐*Experienced Designer;*☐*More test before delivery;*

☐*Fully matured technology;* ☐*Nothing to choose;*

Question 4*: MSA rule in NGLV project for the success of the project: (5 grade of importance)*

☐*Major Factor;*☐*Most Important;*☐*Average Impact;*

☐*Less Impact;* ☐*Nothing Impact;*

Question 5*: TRL/AD2 rule in NGLV project for the success of the project: (5 grade of importance)*

☐*Major Factor;*☐*Most Important;*☐*Average Impact;*

☐*Less Impact;* ☐*Nothing Impact;*

Question 6*: Before this training, your knowledge of MSA, TRL/AD2:*

☐*Know and used;* ☐*Know something about maturity;* ☐*Know about MSA;*

☐*Know a little but never used;* ☐*Know Nothing;*

There were around 100 participants, and 59 copies of the questionnaires were submitted for the questionnaire is an institute or working group divided. One research team attending the training course was required to finish one questionnaire and submit.

Among the 59 samples of answer sheets, 35 copies were strictly related to MSA and TRL/AD2. Others were not technology related work duty. From the statistics, one could reveal that most of the participants are think much of the technology risk but seldom of them knowing the technology maturity while some of them were familiar with the MSA process. The data collected would be analyzed with the second questionnaire.

By the end of November 2013 and 2016, another questionnaire was sent out before the formal assessment meeting of NGLV Project. Two questions were added to the list (as stated below). This time, 45 copies of questionnaires were submitted, and all copies were closed related to MSA and TRL, so every copy counted in.

Question 7*: Usefulness of CTE assessment information management software:*

☐*Very useful;*☐*Most Important;*☐*Average Impact;*

☐*Less Impact;* ☐*Nothing Impact;*

Question 8*: CTE number using MSA to control the risk:*_______

From the two round of questionnaire, we can take some of the statistics as the following.

✓ **Rule of Technical Risk in NGLV Project:**

There was a biggish change that most of the participants have agreed that the technical risk is significant and 2013 has a rise of Major Factor to 73.33% from 48.57% in 2011.

Rule of technical Risk	2011	%	2013	%
Major Factor	17	**48.57%**	33	**73.33%**
Most Important	12	**34.29%**	9	**20.00%**
Average Impact	3	**8.57%**	2	**4.44%**
Less Impact	2	**5.71%**	1	**2.22%**
Nothing Impact	1	**2.86%**	0	**0%**
total	35		45	

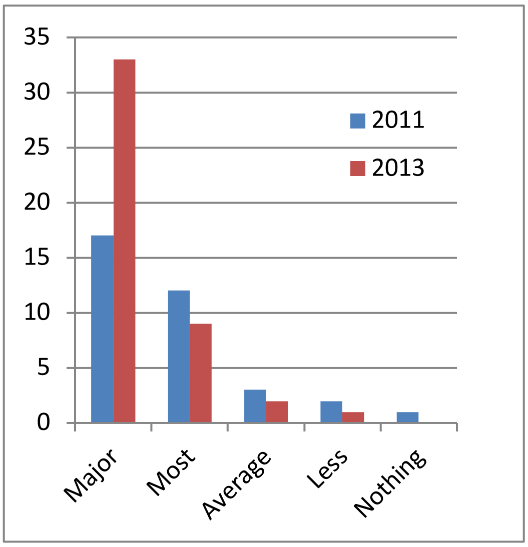

Figure 8-10: The MSA Questionnaires statistics (1)

✓ **Rule of MSA in NGLV Project:**

There was a slight improvement besides 2011, and also most of the participants have agreed that MSA plays a significant rule. The data of 2013 has a rise of Major Factor and Most Important in 2011.

Rule of MSA	2011	%	2013	%
Major Factor	18	**51.4%**	22	**48.9%**
Most Important	10	**28.6%**	16	**35.6%**
Average Impact	5	**14.3%**	6	**13.3%**
Less Impact	1	**2.9%**	1	**2.2%**
Nothing Impact	1	**2.9%**	0	**0%**
total	35		45	

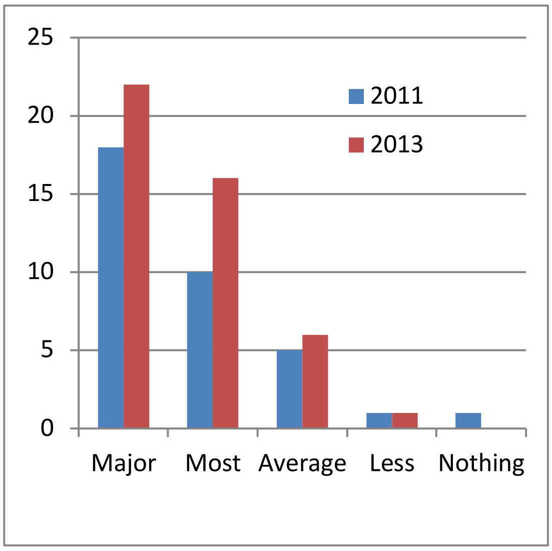

Figure 8-11: The MSA Questionnaires statistics (2)

✓ **Rule of TRL/AD2 in Project:**

There were tremendous improvements between the two questionnaires. Due the TRL/AD2 newly introduced to China, so most of the participants have changed and agreed that TRL/AD2's important rule. The data of 2013 have both raises of Major Factor and Most Important in 2011.

Rule of MSA	2011	%	2013	%
Major Factor	4	**11.4%**	23	**51.1%**
Most Important	9	**25.7%**	12	**26.7%**
Average Impact	12	**34.3%**	6	**13.3%**
Less Impact	5	**14.3%**	4	**8.9%**
Nothing Impact	5	**14.3%**	0	**0%**
total	35		45	

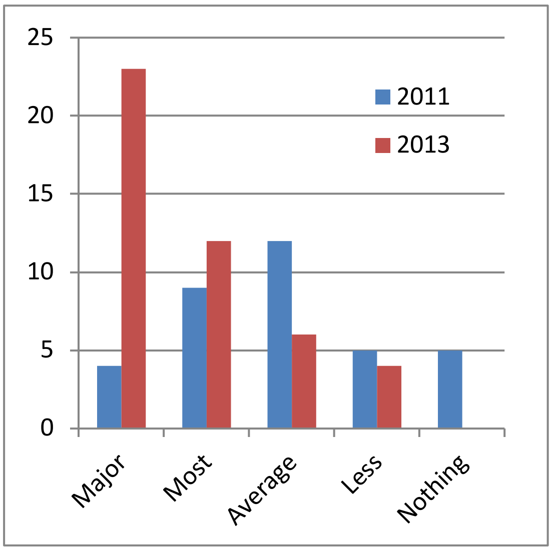

Figure 8-12: The MSA Questionnaires statistics (3)

✓ **Knowledge of MSA and TRL/AD2 before training:**

The data shows that improvements between the two questionnaires. The data of 2013 have both raises of knowledge of MSA and TRL/AD2 in 2011.

Knowledge of MSA and TRL/AD2	2011	%	2013	%
Know and used	2	**5.7%**	35	**77.8%**
Know about TRL/AD2	4	**11.4%**	3	**6.7%**
Know about MSA	11	**31.4%**	5	**11.1%**
Know a little but never used	12	**34.3%**	2	**4.4%**
Know Nothing	6	**17.1%**	0	**0.0%**
total	35		45	

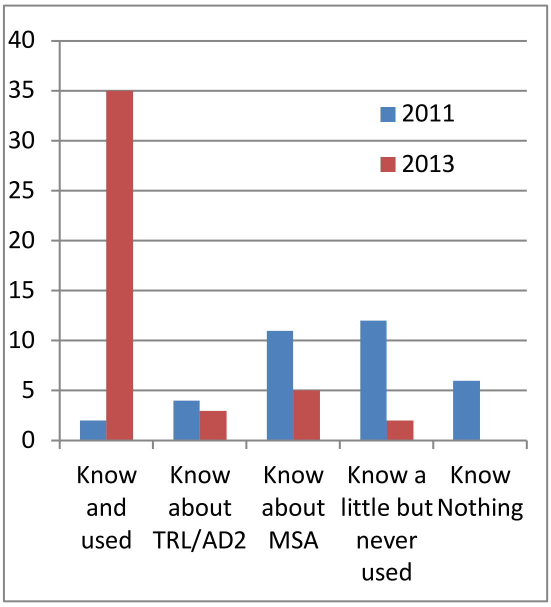

Figure 8-13: The MSA Questionnaires statistics (4)

✓ **First Choice of Method to Control Technology Risks**

The data shows that significant changes between the two questionnaires. The data of 2013 have tremendous raises of "Fully Matured Technology" to 68.9% from 8.6% in 2011.

First Choice of Method to Control Technology Risks	2011	%	2013	%
Technology Review	14	**40.0%**	7	**15.6%**
Experienced Designer	10	**28.6%**	2	**4.4%**
More test before delivery	6	**17.1%**	5	**11.1%**
Fully matured technology	3	**8.6%**	31	**68.9%**
Nothing to choose	2	**5.7%**	0	**0.0%**
total	35		45	

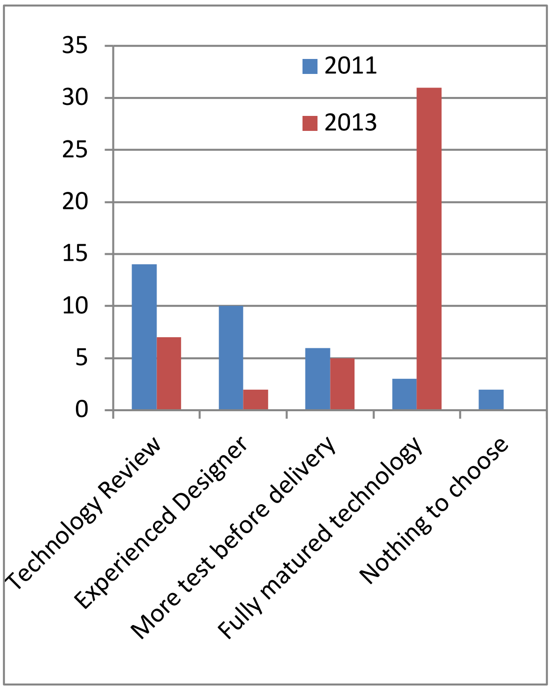

Figure 8-14: The MSA Questionnaires statistics (5)

✓ **Usefulness of CTE assessment information management software:**

This question was added to check if the software were recognised by the user after deployed. The data of 2013 and 2016 showed the software has good feedback increased.

Usefulness of software tool	2013	%	2016	%
Very Useful	15	**33.3%**	**22**	**48.9%**
Most Important	22	**48.9%**	**16**	**35.6%**
Average Impact	5	**11.1%**	6	**13.3%**
Less Impact	3	**6.7%**	1	**2.2%**
Nothing Impact	0	**0.0%**	0	**0.0%**
Total	45		45	

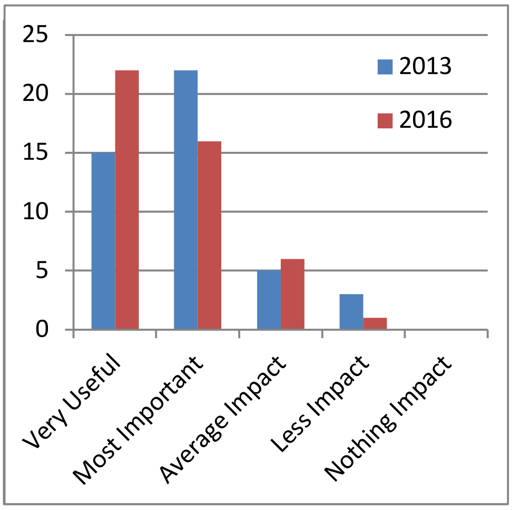

Figure 8-15: The MSA Questionnaires statistics (6)

From the above statistics, one can conclude that the MSA approach and the supporting software were well accepted, and the CTE number of using MSA approach to gain insight into technology risk has reached above 50. That was evidence that the method was better than other methods used before (including Technology Review, Experienced Designer, and putting more test before delivery).

8.4.2 CASE-9: Spiral MSA based Insight of Mission Technology Risk

The case study was conducted by the pre-research PM office, which also cooperated with China National Space Center to have a Phase 0 pre-research case about the X-Ray telescope satellite project, using TRL/AD2 and MSA to insight the technology risk.
The X-ray observation of the sun was attracted to the research debates (Pareschi and Ferrando, 2006). The scientists from National Astronomical Observatories of China proposed a satellite mission of X-ray focal telescope onboard a satellite, capture the X-ray behand a distinctive pattern of the aperture in the shelter. The distance between the aperture shelter and the X-ray receiver should be 20 to 50 meters. The Phase 0 pre-research is to give the brief mission architecture and determine the TRL and AD2 of CTE.

- ✓ **First Preliminary Mission Architecture and its TRL/AD2**

The mission included a two satellite with formation fly, with the front satellite(S1) equipped with the aperture shelter, and the telescope satellite(S2) behind will maintain the position to the front one within the solid angle not more than 0.18^{o}， to capture the modulated X-ray from the sun passing through the aperture of S1, by using X-ray detector. (Jiang et al., 2018b)

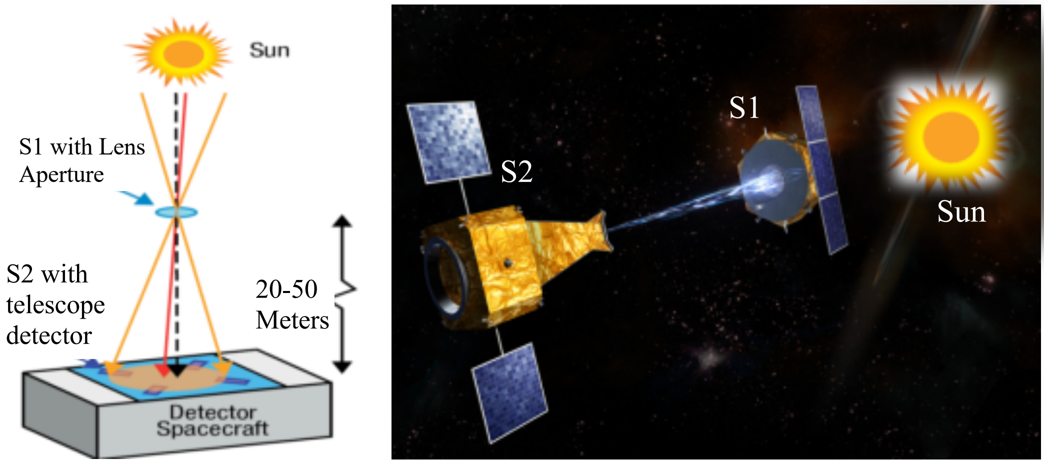

Figure 8-16: The Modulated Dual X-ray Satellite proposed in SSO orbit

This idea about the dual X-ray probe satellites should be in SSO orbit. Then the science team issued a brief mission statement to the Mission Modelling and Simulation Lab of National Space Center. The lab finished a modelling of the dual satellite formation flight architecture. Due to the orbiting control sensitivity, the angle of the two satellites to the sun changed periodicity from 0^{o} to 180^{o}, so the time duration that could get the proper angle only about 40 seconds within the orbit cycle of 98 minutes. So in this mission configuration, the TRL of CTE (Precision Formation Fly, orbit control of dual satellite, positioning technology, etc.) were high enough (above TRL7), and mission goal AD2 were middle (below AD2 of 4), but the efficiency of probing was not satisfied(Ambrosini, 2018, Fan et al., 2017).

✓ **Second Risk Synthesis of Mission Architecture and its TRL/AD2**

After getting the report of SSO dual satellite simulation, the scientist team proposed the second mission configuration about putting the two satellites around the Lagrange Point (L1). The Lagrange point L1 of sun and earth is a location between the two where the combined gravitational forces of sun and earth (as the figure 8-17). The equal centrifugal force felt by the satellites makes L1 the point of equilibrium where a spacecraft could "parked" with minimum orbiting fuel so that the two satellite can be formation fly there and maintain the distance of two(as the figure shows figure 8-18) and the pointing angle to the sun.

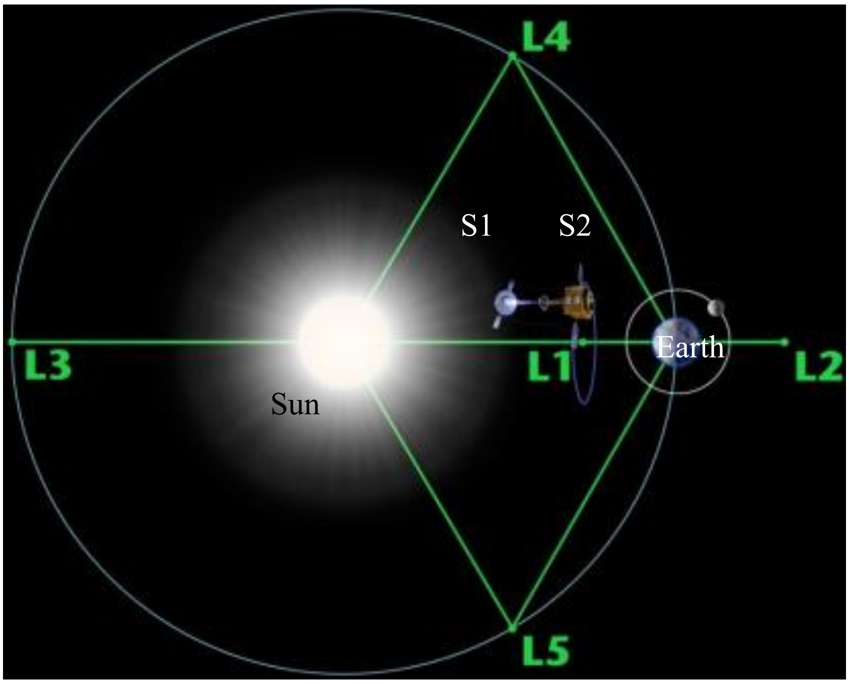

Figure 8-17: The Modulated Dual X-ray Satellite in Lagrange Point (L1)

The simulation showed that the angle and distance variation as the following. The angle was varied within 0.16 °, and the distance of the dual satellite was within the range of 39 meters and 42 meters.

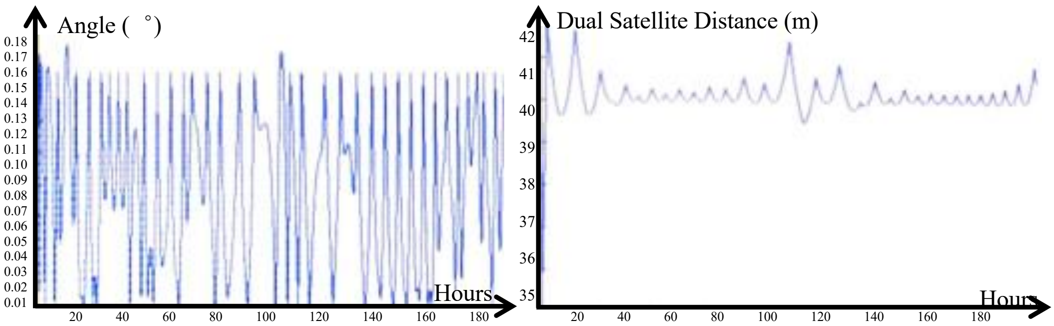

Figure 8-18: The Dual X-ray Satellite Distance and Angle in Lagrange Point (L1)

From the modelling and simulation, we got the proper pointing mechanism. But the CTE of this mission configuration shifted to the orbit transfer trajectory that the two satellites need travel 1.5 million kilometres from the earth LEO to Lagrange Point (L1) towards the sun. The TRL(AD2) for Orbit Insertion, Transfer Trajectory, Extra-Lang Distance Telemetry were TRL6 (4), TRL4 (6) and TRL 3(7) for China Space Industry, while internationally successful probes missions such as ISEE-3, LISA, SOHO, ACE, WIND, and DSCOVR(Jiang et al., 2018b). The AD2 of the CTEs were unplanned so beyond current capacity in China.

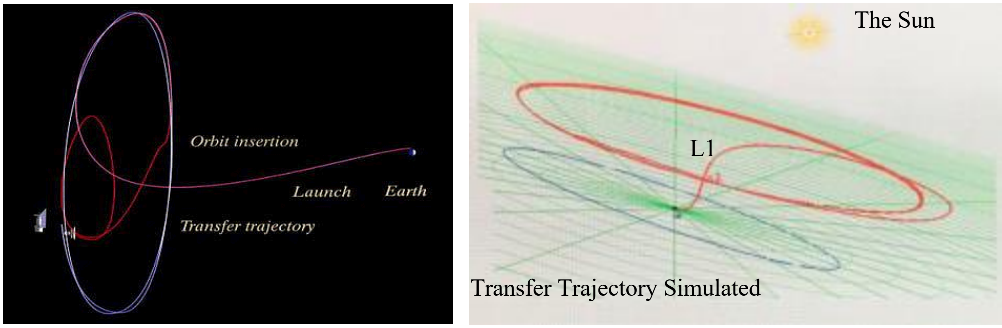

Figure 8-19: The CTE of Lagrange Orbit and Transfer Trajectory of Dual Satellite

- ✓ **Third Risk Synthesis of Mission Architecture and its TRL/AD2**

The third round of the synthesis came up with the satellite engineers who gave satellite architecture equipped with a long boom sticking the aperture shelter on its head. The boom should be at least 25 meters in length to fulfil the focal requirement. This configuration did not fuse with formation fly technologies, so the overall architecture was a shrink spacecraft and easy to choose the orbit. But the technology about the long boom related technics were brought forwards such as the folding and unfolding mechanical structure design and reliability, as while as the posture control of the satellite and the detector deployment technologies(JIANG et al., 2018a). Those CTEs need to assess the technology risk and act as the critical decision factors.

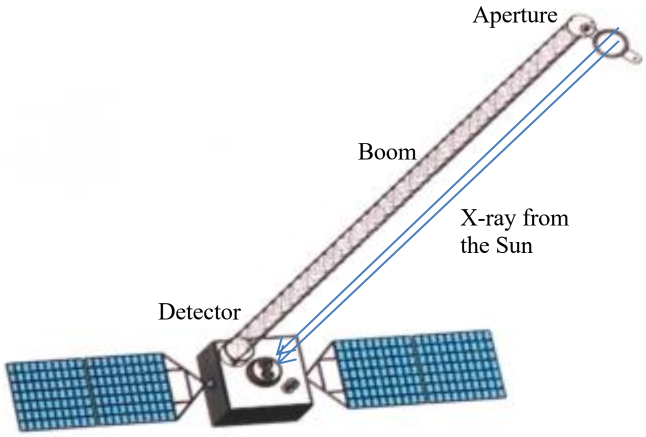

Figure 8-20: The CTEs of One Satellite with Boom Aperture

The TRL and AD2 of CTEs of the configuration three were assessed as the TRL level middle and AD2 middle. Most of the technologies have finished laboratory test or demonstration. As above three configurations, the last one would be the best choice.

As a conclusion of the MSA based insight of the mission technology risks, the different configuration of the sun X-ray probe showed how the expert team (scientists from National Observation team) and the simulation team (Mission Phase 0 modelling team) working together, how the scientific hypothesis were synthesised with the quantitative data and models to form a spiral insight, with the help of TRL and AD2 assessment. This case was performed with the interaction between the two teams and by the help of MSA software tool. So it has demonstrated the power of spiral insight of science problem.

8.5 SUMMARY

This chapter presents illustration cases for TRL/AD2 assessment, visualised decision-making supports, computational process, and the MSA approach example and questionnaires.

From the research point of view, the methods proposed should be validated or verified to show its capacity or performance. As this thesis is focused on engineering management with decision-makers' and researchers' experiences involved in, the most finding are not easily to validated or verified to be better than traditional methods. So this thesis is deployed case studies to demonstrate or to illustrate that the new methods are practical and more efficiency. All the cases are aimed to illustrate that the new assessment methods and integrated MSA approach is more efficient and more accurate.

As a conclusion of the case studies, the results obtained with these new methods, including the GA algorithm, etc., are complied with the best-synthesised experience achievements assigned by authoritative experts. AD2 diagrams are more intuitional and easy accessibility. Accuracy is enhanced by combining quantitative and qualitative methods to form a spiral MSA approach with assistance from the software platform. All the cases together have covered all the innovation of this research.

The following Table 8-6 summarises all the cases combined to cover all the innovation of this research.

Table 8-6: Summary of all the case studies to check the coverage of demonstration

Case Number	Case Contents	Purpose	Result
Case-1	optical mouse sensor technology	Different Technologies Result in Different AD2 within same TRL span	Shown the assessment was useful to reveal the different
Case-2	Ka-band Relaying Satellite Telecommunication	Efficient of new TRL assessment method	More efficient of the new method to reduce work payload from 2 weeks to 3.5 days
Case-3	Thrust Chamber of Hydrogen-oxygen Rocket Engine	Using new TRL attributes to demonstrate new method effectiveness and efficiency	With appendix B, the complete case shown the new method could focus on the key features to reveal the source of risks
Case-4	Parameter Selection Accuracy Analysis Experiment	Using GA to identify the weight factor during AD2 synthesis	The new method was demonstrated the usefulness
Case-5	AD2 Accuracy Analysis Experiment	Compare the traditional Bilbro AD2 method and the new calculated AD2 method	The new method was more accurate, avoiding experts subjectiveness
Case-6	Fabricating Membrane Thermopile Sensors	Visualisation of low TRL level assessment	Visualisations of the assessment information were useful to support decision-making
Case-7	Designing High-Velocity Thrust Chamber	Visualisation of middle TRL level assessment	
Case-8	Liquid Hydrogen/Oxygen Thrust Chamber	Visualisation of high TRL level assessment	
----	MSA Approach Questionnaire	To collect feedback about MSA and software tool to make sure new method is well accepted and useful	Recognition of MSA with TRL and AD2 is distinct and improved since its introduced to practice, and the software is useful as the user feedback
Case-9	X-Ray telescope satellite project Pre-Research risk synthesis	Technology Risk Assessment using MSA Spiral to gain insight of technology risk	Demonstrated the MSA Approach with TRL and AD2 enhanced is a powerful method to identify Technology Risks

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Chapter 9 Conclusion and Future Works

9.1 SUMMARY OF RESEARCH INNOVATION

It is necessary to introduce innovative technology when traditional technology fails to meet the developing requirements. There are some uncertainties during the process of technological development as a consequence the manager needs to master the developing technology process comprehensively, to guarantee the smooth proceeding of the project. The Next Generation Launch Vehicle project has a typical technology risk to tackle. In aiming to make a suitable and practical assessment of the technology maturity and decision-making support relevant to ensure project success, a set of effective methods for assessing TRL/AD2 and application procedure was researched and realised in the thesis.

The research initiated from the technology risk management requirements, while the research was to seek the nature of the technology risk. After introduced TRL based technology maturity management and merged to traditional Chinese System Engineering and Meta-Synthesis Approach, a refined qualitative TRL assessment method was proposed. A supporting software platform was developed. The PM office arranged a technology risk evaluation. At the end of first-round TRL assessment, problems raised reflecting the understanding of the method, including self-assessment got "FAKE" higher TRL scales, lack consistency which means TRL scales varies team to team for same CTE, and third-party assessment has low consistency. Also, the assessment result cannot be future validated for lacking primary assessment evidence. Meanwhile, quantitative AD2 results was needed to assist the R&D process, to know how much effort is adequate to advance lower TRL. The research of quantitative AD2 assessment and unified assessment information management software were bringing forwards. Then the second round of technology assessment achieved an acceptable consistency of TRL and AD2 assessment. An invention patent of attribute-based assessment method of TRL was approved, some journal papers were published. The PhD thesis then formed to seek the nature law of technology risk, build a mathematic model of assessment information and integrate the methods to a MSA spiral process with a supporting software platform.

The TRL is considered as the foundation of AD2, the concepts related to TRL and AD2 were analysed in the thesis, an assessment unified evidence chain was constructed to support the insight of technology risk via TRL/AD2 assessment. The findings were summarised as follows:

(1) Maturity attributes based TRL assessment method.

Mainly aimed at the detailed assessment features of TRL, the traditional TRL based technology maturity evaluation method makes a checklist judgment of "YES-NO" on the current state of technology. An improved maturity attributes based technology maturity evaluation method established in the thesis, keeping the state information of technology on each evaluation rule, digitized the state value into the numerical value between the interval of [0,1], expanded and constructed the supporting information chain of equivalence relation between technology maturity and assessment evidence, thereby improving the integrity of technology maturity evaluation.

(2) Unified evidence chain based AD2 computing method.

The specific numerical information of certain key technology developing from the current maturity state to the target maturity state was given by the AD2 evaluation evidence chain; then the integrating formula was established to calculate the AD2 value via technology maturity information. Integrating formula included two type important parameters: weight values during assessment feature integration and state density function parameters, the former were optimised and selected by a genetic algorithm, and the later was inferred based on the fundamental property of AD2 by the expert group.

(3) Qualitative-quantitative comprehensive integration method using the MSA approach.

A method based on Meta-Synthesis System Approach was adapted to combine the quantitative calculation by a computer tool (Machine) and the qualitative judgment by an expert group (Human). Besides, several iterations of Man-Machine interaction were proposed to improve the accuracy of the evaluation of difficulty.

(4) Technology maturity and difficulty visualisation method to assist in decision-making.

Two-dimension diagram of technology assessment and maturity difficulty evaluation was established to support the decision-making process. Y-axis is the assessment feature of technology maturity, and its X-axis is the corresponding technology related current state value and target state value of evaluation rule characteristic. State distribution diagram of technology maturity includes the background information relevant to the maturity state density function, which is to show the difficulty density of technology state change. Thereby, some decisions and suggestions according to state distribution diagram were proposed.

(5) Technology maturity information management software development and utilisation.

The assessment method could be assisted by a computer software tool and be given the detailed information management ability. The essential function of the software is to assist the risk management in data handling and process assistance. The user of the software includes the PM Officer, research engineer, project quality manager, technology assessors and all other related staffs. The whole content of the software should include a set of management standards, a series of methods or tools, and an information management system. The software tool has the facilities of report documentation generation, which could generate different reports for managers, engineers and costumes automatically. The questionnaire shows the usefulness of the software.

9.2 THE CONCLUSION OF CONTRIBUTIONS TO KNOWLEDGE

The key finding of this research among the technology evaluation experiments in the New Generation Launch Vehicle project (NGLV) was taken as a PhD research subject to seek the nature of the technology risk. Several illustrative case studies and questionnaires were carried out to evaluate the research outputs. The innovation achievements and contributions to knowledge were concluded as follows:

(1) Essential characteristics of TRL and AD2 were studied and analysed, a mathematical form of technology maturity information was defined. Then a detailed analysis was made of the fundamental property of AD2. For the purpose of technology assessment, the **equivalence evidence chain** was formalised as the mathematic model by “necessary” and “sufficient” efforts of promoting technology maturity from the current level to the target level.

(2) A new AD2 **computational method** was presented. An evaluation evidence chain gained by the improved technology maturity evaluation method was applied as the input information to establish the **mathematical integral formula** used to calculate the AD2. Weight value integrated by assessment features in the integrating formula was optimised and selected by a genetic algorithm, and the state density parameter in integrating formula was inferred via the analysis on the basic property of AD2, thus giving the algorithm expression of a complete integral calculation process.

(3) An improved TRL based technology maturity evaluation method was presented. The maturity attributes based TRL evaluation method was introduced, a digitalized processing was made for the traditional evaluation result of “YES-NO” regarding the evaluation rule characteristic of technology maturity, the corresponding state value of technology to be evaluated on the evaluation rule characteristic was kept, so as to offer effective data for the **MSA based quantitative and qualitative assessment methods** of AD2, and

well-integrated to the Risk Management of System Engineering. MSA approach was supported by a dedicated software platform with the assessment process, information management and visualisation decision-making tools.

To sum up, the research presented in this thesis is the first piece of work to integrate the TRL and AD2 considering both western system engineering best practices and oriental system philosophy. By integrating a qualitative and quantitative spiral insight MSA approach, the work will help to achieve the success of complex system development project.

9.3 RESEARCH LIMITATIONS

This research was initiated from the requirements of a critical technical project to identify and control the technology risk, but the thesis concluded the research far beyond the requirements from the project office to seek the nature of technology risk. The research limitations or boundaries are:

- ✓ **Decomposability of WBS Structure:**

The methods of four maturity attributes based TRL assessment and numerical integration based quantitative AD2 assessment is rooted from the complexity of technology development, so the methods are all based on the modern project management theory, the assumption that system could be decomposed to inter-connected sub-systems, and each sub-system also could decompose to “sub-” “sub-” systems, until to a basic R&D or manufacturing tasks. The critical technology under assessment is derived from the decomposition WBS structure. So the TRL/AD2 assessment method should be adequate for regular complex project with a sufficient top-down decomposition WBS presentation, but may not suitable for systems with the non-structure or self-adaptive, self-organised behaviour, etc.

- ✓ **All Efforts to Advance Maturity could Form a Simple Set:**

The quantitative AD2 assessment method mainly focuses on the technologies which efforts to advance its maturity could be described as a simple set (or after de-coupling) with the elements of all the efforts, that is to say, all the efforts of developing the CTE are distinct, not overlap and exclusive. One can break down its coupling relations among the CTE efforts, and using cost or such cardinal value to map the elements of the set to build numerical integration formula. So if only the WBS of the project can be mapped to a simple set with the mapping of the elements to a cardinal/interval value range, the numerical integration of AD2 would be applicable.

- ✓ **Method and Software were Derived and Integrated to Chinese System**

Engineering:

The assessment and management process was merged the western TRL/AD2 based best practice and oriental system engineering philosophy, as a consequence, the new method was integrated to Chinese System Engineering, and the software and tools were kept abreast of the IT upgrading to the Project Support Environment. While the process and tools are not limited to the oriental engineering, it surely could act as a reference for other countries, but the tools is Chinese language in its user interface.

- ✓ **MSA could Gain Insight but cannot Guarantee New Technologies Breakthroughs:**

The MSA approach could get an insight into new technologies gradually and show the trends of them, with the help from the qualitative hypothesis to quantitative validation, taking both advantages of expert experiences and computational capacity. By this approach, the insight of technology risk could be spirally revealed. However, the insight of the risk cannot take over the R&D research and other technology domain efforts, for which are the irreplaceable embodiment of the technology breakthroughs. Also, no one can guarantee to reach a high peak of technology innovation or when dawn of victory will come.

9.4 PROSPECT OF FUTURE WORKS

(1) Technology maturity state value

The corresponding state value of specific key technologies on each assessment feature is the foundation of the visualisation and calculation process of AD2 and its accuracy directly influences the accuracy of the computing result of technology maturity difficulty. There is a particular gap between the assessment feature of the current technology maturity state value and the demand of a large complex project, so it is necessary to improve the assessment feature of technology maturity state value regarding the detailed conditions of crucial technology in the project, so as to improve its accuracy.

(2) The weight value of technology maturity assessment feature integration

The weight value of technology maturity assessment feature is an essential parameter of the integrating formula used to calculate technology maturity difficulty, compared with the weight value gained from traditional single expert experience, weight value optimized and selected by the genetic algorithm can be more objective, so as to improve the accuracy of weight value. There also exists a problem on how to optimise the process to improve the efficiency of comprehensive integration as to that combining the experience of the expert group mentioned in the thesis.

(3) Parameter estimation on technology maturity state density function

Technology maturity state density is used to express the difficulty degree of technology state change during maturity development, and it exerts a significant role in the process of integration. The selection range of parameters in state density function was determined based on the property of technology maturity difficulty, but it failed to gain the value of the parameter directly, so further confirmation for parameters in the state density function is required in order to make the determination process of parameters more objective and accurate.

(4) Establishment of a knowledge base system supporting key projects

Technology maturity is significant for system success; by gradually accumulating the information extracted from data formed during project implementation and converging knowledge by information, a knowledge base system should be formed. Meanwhile, the utilisation of knowledge was improved by applying such new techniques as artificial intelligence (AI) and big data to gradually build an integrated intelligent system with Man-Machine integration (MSA) and Human-Internet integration featured by project decision-making wisdom.

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Appendix A PAPERS AND PATENTS DURING PHD STUDY

A.1 PAPERS

[1] Computation of Advancement Degree of Difficulty Based on Genetic Algorithm[J]. Transaction of Beijing Institute of Technology, 2011, Volume 31, Issue 4 : 472-476

[2] A Computing Method of Advancement Degree of Difficulty Based on Numerical Integration [C]. 2011 3rd International Conference Machine Learning and Computing, Singapore, 2011 (V1): 457-460, IEEE Press

[3] The Application of Visualisation Technology in Advancement Degree of Difficulty Computing Process [C]. 2011 International Conference on Information Systems and Computational Intelligence, Harbin, China, 18-20 Jan 2011(V2): 115–118, IEEE Press

[4] A Visualization Method of Technology Maturity Based on Fuzzy Theory[J]. Future and Development, 2011, Volume 34, Issue 8: 35-38

[5] A R&D Risk Management Method of Weapon Based on Advancement Degree of Difficulty [J]. Aerospace Control 2011, Volume 29, Issue 5: 77-81

[6] Software Risk Analyse based on software technology Readiness Level[C]. Chinese Society of Astronautics 2011, Guiyang, China, 2011: 176-180

[7] Principle Research and Assessment Experiments of Complex Aerospace Software System Risk [C]. 2013 Conference of Software System Expert Group, Wuhan, China

[8] Mechanism Study and Evaluation of Aerospace Software System Risk [J], Digital Military Industry, 2014 Volume 4:48-53

[9] Practice and Suggestion of High School Student Satellite for Science Education Purpose: Take the Bayi-Youth Satellite as an Case Study[C], First Technology Forum on Student Micro/Nano-Satellite, Harbin Institute of Technology, Harbin，China，2017:Part 4

[10] Research and Suggestions on Project Management of Educational Satellite for Middle School[J], Aerospace China, 2018, Volume 1:46-50

A.2 PATENT OF INVENTION

A New Technology Readiness Level Assessment Method Based on Maturity Attributes，ID：CN102890753A，Date：2013.01.23，Inventor (3rd)

A.3 SOFTWARE COPYRIGHT

2012SR132812 Technology Maturity Information Management System V1.0
Register accepted: 24 Dec 2012

2012SR132769 Software Independent Evaluation Information management system V1.0
Register accepted: 24 Dec 2012

Note:

Due to the main work responsibility change of the author, no new papers closely related to technical maturity was published from 2014 to the year PhD thesis submitted (2017), while the methods proposed and the software tools developed were continually used. Newly questionnaire about the methods and tools in 2016 case study was collected and briefly reviewed in chapter 8.

A conference presentation was given on January 2017. Also, a co-authored paper about the educational satellite project including was discussed and presented in Aerospace China Journal , Space System and Technology session, January 2018.

Appendix B EVALUATION CASE OF HYDROGEN/OXYGEN ENGINE FOR NGLV

B.1 CASE STUDY BRIEF DESCRIPTION

This case study takes the first hydrogen-oxygen rocket engine developed by China Aerospace Science and Technology Corporation for New Generation Launch Vehicles Programme (NGLV), the case adopts the assessment method with proven technique and equivalent evidence to establish the evidence chain of “mature technique of hydrogen-oxygen rocket engine” from the elementary to the advanced development processes, i.e. from the discovery of fundamental principles, proposition and simulation of application assumption, technical pre-research, principle prototype test and project presentation to the final successful application in flight missions. This plays a specific demonstration and illustration role for establishing complete scenes of difficulty degree of proven technique and understanding and mastering the evaluation method for evidence method.

For the evaluation case of technology maturity for the engine, it first needs to conduct the WBS decomposition and CTE identification for the whole application system (NGLV) and then select the representative CTE - liquid hydrogen and oxygen thrust chamber (thrust chamber for short) for evaluation of technology maturity, including the development of assessment features of TRL 1 ~ TRL 9 levels as well as collection and confirmation of assessment evidences. The assessment is basically conducted according to the actual practical situation of the engine; small adjustments are made as well. For example, the requirements for performance indicators are gradually elaborated in actual projects; moderate supplements for early performance are also made in the case. Also, for the particular case of temporary changes due to actual development, the local “ideal” adjustment of correct order is made. As the development cost of the engine is classified to business sensitive, digital results of corresponding final costs are deleted during the difficulty assessment. However, the application demonstration of methods is complete, which does not influence the value of the case.

B.2 SYSTEM OVERVIEW

The chapter mainly introduces the summary of system to be assessed (pump-fed liquid oxygen and hydrogen rocket engine), including the system name identification, developing institution, development target, mission requirement background, main functions (including main components, main functions and operating principles), main performance (including various technical indicators generally required, such as the performance parameters and structure parameters) and operating environment.

Table B-1 System Overview

System Name	Pump-fed liquid oxygen and hydrogen (Lox/LH2) rocket engine
Developing Institution	China Aerospace Science and Technology Corporation
Development Target	To develop the Stage 3 main engine for NGLV, with the code of YF-73.
Mission Requirement Background	To launch a geostationary satellite with the mass being greater than 1,000 kg, the specific impulse of the engine for launch vehicle with conventional chemical propellant used is relatively low, and the mass of such satellite shall be no more than 900 kg. Therefore, its launching capability cannot meet the requirement of launch mission for a geostationary fixed-point communications satellite. As the specific impulse of the hydrogen-oxygen engine is high (about 30% higher than that of the conventional chemical propellant engine), it can greatly increase the payload of the vehicle and reduce its take-off weight, being the optimised power plan for the launch vehicle.
System Functions	The pump-fed liquid oxygen and hydrogen rocket engine YF-73 is a power system composed of thrust chamber, turbo pump, fuel-gas generator, various types of valves and adjusters, racks and pipelines. The main function of the YF-73 engine is to provide power for the launch vehicle as the main engine of the third stage for NGLV launch vehicle. Operating principles of the system: supply the liquid hydrogen and oxygen to the hydrogen and oxygen pumps through the liquid-hydrogen and -oxygen storage tanks of the launch vehicle, and then send such liquid hydrogen and oxygen, after being pressurised, to the thrust chamber through pumps for combustion with the fuel-gas generator. The combustion products in the thrust chamber will erupt from the Laval nozzle at the end and produce thrust. The fuel gas of relatively-low temperature produced by the fuel-gas generator will be used to drive the turbine of turbopump. The turbine is the power to drive the liquid hydrogen and oxygen pumps. The fuel gas with work applied by the turbine, when discharging from the turbine, will also produce certain thrust, which is however of small flow, low specific impulse and low thrust. Moreover, valves, orifice plates and venturi tube are equipped with for liquid hydrogen and oxygen pipelines in the front of pumps, thrust chambers and fuel-gas generators to control the operating procedures and performance of the engine. In front of the fuel-gas generator, a stabilizer is also equipped with to adjust the thrust of the engine. Valves controlling low-temperature liquid are controlled by separate electric-air valves. Therefore, the engine is also equipped with components such as high-pressure helium tank, decompressor and cables for controlling the electric-air valves. Moreover, the control system in the launch vehicle will conduct the procedure control for the operation of the engine. Fig.: Schematic Diagram of Principle for Pump-fed Liquid Oxygen and Hydrogen Rocket Engine
System Performance	Vacuum thrust: 44.43 KN; Vacuum specific impulse: 4119 N•S/Kg; Total flow of propellant: 10.786 Kg/S; Mass mixing ratio of propellant: 5.0; Standard conditions of pump inlet: pressure of hydrogen-pump inlet: 0.245 MPa;

	medium temperature of hydrogen-pump inlet: 20 K; pressure of oxygen-pump inlet: 0.294 MPa; medium temperature of oxygen-pump inlet: 90 K; Mass of engine: 245 Kg; Overall dimensions of engine (height × diameter): 1,438 mm × 2,220 mm; Operating time of engine: 480 s (the first operation), 200 s (slide) and 270 s (the second operation); At the time of acceptance, the engine operates for two times: 800 s for the first operation and 600 s for the second operation. No interval time is required then (generally for several hours).
Operating Environment	The operating environment of the YF-73 engine is the space environment of NGLV flight. With the non-aspirating feature of YF-73, the operating condition will not be influenced by the atmospheric pressure, which has little influence on the engine performance. The YF-73 engine will turn on twice in the air, sliding in between; thus the secondary ignition starting is required under the vacuum condition.

B.3 SYSTEM WORK BREAKDOWN STRUCTURE

This chapter mainly describes the Work Breakdown Structure (WBS) of launch Vehicle. The system WBS takes hydrogen-oxygen engine as the main part, and gives the detailed WBS of the engine; all the other part just gives the brief decomposition. The WBS decomposition includes two sorts of elements; one is the parts or techniques of the product, another is the task or methods, such as general design, test, etc.

Table B-2 System WBS

Decomposition Level	Decomposition Result
1	rocket body structure
2	Control System
3	Stage One propulsion system
4	Stage Two propulsion system
5	Stage Three propulsion system
5.1	Stage Three Main Engine (YF-73)
5.1.1	thrust chamber
5.1.1.1	thrust chamber Heading
5.1.1.1.1	Inspirator and its structure
5.1.1.1.2	Mental multi-hole orifice(baseboard)
5.1.1.2	thrust chamber body
5.1.2	Turbopump
5.1.2.1	Liquid Hydrogen Turbopump
5.1.2.2	Liquid Oxygen Turbopump
5.1.2.3	gas turbine
5.1.2.4	reduction gearbox
5.1.2.5	Turbopump assembly
5.1.2.5.1	ultralow temperature super-speed bearing
5.1.2.5.2	low-temperature dynamic seal
5.1.2.5.3	Hydrogen Oxygen Turbopump Body thermal isolation technology
5.1.2.5.4	High-Speed flexible shaft dynamic stabilization
5.1.2.5.5	Cryogenic high-speed gear surface lubrication technology

5.1.2.5.6	Turbine pump assembly and the nuclear leak detection technology
5.1.3	Gas generator
5.1.3.1	The Gas generator-head part
5.1.3.2	The Gas generator-body part
5.1.4	Self-active device
5.1.4.1	Liquid hydrogen pump valve (front)
5.1.4.2	the liquid oxygen pump valve (front)
5.1.4.3	Liquid hydrogen main valve
5.1.4.4	Liquid oxygen main valve
5.1.4.5	Liquid hydrogen secondary system control valve
5.1.4.6	Liquid oxygen secondary system control valve
5.1.4.7	Liquid oxygen regulator valve
5.1.4.8	Liquid hydrogen precooling releasing valve
5.1.4.9	Liquid oxygen precooling releasing valve
5.1.4.10	Helium pressure reducing valve
5.1.4.11	Electric air valve
5.1.5	The overall structure of rocket
5.1.5.1	Engine frame
5.1.5.2	Engine duct
5.1.5.3	Starting gas cylinder
5.1.5.4	Thrust chamber gunpowder igniter
5.1.5.5	Liquid oxygen evaporator
5.1.5.6	Liquid hydrogen heater
5.1.5.7	Low-temperature adiabatic engine scheme research
5.1.6	Engine system integration
5.1.6.1	Engine system placement research and determination
5.1.6.2	Engine performance tuning
5.1.6.3	Engine working process research and determination
5.1.6.4	Engine test plan formulation
5.1.6.4.1	The sea level commissioning plan formulation
5.1.6.4.2	Vacuum conditions for commissioning plan formulation
5.1.6.4.3	Nozzle test with the scheme in full flow rate
5.1.6.5	Cryogenic engine blow out precooling scheme research and determination
5.1.7	Material and craft
5.1.7.1	Metal porous permeability panel development
5.1.7.2	high strength stainless steel development under Liquid hydrogen temperature
5.1.7.3	High-performance foam thermal insulation materials and process research
5.1.8	Liquid hydrogen production and application
5.1.8.1	industrial production of liquid hydrogen
5.1.8.2	Liquid hydrogen storage and transportation
5.1.8.2.1	High pressure and low pressure developed adiabatic container
5.1.8.2.2	Liquid hydrogen highway transport vehicle
5.1.8.2.3	Liquid hydrogen railway truck
5.1.8.3	Liquid hydrogen equipment sealing technology
5.1.8.4	Liquid hydrogen equipment leak detection technology
5.1.8.5	research and development of safety standard of Liquid hydrogen usage
5.1.9	Test platform construction
5.1.9.1	Component test platform construction at low temperature
5.1.9.1.1	Cryogenic valve test bench
5.1.9.1.2	Thrust chamber extrusion testbed

5.1.9.1.3	Vacuum ignition test platform
5.1.9.1.4	Gas generator squeezing test-bed
5.1.9.2	Engine test bed
5.1.9.2.1	Engine test bed (ground) sea level conditions
5.1.9.2.2	Simulated altitude full flow aero-engine test
5.1.9.2.3	The engine vacuum ignition testbed
5.2	The third stage of propellant storage tank pressurisation and discharge system
……	……
5.3	The propellant management system
……	……
6	Outer measuring and safety system
……	……
7	Telemetry system
……	……
8	Propellant utilisation system
……	……

B.4 IDENTIFICATION OF CRITICAL TECHNOLOGY ELEMENTS (CTES)

✓ **CTEs Primary Selection**

Identification principles (or reasons for eligible) Critical Technology Elements (CTEs):

A. Does this technology have important impacts on system operation demands (functions and performances) and cost or progress?

B. Is this technology able to cause main development or demonstration risks?

B.1. Is this technology new or novel?

B.2. Is this technology the application of a modified technology which has been successfully applied before (is it the technology required to be improved)?

B.3. Is this technology applied to the corresponding new environment after repackaging?

B.4. Does the expected operating environment of this technology or the performance to which it has been up to goes beyond the initial expected design or demonstration capability of it?

Only when a certain technology meets principles A (great significance) and B (high risks; among which, principles from B1 to B4 provide several occasions which may give rise to high risks) simultaneously, it can be deemed as the critical technology.

Granularity (that is the level of CTE at WBS) of CTE is related to evaluation purposes, and it is usually determined by specialists. In principle, CTE should appear at the bottom level of WBS.

✓ CTE Checklist

According to identification principles of CTEs, and combining current technical state, a bottom-up method is adapted to perform general surveys for WBS tree structure. For items which can be identified as CTE, functions, current technical maturity state, critical technology problems required to be solved, operation environment and reasons for being selected in the system are described separately for every CTE so as to form a preliminary selection checklist of CTEs (Note: some CTEs are ignored). For details, please refer to the table below.

Table B-3. Preliminary Selection Checklist for CTEs of System

CTE ID.	WBS No.	CTE Name	CTE Description	Reasons for Selection	
				Reason ID	Descriptions
1	5.1.1	Thrust Chamber	A thrust chamber is constituted by the top part (inspiratory and constructions; porous metal panel) and the body to complete propellant energy conversion and the function of propellant generation primarily; it is one of the core components of a turbopump-fed liquid hydrogen-oxygen engine. At present, thrust chamber development technology maturity is low; especially for a new propellant which has never been applied, it is not allowed to turn into the engineering development phase directly. Main development work of a thrust chamber includes development of inspirator; head construction development for inspirator; heat transfer structure development for the body; as well as the development of sprayer nozzle modelling and structure. Among them, the inspirator should not only be ensured to achieve high energy exchange efficiency, but the stability of combustion; or, measures can be taken to solve potential combustion instability problems. Concerning the head construction, the inspirator should be settled rationally, the propellant trend, as well as the structural static and thermal strengths, need	A	**Great Significance** A thrust chamber mainly aims to complete propellant energy conversion and the function of propellant generation. As one of the core components for the implementation of a turbopump-fed liquid hydrogen-oxygen engine with a high specific impulse, it has a direct influence on the performance of the engine. Meanwhile, for other relevant components, they are gradually integrated and tested by centring on this thrust chamber; therefore, the thrust chamber has a substantial impact on the development progress of engine. In a word, the thrust chamber can greatly influence both functions and performances of an engine together with the cost and duration of the project.
				B4	**High Risks** When a new propellant combination is adopted, data of other propellants cannot be fully utilised; consequently, the related explorations must be carried out again, and undiscovered new problems may arise and require to be solved. For example, kerosene as refrigerant brings a gumming problem, while liquid hydrogen, hydrogen peroxide and

			to be well solved. Regarding the body part design, heat transfer and thermal structure problems are solved. For sprayer nozzle modelling, ejection efficiency problems of airflows should also be solved to improve the specific impulse.		materials bring problems of structure thermal stress, pyrolysis and catalyst decomposition, etc. respectively, which are figured out during pre-researches. As a result, pre-researches must be performed to fully grasp the property of such propellants and obtain various fundamental data required by designs; then, product development can begin. This process is usually lengthy, and it is difficult to make a determinacy plan for inevitably successful outcomes.
2	5.1.2.1	Liquid Hydrogen Pump	Turbopump of the YF-73 engine is composed of hydrogen pump, gas turbine, reduction gearbox and oxygen pump. The liquid hydrogen pump and the gas turbine are co-axial; there is a small transmission gear on the middle part of this axle, and it fits with a big gear wheel through the intermediate gear to form a reduction gearbox; furthermore, the big gear wheel is co-axial with oxygen pump to drive the pump to rotate at a low speed. The main function of it is to elevate low-pressure liquid hydrogen and	A	**Great Significance** A turbopump mainly completes the function of elevating the low-pressure liquid hydrogen-oxygen provided to the engine by the rocket to the high pressure required by the thrust chamber. As one of the core components of the engine, it has a direct influence on its performances. As a result, the turbopump has significant impacts on both the function and the performance of an engine as well as the cost and duration of the project.

			oxygen which are provided by rocket to a high pressure demanded by the thrust chamber. Therefore, the turbopump is one of the core components of turbopump-fed liquid hydrogen-oxygen rocket engine. Both liquid hydrogen pump and oxygen pump are centrifugal pumps which are ancient hydraulic machinery. In principle, the technology is mature, so is that of liquid oxygen pump. However, the liquid hydrogen pump is rather special in three problems. First, low specific gravity (0.07kg/L) of liquid hydrogen leads to two issues about the obtainment of required pressure rise and a series of other problems that are caused by high speed running that is needed by pressure rise, such as dynamic stability of high-speed shaft as well as the development of high-speed bearing (with a high DN value). The second is the problem of low temperature; due to boiling points of liquid oxygen -183℃ (or 90K)) and liquid hydrogen -283℃ (or 20K)), any non-metallic material including lubricants cannot be used so as to avoid pump oxygen corrosion caused by propellant oxidation, which can interfere the normal running of them and give rise to heat insulation and precooling. Third, hydrogen molecules are very small and can be leaked easily; it is unsafe for them to stay in the air; however, the static seal problem is difficult to be solved. Hence, research in advance should be performed.	B4	**High Risks** Although hydro-centrifugal pump and turbopump technologies are both rather mature, due to changes in the medium, liquid hydrogen is substantially different from water regarding their physical properties. Hence, impacts which are generated by such changes should be studied deeply and found out the corresponding solutions. If such work is left uncompleted, the rocket engine that adopts liquid hydrogen-oxygen propellant cannot be applied in engineering development models. Consequently, the relevant technical risks are very high.
……	……	……	……	…	……

✓ **Technologies which not be identified as CTEs and the reason**

To some technologies that were not identified as CTEs (some of them were elided in the following list), gives the main reason that the technologies were matured enough for the project. The following list gives a collection:

Table B-4 Reasons for the technologies were not CTEs

WBS No.	WBS Name	Reason for Matured Enough
5.1.2.2	Liquid oxygen pump	Have already had other rocket engine using liquid oxygen pump, YF - 73 liquid oxygen pump with liquid hydrogen pump belongs to a turbine pump, its technology has already been covered at low temperature.
5.1.2.3	Gas turbine	Have already had the successful experience of other rocket engine gas turbine, the technology is mature.
5.1.2.4	Reduction gearbox	Have already had the successful experience of other rocket engine reduction gearbox, the technology is mature.
……	……	……
5.1.3	Gas generator	At that time all rocket engine in our country as the gas generator re-cycle system, YF - 73 can also be based on the experience of the hydrogen and oxygen thrust chamber pre-research
5.1.4	Self-active device	Have already had the successful experience of another rocket engine automatic machine design.
5.1.5	The overall structure of Rocket	Have already had the successful experience of another rocket engine overall structure design.
5.1.6	Engine system integration	Have already had the successful experience of other rocket engine system integration
5.1.7	Material and craft	In the pre-research of thrust chamber and turbine pump has been covered.
……	……	……
5.1.9	Test platform construction	Have already had other rocket engine test platform construction and use of experience
……	……	……

✓ **CTEs final filtrate**

After the WBS and preliminary selection of CTEs, the experts group which designated by the project office will give the final filtrate based on the documents of the WBS and CTEs.

B.5 THRUST CHAMBER ASSESSMENT

B.5.0 DESCRIPTION OF OPERATING ENVIRONMENT OF THRUST CHAMBER

The operating environment of thrust chamber of turbopump-fed liquid oxy-hydrogen is the flight space environment of the rocket. On the one hand, the non-aspirating feature of the liquid oxy-hydrogen engine chamber protects the operating environment from the atmospheric pressure, which ensures that the engine performance suffers little influence of atmospheric pressure. On the other hand, as the engine will be started for two times in the air with sliding, the second ignition to start up is required in the out-space vacuum.

Thus space environment stimulation of oxy-hydrogen engine chamber is simple and may be realised in the altitude simulation test with such main contents as ground nozzle overflow test and vacuum ignition test. The oxy-hydrogen engine ground testbed can achieve the environment required by TRL 5 and the ground testbed together with the altitude simulator test bed (ground nozzle overflow test and vacuum ignition test) can achieve the environment required by TRL 6. The engine chamber with sufficient tests and qualified altitude simulator test can be applied in various ground and flight tests of rocket directly.

B.5.1 Thrust Chamber TRL 1 Assessment features and Evidence

Table B-5 Thrust Chamber TRL 1 Assessment features and Evidence

TRL 1: Basic principles observed and reported				
Assessment Attributes	**Assessment Criteria**	**Assessment feature of CTE**	**Assessment Evidence from research institute**	
			Supporting information on assessment feature	**Conformity**
Integration level of technology entity and system	-	-	-	-
Fidelity of final product relative to technology entity	Fundamenta ls	Discovery of and reports on fundamentals of thrust chamber	(see Note1)	Such evidence as test report and Apollo project report.
Fidelity of demo environment relative to operating environment	-	-	-	-
Conformity of demo performance to expected performance	-	-	-	-

Note1:

The England chemist Henry Cavendish, France chemist Laurent Lavoisier et al. had found the phenomenon earlier in the 1700s that pure hydrogen, as fuel, will react with pure oxygen to produce vapour. Sweden engineer Laval found the fundamentals of "flow velocity amplifier" and invented Laval Nozzle in the 1880s.

If the hydrogen and oxygen are mixed at a certain flow, the combustion may produce high-temperature vapour and redundant hydrogen or oxygen (subject to the mass ratio of them; if the mass ratio of flow rate is 1/8, the combustion is complete combustion). The combustion gas is exhausted in the form of supersonic flow after treatment of Laval Nozzle and generates thrust.

In the 1960s, America attached great attention to the research and development of high thrust hydrogen-oxygen rocket engine. Adopting such high thrust hydrogen-oxygen rocket engines for the two-stage and three-stage rockets, the "Saturn v", with a takeoff weight of only 1,950ton, and a simple structure, advanced performance and reliable performance, has made manned lunar-landing for six times successfully.

B.5.2 Thrust Chamber TRL 2 Assessment features and Evidence

Table B-6 Thrust Chamber TRL 2 Assessment features and Evidence

TRL 2: Technology concept and/or application formulated				
Assessment Attributes	**Assessment Criteria**	**Assessment feature of CTE**	**Assessment Evidence from research institute**	
			Supporting information on assessment feature	**Conformity**
Integration level of technology entity and system	-	-	-	-
Fidelity of final product relative to technology entity	Technological concept and application assumption	(see Note2)	(see Note3)	Paper and theories calculation model.
Fidelity of demo environment relative to operating environment	-	-	-	-
Conformity of demo performance to expected performance	-	-	-	-

Note 2:

Chinese aerospace research institute has put forward the idea of R&D of a liquid hydrogen propellant rocket engine with a high specific impulse (liquid hydrogen-oxygen thrust chamber is the major part of such engine) and conducted initial estimate to the performance *achieved by the liquid hydrogen-oxygen thrust chamber.*

Note 3:

Under the background of R&D of the hydrogen-oxygen engine and its successful application in America and based on the advanced performance (high specific impulse) of the hydrogen-oxygen engine, a low takeoff weight of rocket and other features, Chinese aerospace research unit put forward the assumption of R&D of high thrust hydrogen-oxygen engine.

The initial estimate has been conducted to the possible performance of liquid hydrogen-oxygen thrust chamber. The estimated specific impulse will reach about 4000n·s/kg with an increase of about 30% compared to the rocket engine using general chemical propellants. Besides, the carrying capacity of the rocket will meet the launching requirements of the 1,000kg synchronous fixed-point satellite.

B.5.3 Thrust Chamber TRL 3 Assessment features and Evidence

Table B-7 Thrust Chamber TRL 3 Assessment features and Evidence

TRL 3：Analytical and experimental critical function and/or characteristic proof-of-concept				
Assessment Attributes	**Assessment Criteria**	**Assessment feature of CTE**	**Assessment Evidence from research institute**	
			Supporting information on assessment feature	**Conformity**
Integration level of technology entity and system	Technology Itself	Thrust chamber components using gas hydrogen and oxygen	Thrust chamber	-
Fidelity of final product relative to technology entity	Mathematical model and/or test facilities for proof of concept	Aerothermodynamic calculation of rocket engine. The building of simple thrust chamber tester.	(see Note4)	Mathematical model, simulation tools, lab equipment for proof of concept (water cooling)
Fidelity of demo environment relative to operating environment	Virtual and/or laboratory environment	Ground environment	Ground oxy-hydrogen thrust chamber test bed. Thrust=200kg	Qualified
Conformity of demo performance to expected performance	Demo performance conforms to expected performance.	Performance level which will be achieved in the future and was obtained from the aerothermo-dynamic	Design performance: Specific impulse≥4000n·s/kg; Combustion efficiency ≥0.98. Demo performance: Specific impulse=3800n·s/kg; Combustion efficiency =0.98. As the specific impulse depends on the design (such as shape of	Ground demo test equipment; test report.

		calculation. Design performance meets the expected performance while the demo performance conforms to the design performance.	nozzle), it can be deemed that the demo performance conforms to the design performance and the design performance meets the professionals' expected performance if the preliminary test achieves a specific impulse of 3800n·s/kg, the demo result is close to the expected value which is 4000n·s/kg.	

Note 4:
The oxy-hydrogen mass ratio analysis and calculation model for high specific impulse are built based on the classic aerothermodynamic calculation theory of rocket engine. The optimised calculation shows that the oxy-hydrogen mixture with a mass ratio of 5/1 may produce the highest thrust (i.e. The highest specific impulse) with the major components of the combustion gas is high-temperature vapour and certain hydrogen. The calculation and analysis show that the specific impulse of the oxy-hydrogen engine will reach 4000n·s/kg which is 30% higher than the general rocket engine and is with obvious advantages.
The tester of oxy-hydrogen thrust chamber was built, and oxy-hydrogen thrust chamber (the wall of thrust chamber was cooled by the water from tester) was developed for the combustion test from which such parameters as combustion efficiency were obtained. The following contents were verified in the combustion test: lower ignition energy, easy to ignite, good combustion stability, combustion efficiency of 0.98, a specific impulse of 3800 n·s/kg close to the estimation. The correctness of analysis and feasibility of R&D of thrust chamber with hydrogen as fuel were verified.

B.5.4 Thrust Chamber TRL 4 Assessment features and Evidence

Table B-8 Thrust Chamber TRL 4 Assessment features and Evidence

TRL 4: Component and/or breadboard validation in laboratory environment				
Assessment Attributes	**Assessment Criteria**	**Assessment feature of CTE**	**Assessment Evidence from research institute**	
			Supporting information on assessment feature	**Conformity**
Integration level of technology entity and system	Component level	Thrust chamber components including liquid hydrogen-oxygen devices.	A completely independent thrust chamber component. This chamber which can be integrated with liquid hydrogen-oxygen devices is composed of the top, the body and the sprayer nozzle.	Components of an independent thrust chamber
Fidelity of technology entity relative to final products	Principle prototype with low fidelity	Liquid hydrogen-oxygen thrust chamber with low thrust and all functions.	A thrust chamber with a thrust of 800 kg, which utilises liquid hydrogen-oxygen as its propellant, has been developed. The body part of this all-function chamber adopts liquid hydrogen regeneration cooling. Comparing with the previous	Principle prototype development (liquid hydrogen regeneration cooling)

			gas hydrogen-oxygen thrust chamber, it has been improved from perspectives of functions (due to the development of the adoption of gas hydrogen-oxygen propellant to that of liquid hydrogen-oxygen, the body of this thrust chamber has been modified from water cooling to liquid hydrogen regeneration cooling) and performances (its thrust is enhanced from 200kg to 800kg).	
Fidelity of demonstration environment relative to operating environment	Laboratory environment	Ground environment	Ground test stand (Thrust chamber test stand for a liquid hydrogen-oxygen pressure-fed supply system)	Pressure-fed test stand
Conformity of demonstrated performance to the desired performance	Demonstrated performance conforms to the desired performance.	A proper performance which can verify the feasibility of principle can be achieved (for example, hundreds of kilograms of thrust). Design performance and demonstrated performance satisfy and conform to the desired performance respectively.	Design performance: thrust=800Kg; specific impulse≥4000 N·S/Kg; chamber pressure =2.0MPa; combustion efficiency≥0.98. Demonstrated performance: thrust=800Kg； specific impulse =4100 N·S/Kg; chamber pressure =2.0MPa; combustion efficiency≥0.99. While the demonstrated performance conforms to the design performance, the design performance otherwise accords with the desired performance given by the assessment team.	Meet the requirements

B.5.5 Thrust Chamber TRL 5 Assessment features and Evidence

Table B-9 Thrust Chamber TRL 5 Assessment features and Evidence

TRL 5: Component and/or breadboard validation in a relevant environment				
Assessment Attributes	**Assessment Criteria**	**Assessment feature of CTE**	**Assessment Evidence from research institute**	
			Supporting information on assessment feature	**Conformity**
Integration	Component	The thrust	A completely	Meet the

level of technology entity and system	level with the integration level enhancement	chamber is integrated with other components into a liquid hydrogen-oxygen engine.	independent liquid hydrogen-oxygen engine demonstrate prototype with turbopump-fed gas-generator circulation. For such an engine, thrust chamber, turbopump, fuel gas generator and actuator, etc. are integrated together primarily.	requirements
Fidelity of technology entity relative to final products	Principle prototype with a medium fidelity.	The thrust is close to that of an envisioned final product; in addition to a single thrust chamber, the liquid hydrogen-oxygen engine can be started at a time without any sway.	A single thrust chamber with a thrust of 4,000kg is developed, and the engine can be started at a time without any sway. Comparing with the preceding thrust chamber, the thrust is improved from 800kg to 4,000kg, while the chamber pressure is enhanced from 2.0MPa to 2.6 MPa.	Meet the requirements
Fidelity of demonstration environment relative to operating environment	The corresponding environment with a low fidelity	Ground environment	Ground environment (engine test stand)	Meet the requirements
Conformity of demonstrated performance to the desired performance	Demonstrated performance conforms to the desired performance	The proper performance based on which engineering application feasibility can be verified is achieved. For example, while the thrust is 3500-4000Kg, the specific impulse > 4200 N·S/Kg, chamber pressure > 2.0MPa. Design performance conforms to the desired performance, and the demonstrated performance	Design performance: thrust=4000Kg; specific impulse≥4200 N·S/Kg; chamber pressure=2.6MPa; combustion efficiency≥0.98; blending ratio of engine=5.0. Demonstrated performance: thrust=4000Kg; specific impulse=4200 N·S/Kg; chamber pressure=2.6MPa; combustion efficiency=0.98; blending ratio of engine =5.0. Demonstrated performance conforms	Meet the requirements

		accords to design performance.	to design performance, and design performance accords with the desired performance of the assessment team.	

B.5.6 Thrust Chamber TRL 6 Assessment features and Evidence

Table B-10 Thrust Chamber TRL 6 Assessment features and Evidence

TRL 6: System/subsystem model or prototype demonstration in an operation environment				
Assessment Attributes	**Assessment Criteria**	**Assessment feature of CTE**	**Assessment Evidence from research institute**	
			Supporting information on assessment feature	**Conformity**
Integration level of technology entity and system	System or subsystem level	The integration level basically reaches that what is required by the third-sublevel main engine subsystem of the rocket.	A structural concept of one turbopump with four thrust chambers is adopted so that four thrust chambers with a thrust of 1,100kg can be integrated into the engine in parallel to form the third-sublevel main engine of the rocket.	Meet the requirements
Fidelity of technology entity relative to final products	Engineering prototype of the medium fidelity	Both functions and performances are able to meet requirements of the General Assignment Book (for example, multiple thrust chambers, secondary start-up and sway); and the chamber coordinate with other parts of the engine to operate.	According to design plan description requirements from NGLV third sublevel for its main engine, thrust chamber, turbopump and all components of the engine are designed, manufactured and integrated. A thrust chamber is constituted by four small thrust chambers that can sway and have a thrust of 1,100kg; in total, the trust of this chamber is 4,400 approximately. Regarding the structure, it is able to sway (which fails to be performed by this chamber in practice); the chamber coordinates with other parts of the engine to operate.	Meet the requirements
Fidelity of demonstration environment relative to operating environment	The corresponding environment with a medium fidelity.	Ground environment and high altitude simulation environment	Ground environment (complete machine test stand for YF-73 engine) and high altitude simulation environment (altitude simulation test stand where vacuum firing and nozzle full flow test can be carried out)	Meet the requirements

Conformity of demonstrated performance to the desired performance	Demonstrated performance conforms to the desired performance.	Performance of the engine which is closely related to the thrust chamber is able to fundamentally meet requirements of the assignment book (for example, the thrust satisfies the assignment book requirements, so is the specific impulse). Design performance conforms to the desired performance; while demonstrated performance accords with design performance.	Design performance and demonstrated the performance of an engine that is closely related to the thrust chamber is as follows. Design performance: thrust=4400Kg; specific impulse=4200 N·S/Kg; blending ratio of engine=5.0. Demonstrated performance: thrust=4400Kg; specific impulse=4200 N·S/Kg; blending ratio of engine =5.0. Demonstrated performance conforms to design performance; while design performance accords with the desired performance of the assessment team.	Meet the requirements

Notes 5:

According to the practical development process of a hydrogen-oxygen engine, no vacuum firing experiments are performed under a high altitude simulation environment during engineering pattern, prototype sample and test specimen; however, secondary start-up failures took place several times during flight test, and service stages and they lead to failures of tests and missions. Through fault studies, the fault cause is ultimately determined to be the vacuum firing. Afterwards, vacuum firing experiments are conducted under a circumstance of high-altitude simulation. This problem indicates that in the process of engine development, the corresponding simulation environment which is required by vacuum firing is not tested before the flight test. As technology maturity method particularly stresses the tests which are carried out for the corresponding simulation environment before flight test, this fault case can serve as one of the significance of TRL assessment.

B.5.7 Thrust Chamber TRL 7 Assessment features and Evidence

Table B-11 Thrust Chamber TRL 7 Assessment features and Evidence

TRL 7: System prototype demonstration in an operational environment				
Assessment Attributes	**Assessment Criteria**	**Assessment feature of CTE**	**Assessment Evidence from research institute**	
			Supporting information on assessment feature	**Conformity**
Integration level of technical entity and system	System level	Engine subsystem is integrated into NGLV rocket.	The YF-73 engine is integrated into NGLV rocket system.	Meet the requirement
Fidelity of technical entity relative to the final product	High-fidelity engineering prototype	Function and performance fully meet the requirement of the assignment book, engine and related part of the rocket can work concertedly, besides, and such aspects as reliability reach the general requirement of maiden flight proposed by the project.	YF-73 engine thrust chamber enters prototype sample and sample engineering development stage successively after the model stage. All functions, performances, structures, weight, etc. of thrust chamber fully reach the requirement assignment. It has passed the engine ground evaluation test, rocket propulsion system commissioning and rocket commissioning, various tests related to limiting conditions have been carried out, it has reached the general requirement of maiden flight proposed by the project. Besides, the flight test has been made.	Meet the requirement
Fidelity of demonstration environment relative to the operating environment	Operating environment	Space environment	Space environment of NGLV rocket flight (engine ground test environment, rocket propulsion system test bed, rocket commissioning environment, NGLV rocket launching proving ground; rocket flight test has been made)	Meet the requirement
Conformity of demonstration performance relative to the	Demonstration performance conforms to the desired	Engine performance closely related to thrust chamber fully	Design performance and demonstration performance of engine closely related to thrust chamber are as follows: Design performance: Vacuum thrust≥44.43KN,	Meet the requirement

desired performance	performanc e.	meets the general requirement of assignment book. Design performance meets the desired performance. Besides, demonstration performance accords with the design performance.	precision ±3%; Vacuum specific impulse≥4119N•S/Kg; Mass mixing ratio of propellant=5.0, precision ±5%. Demonstration performance: Vacuum thrust≥44.43KN, precision±3%; Vacuum specific impulse≥4119N•S/Kg; Mass mixing ratio of propellant=5.0, precision ±5%. During test flight of rocket, the first operation turns off normally, the second start is successful, and it indicates that performance of the thrust chamber reaches the requirement. Demonstration performance meets the design performance.	

B.5.8 Thrust Chamber TRL 8 Assessment features and Evidence

It shows that the main work of TRL 8(Actual system completed and "flight qualified" through test and demonstration) includes various tests and evaluations in finalizing/flight model phase, such as evaluation test and acceptance test. There is no finalizing stage for rocket currently (the carrying capacity of each rocket is different. However, some experts in China also suggest that rocket shall be finalized), various evaluation tests and acceptance tests relevant to rocket engines are completed before the maiden flight, that means this part of work has been done in TRL 7, so there is no TRL 8 in thrust chamber, and it directly enters TRL 9 after reaching TRL 7.

B.5.9 Thrust Chamber TRL 9 Assessment features and Evidence

Table B-12 Thrust Chamber TRL 9 Assessment features and Evidence

TRL 9: Actual system flight proven through successful mission operations.				
Assessment Attributes	**Assessment Criteria**	**Assessment feature of CTE**	**Assessment Evidence from research institute**	
			Supporting information of assessment feature	**Conformity**
Integration level of technical entity and system	System level	NGLV rocket	YF-73 engine is integrated into NGLV rocket.	Meet the requirement
Fidelity of technical entity relative to the final product	Product	NGLV rocket	Thrust chamber product of YF-73 turbopump-fed LH_2/LOX rocket engine	Meet the requirement
Fidelity of demonstration environment relative to the operating environment	Operating environment	Space environment	NGLV rocket successfully performs the space environment of commercial launch task.	Meet the requirement
Conformity of demonstration performance relative to the desired performance	Demonstration performance conforms to the desired performance.	Geostationary communication satellite weighing 1000kg is sent to the pre-selected orbit.	NGLV successfully performs the commercial launch task.	Meet the requirement