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Yi Ren
School of Reliability and Systems Engineering
Beihang University
Beijing, China

Cheng Qian
School of Reliability and Systems Engineering
Beihang University
Beijing, China

Dezhen Yang
School of Reliability and Systems Engineering
Beihang University
Beijing, China

Qiang Feng
School of Reliability and Systems Engineering
Beihang University
Beijing, China

Bo Sun
School of Reliability and Systems Engineering
Beihang University
Beijing, China

Zili Wang
School of Reliability and Systems Engineering
Beihang University
Beijing, China

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Preface

Reliability, maintainability and supportability are the fundamental basis to provide high efficiency and reduce life cycle cost for the high-tech equipment. At present, with the rapid development of equipment products, we have deeply realized the harmfulness of the inconsistency design between functional performance characteristics and general characteristics (also called hexability which includes reliability, maintainability, supportability, testability, safety and environmental adaptability). And we have paid high attention on the ideological level and strict evaluation on the management level to try to avoid that problem. However, we are constrained at the technical level by the lack of systematic and effective methods. In practical situation, the product designers find it difficult to understand, master and utilize the complicated hexablity design methods. This results that the hexability design is disconnected from the functional performance design, and the hexability design results cannot affect the design of the product. The traditional reliability system engineering (RSE) methods are carried out mainly based on management. These methods provide "soft requirements" to the product design process but cannot create "hard constraints." For this reason, this book proposes the model-based reliability system engineering (MBRSE) methodology, by taking the unified models as the basis, taking the model-based fault prevention, detection and remedy as the core, and synergistically using different kinds of hexability design methods to carry out the integrated design of both functional performance and hexability. It inherits the management method of RSE and gives the overall design framework from the implementation perspectives. In this book, MBRSE is systemically elaborated from the following aspects:

(1) The engineering requirement background and technology development status of MBRSE. This book summarizes the birth and development process of hexability technologies in foreign countries, as well as the development process of RSE in China in the past 20 years. Facing to the reality that China has a different industrial foundation and design concept compared to Western countries, Prof. Weimin Yang of Beihang University proposed the concept and connotation of RSE to adapt Chinese national conditions. And subsequent researchers gradually

developed a theoretical and technical framework and created a professional engineering design theory considering Chinese characteristics. Through research and analysis, the problems faced in the implementation of traditional RSE methods are summarized in three aspects. First, an integrated design methodology is missed to hardly establish a design process model on both functional performance and hexability, and the hexability work can only rely on qualitative, cumbersome work items that are difficult to be implemented synchronously. Second, a universal unified design theory and method throughout the whole process of product development is missed to hardly establish a design method model on both functional performance and hexability. Third, an advanced integrated design software platform is missed to hardly integrate the hexability design six software tools into the digital environment of product design. These problems result in the main reason of proposing the MBRSE method.

(2) The basic principles, basic models and technical framework of MBRSE. The main research categories and theoretical significance of MBRSE are firstly elaborated, and the conceptual models of MBRSE are then developed. These conceptual models include the principle models and technical framework of MBRSE. By taking the fault ontology as the core, the concept and relationship of the product faults in the design process are unified, and the model unification and sharing mechanism of MBRSE are provided. Driven by the forward evolution process of the unified model, the meta processes oriented to both a completely new design and inheritance design are established, respectively, to provide the process control mechanism of MBRSE. In addition, based on the mapping theory on the requirement domain, functional domain and physical domain, the domain extension and design process mapping principle for the model-based hexability design are presented. And the MBRSE process model is also provided, including the unified process framework, the unified process plan and reorganization method and process model, and comprehensive analysis and evaluation method of the process.

(3) MBRSE design methods. The MBRSE design methodology is established by taking the unified model as the center. Firstly, a model-based multi-mode fault systematic identification method is proposed. According to the hierarchical structure and unified evolution process of the product, the global identification of the component functional fault is implemented to achieve the function maintenance. Then the global identification of the physical fault is implemented after the function-physics mapping. Based on the component fault, the interface fault, transmission fault and error propagation fault are further analyzed to implement the emergent identification of the system fault. 其Then, combined with the hexability design goals, a model-based synthetic control method for design goals is proposed by considering both functional performance and hexability design goals. Its core is to formulate a closed-loop fault mitigation strategy according to the faults identified by the system and give feedback on the evaluation process of the hexability indices indicators to ensure the implementation of them and application of using the hexability indices in the product design process.

(4) MBRSE design platform and engineering application cases. Based on the theoretical models of MBRSE, the integrated design model, process model and tool integration model are established to develop the integrated design platform for the whole system and whole process. Then by taking a terrain mobile robot platform as an example, the MBRSE method, platform and software tools are applied from the demand analysis to the determination of the design plan for the verification purpose.

This book is divided into nine chapters. The RSE development stage is firstly introduced, and then the basic theory, unified models and global evolution methods of MBRSE are given. Next, the model-based fault identification and control, MBRSE development process model and MBRSE integrated platform are mainly introduced. Finally, the latest development of the integration research between digital twin and RSE is discussed.

This book is for engineers, technical managers and consultants in the aerospace, automotive, civil and ocean engineering industries and in the power industry who want to use, or are already using, reliability engineering methods. It was firstly released in Chinese and then translated into English. During this process, Prof. Zili Wang provides a professional guidance until the finalization of the book. The authors would like to sincerely thank him for his great concern and support. In addition, we would like to express our utmost thanks to Prof. Dariusz Mazurkiewicz from Lublin University of Technology, for all his contributions in editing and proofreading to this book. Our special thanks also goes to many of our colleagues, Post-Docs and Ph.D. students who contributed to the book in various ways.

Beijing, China

Yi Ren
Cheng Qian
Dezhen Yang
Qiang Feng
Bo Sun
Zili Wang

Contents

Chapter 1
Development Phase of Reliability Systems Engineering

Abstract This chapter provides a systematic overview of the advent and evolution of hexability technology in China, and introduces the challenges and new development requirements in a new ear. Then, starting from the concept of system engineering, it reviews the establishment process, fundamental definition and philosophical connotation of Reliability System Engineering (RSE). Next, the theoretical and technical framework of reliability system engineering is given from three aspects, including the basic theory, basic technology and integrated technology. Finally, the prospective trends in the development of RSE in China are outlined based on the discussions of the emergence and development of MBSE.

Keywords System engineering · Reliability system engineering · Definition and connotation · Theoretical and technical framework · Modeling

1.1 Background of Reliability System Engineering

1.1.1 The Development History of RMS Engineering in Foreign Countries

Reliability, maintainability, supportability, testability, safety and environmental adaptability (herein referred to as hexability or RMS, which can also be simply represented by reliability, in other words, the RMS and reliability involved in this book generally refer to hexability) are the characteristics of the product required during its practical use. From a simple and clunky carriage in ancient times to a sophisticated and complex nuclear power plant in modern times, end users all hope that the product can work 'solidly' under various conditions, with no faults, few faults, or at least no fatal faults. And whenever a fault occurs, it can be quickly and accurately located, the failed part is easy to be repaired or replaced, and the maintenance is supported by professional experts and reliability tools in time. Such simple expectations for these characteristics of the product by the end-users are not naturally established and need to be realized in the hexability design of the product.

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In the era of the traditional handicraft industry, product design is based primarily on the experience of designers through its long-term accumulation in practice. In the early industrial age, products were relatively simple, hexability problems could be solved only based on engineers' experience, and therefore special design activities were not necessary to carry out. Hexability, regarded as an engineering design discipline, was gradually formed and developed in World War II. During World War II, military equipment was developed in a short time, usually characterized by a complicated structure and low technological maturity, resulting in a large number of hexability problems in its use. For example, Nazi Germany's V-2 rocket was developed in only two years, but it was constructed with the use of up to 220,000 parts and components owned. In addition, many new technologies such as liquid rocket engines, inertial navigation, and automatic flight control system were introduced for the first time. Its flight altitude reached 100 km and its speed reached Mach 48. Due to the substantial increase in system complexity, the massive adoption of new technologies and unprecedented working conditions, reliability has become a key technical problem in the development of the V-2 rocket. To evaluate the reliability of the V-2 rocket, R. Lusser, one of the V-2 rocket developers, first proposed a probability multiplication rule by treating the rocket system as a series model, to calculate the reliability of the system by the sum of the reliability of its each component. Although the importance of reliability has already been realized, due to the lack of effective technical and management methods, the reliability of the V-2 rocket has not been well resolved, making its actual combat effectiveness much lower than expectations. In addition, in World War II, the rise of electronic products such as radar greatly improved the performance of weapons and equipment. However, 60% of airborne electronic equipment in the United States could not be used after being shipped to the Far East, and 50% of electronic equipment failed during storage, which led to severe restrictions in its combat effectiveness.

Aiming to the hexability issues exposed during the use of various equipment in World War II, modern reliability engineering technology was first born in the United States in the 1950s, and gradually expanded to specific characteristics such as maintainability, supportability, testability, safety and environmental adaptability. For more than 70 years, many countries around the World have put great importance on the theoretical researches and engineering application methods of hexability. The hexability technology has achieved considerable development and obvious application results. A technical system was formed and developed from single technology to integrated technology composed of three parts including requirement determination, design and analysis, validation and evaluation. The technological development has gone through the following 5 stages:

1.1.1.1 Stage of Solving Typical Issues (1940s–1960s)

In order to address the high fault rate of electronic products in World War II, the United States established the Electronic Tube Research Committee in 1943 to study reliability issues in electron tubes. In 1951, the Airlines Electronic Engineering Committee (ARINC) formulated the earliest reliability improvement plan and published the ARINC report in 1952, to define the terminology of reliability, and first clarified the random characteristics of Time To Failure (TTF) factor. Also in 1952, the US Department of Defense established Advisory Groupon Reliability of Electronic Equipment (AGREE); In 1955, AGREE began to implement a comprehensive reliability development plan covering the stages of design, testing, production to delivery, storage and use, and in 1957 published the research report "Reliability of Military Electronic Equipment", (i.e. AGREE report), which elaborates the procedures and methods of reliability design, testing and management of military electronic equipment from nine aspects, and determines the development direction of reliability engineering in the United States. The AGREE report has become a foundational document for the development of reliability, marking that reliability has become an independent discipline, and its publication is considered as an important milestone in the development of reliability engineering.

However, from engineering perspective, reliability engineering was not used to promote systematically weapons and equipment development in a planned way, but focused on the solution of detailed problems. Second-generation fighters such as F-4 and F-104 developed by the US Army in the 1950s represented very low reliability, low combat readiness, low attendance, and high maintenance and support costs in Vietnam War. In the 1960s, aiming to the problem of low reliability of the F-4 and other fighters in Vietnam War, the US military formulated and issued a series of reliability military standards, such as the MIL-STD-785 "Requirements of Reliability Outline for Systems and Equipment" on the basis of the report titled "Reliability of Military Electronic Equipment", and applied them in the development of new, 3rd generation weapons and equipment such as F-14A and F-15A fighters or M1 tanks. Since then, the reliability requirements, reliability outline, reliability analysis, design and reliability qualification tests have been carried out.

1.1.1.2 Stage of Systematical Implementation (1970s–1980s)

In the 1970s and 1980s, both—the United States and the Soviet Union developed a large number of complicated new equipment in order to obtain strategic military advantages. Through the implementation of a number of programs, such as Apollo moon landing, the United States has rapidly improved its scientific and technological military strength and accumulated experience in comprehensively carrying out reliability engineering of large systems. The US Department of Defense established a joint technical coordination group that included reliability, availability, and maintainability that was directly led by Joint Logistics Commanders of the Three-Armed Services to manage the entire process of RMS in the development of equipment to comprehensively strengthen the reliability management of weapon equipment and improve their actual combat capabilities.

In the late 1970s, in the development of weapons and military equipment, the United States began to use reliability development and growth tests, environmental stress screening, and comprehensive environmental tests, and launched relevant standards. In 1980, the US Department of Defense released the first Reliability and Maintainability (R&M) Regulation DoDD5000.40 "Reliability and Maintainability", which specifies the R&M policy of procurement and responsibilities of different organizations in the Department of Defense, and emphasized that the R&M work should be carried out from the beginning of the development of any equipment. In 1986, the US Air Force released the "R&M 2000" Action Plan, which clarified that R&M is an integral part of the combat effectiveness of aviation weapons and equipment. Beginning from management, this plan promoted the development and application of R&M technology, and institutionalized R&M management. The several local wars in the 1990s not only reflected the technological advancement of the US military equipment, but also highlighted its outstanding hexability. Most of the equipment used in those wars were developed or improved in the 1970s and 1980s. This reflects the effectiveness of the systematic implementation of the RMS technologies. Meanwhile, the Star Wars program and the development of stealth fighters during that period have also promoted the technological improvement of reliability engineering, such as the researches of highly accelerated life testing (HALT), highly accelerated stress screening (HASS), software reliability, and network reliability, analysis of Physics of Failure (POF), failure mode and effects analysis (FMEA), testability modelling, virtual maintainability analysis, integrated support simulation analysis, and other technologies, and are gradually being applied in the development of new generations of equipment.

1.1.1.3 Stage of Standstill and Retrogression (1990s–Early Twenty-First Century)

The United States became the only superpower in the World and faced with reduced threats after the disintegration of the Soviet Union. In order to reduce defense expenditures, the US military carried out defense procurement reforms in 1994. Then-Secretary of the Department of Defense Willem Perry abolished most of the reliability military standards in order to achieve military-civilian integration of equipment procurement and tried to ensure the reliability of equipment through a completely market-oriented approach, thereby saving procurement costs. However, actually this action has caused a continuous decline in the reliability of subsequent weapons and equipment. Between 1996 and 2000, 80% of the new US military equipment failed to reach the required level of operational reliability. There are also other technical reasons. Since the 1990s, the World has entered the information age represented by computers, software, and networks. The integration, informatization, and automation of equipment have become more and more important. Failures and specific requirements in reliability of informatic equipment have many new features that need to be solved from both basic theory and applied technology.

1.1.1.4 Stage of Spiral Rise (Early Twenty-First Century–2015)

After entering the twenty-first century, nearly half of the Weapons and Military Supplies acquisition projects of the US military failed to meet the requirements during their initial test and verification process. Researches in the US Department of Defense have found that serious issues were caused by the failure to implement the reliability of equipment development. For instance, reliability in the design stage was insufficient, reliability design practice of defense contractors did not conform to the best business practice, failure mode effects and criticality analysis (FMECA) and the failure report analysis and corrective action system (FRACAS) did not work, reliability tests of components and systems were insufficient, etc. In order to solve the reliability issues in the development of weapons and military equipment, the US. Department of Defense cooperated closely with industries and the Government Electronics and Information Technology Association (GEIA), and in August 2008 officially released the reliability standard GEIA-STD-0009 “Reliability Work Standard for System Design, Development, and Manufacturing” [1] for the use in defense systems and military equipment development and manufacturing, and once again strengthened the reliability work of equipment development. In May 2013, US TechAmerica released the associated TA-HB-0009 “Reliability Program Handbook”. Meanwhile, Physics of Failure (PoF) based reliability design technology has gained high attention and in-depth development, in the use of reliability design of the aero-electronic devices in F-22 fighters and European A400 military freighters. The Maintenance Free Operating Period (MFOP) was first adopted in A400M as the reliability index, instead of the traditional mean flight hours between failures (MFHBF) factor.

1.1.1.5 Stage of the New Technological Revolution (2015–Present)

In 2013, Germany first proposed Industry 4.0, whose core concept is to use a Cyber-Physical System (CPS) to digitize and to make smart the supply, manufacturing, and sales information processing in the production process, and finally achieve a rapid, effective, personalized product supply. In May 2015, China’s State Council officially released “Made in China 2025” to implement the comprehensive implementation of the strategy to make China a strong manufacturing country. Its key content is to promote the deep integration of informatization and industrialization, and to build a Chinese version of Industry 4.0, and pose new challenges to traditional reliability technology. Facing the new targets and new issues in the era of Industry 4.0, network reliability, CPS reliability, autonomous system reliability, system flexibility, and digital twin based reliability technology have been developed rapidly in recent years, and become the research hotspots of reliability technology. In this new age of the technological revolution, theory, technology, methods and tools of reliability technology are all facing new opportunities and challenges.

1.1.2 Global Developing Trends of RMS Engineering

1.1.2.1 Trend of Technological Synthesis and Integration

From the development of a single technology to comprehensive technology and integrated technology, and the integration of functional characteristics, RMS characteristics are both important features of technological development in this period. With the rise of digital design, three-dimensional paperless design, product lifecycle management (PLM), multi-disciplinary design optimization and collaboration in the environment of networks have become the new direction of design technology development, and it has also driven the direction of RMS towards integration. The ways of synthesis and integration can be summarized as follows:

- integration of RMS design and analysis, such as integrated analysis of reliability, maintainability, and availability, integrated design analysis of reliability, testability, maintainability, and supportability, integrated design of RMS and function/performance, etc.;
- integration of reliability test, that is, making full use of the test information of research and development tests, growth tests, environmental tests, and appraisal tests to evaluate product reliability;
- integration of logistic support and diagnostic, that is making use of comprehensive diagnosis to achieve design, production, and maintenance testing integration;
- integration of hardware and software, that is carrying out a comprehensive analysis of the reliability of hardware and software;
- integration of the information about reliability, maintainability and supportability, by establishing an integrated data system for weapons and equipment, various design, production, maintenance and support information from the ordering party, users, the main system and the transfer system can be utilized and shared comprehensively.

The engineering community has always wanted to integrate various design disciplines into the engineering process of the product development system to achieve integrated design performance and various characteristics. The idea of integrated design runs through from the integration of engineering disciplines [2, 3] in the United States in the 1970s to concurrent engineering in the 1990s and the credibility technology that emerged in the 1990s in Europe [4, 5]. The development of complex equipment is a system engineering process composed of different stages of work. System integration based on a systematic idea and basic principles of system engineering is the core throughout the system engineering process [6].

Unlike traditional function/performance design, the engineering profession is used to ensure that the developed system is more reasonable and more effective in the actually used environment. The integration of engineering disciplines refers to the integration of equipment technical requirements, integration of the equipment development process, the integration of the research team, and integration of various design methods (tools). Among them, the interactive and coordinated integrated development process is the core of driving the integration of engineering discipline. The most important part of the engineering disciplines integration lies in professional fields such as RMS. Lockheed Martin adopts matrix management and uses knowledge in specific areas such as reliability, maintainability, human engineering, transportability, safety, electromagnetic compatibility etc. to support product design, and ensure that the system has applicability to realize system engineering process integration in applied environment [6, 7].

With the development of technology, more and more elements such as people, technology, hardware, software, processes, and enterprises are involved in the product system, leading to more and more complicated system application and support processes, and thus giving birth to a new generation of systems engineering methods—MBSE (Model-based Systems Engineering). Such a method, by taking models as the center in system design, becomes the future development trend of system engineering. Its main result is the system model, which is made up of key elements such as system requirements, structure, behavior, and parameters. Reliability, as an important feature of the system, is also integrated into the process of the system model design.

1.1.2.2 Trend of Process Modelling

In recent years, the Georgia Institute of Technology (GIT), the National Aeronautics and Space Administration (NASA), Lockheed Martin, the French PRISME Institute, the International Council on Systems Engineering (INCOSE) and other institutions have all focused on reliability and special feature coordination, mainly using the MBSE method. This method strengthens communication and coordination among multiple users by improving the traceability of requirements, to improve knowledge extraction ability, design accuracy and integrity, thus facilitating information reuse, strengthening the system engineering process, and reducing development risks. At present, the MBSE method has been applied in a wide range of fields including aviation, aerospace, vehicles, ships, electronics, civil products etc. During its application, several researchers have also summarized a general system engineering process, which can effectively realize the integrated design. The most representative examples are the system engineering processes developed by GIT in the US and the PRISME Institute in France.

(1) The system engineering process developed by GIT

GIT has established a system engineering process based on MBSE, as shown in Fig. 1.1. At the same time, taking the excavator as an example, it built a system model, a system operation scenario model, and a factory manufacturing model for production. This process includes a collection of knowledge such as meta-model, profile, model library etc., through the simulation analysis on multi-domain hybrid systems with target optimization model, cost model, reliability model, mechanism dynamics model etc., to realize the impact on system design, to ensure the concurrent

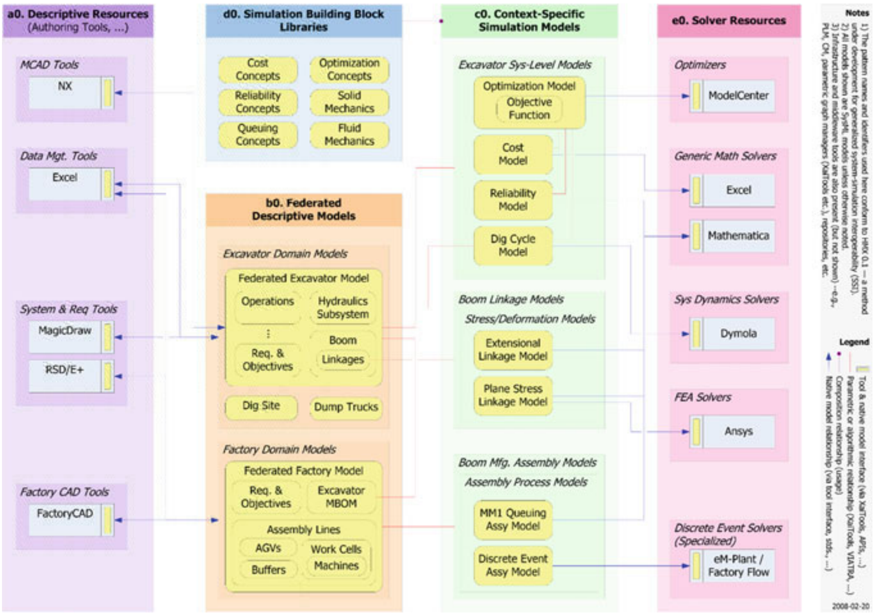

Fig. 1.1 System engineering process based on MBSE method (an example by using the excavator) (color picture provided at the end of the book)

completion of the realization of the system design and reliability target, and finally to achieve the product design scheme.

(2) Modelling reliability engineering technology framework developed by PRISME Institute in France

Taking the unified model as the core, R. Cresent and F. Kratz (PRISME, ENSI de Bourges), P. David (Bourges Université de Technologie de Compiègne) et al. established an FMEA, reliability and failure scenario analysis, real-time embedded system simulation analysis, and the MeDISIS Simulink-based system simulation overall framework, as shown in Fig. 1.2, to realize the integration of reliability and traditional disciplines.

1.1.2.3 New Requirements by the New Technological Revolution

The rise of smart manufacturing and intelligent design based on both the Internet and Internet of Things has greatly reduced the difficulty of traditional design. Then, differentiation and high quality have become the new goals pursued by product design, such as Industry 4.0, Industrial Internet and the Made in China 2025 strategy. Therefore, design, management and assurance of hexability will play more important roles in the design and application of future products. In addition, the next generation

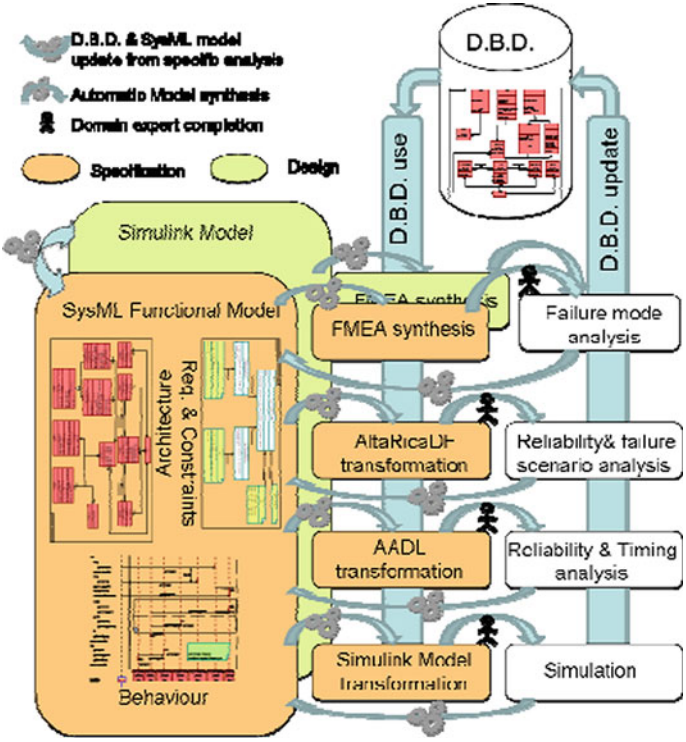

Fig. 1.2 System engineering technology framework (MeDISIS) developed by PRISME Institute in France

of manufacturing based on cyber-physical systems (CPS) (Fig. 1.3) will cause major changes in the modes in product design, production and service. And the traditional hexability design method will face the requirements for further upgrading in order to adapt to such changes, as follows:

(1) Hexability design requirements for small-batch flexible configuration products
(2) Reliability design and validation requirements for intelligent devices.
(3) Design and validation requirements for the hexability of the smart factory/CPS system.
(4) Requirements for hexability design and intelligent products design and PHM design.

1.1.2.4 Industrialization Trend of the Hexibility Technology Industry

With the deepen of the social division of labor and the development of productive services, the manufacturing and service industries are integrated and interdependent, with a more and more ambiguous boundary in between them. In the twenty-first century, service-based manufacturing gradually emerged. The internal demand

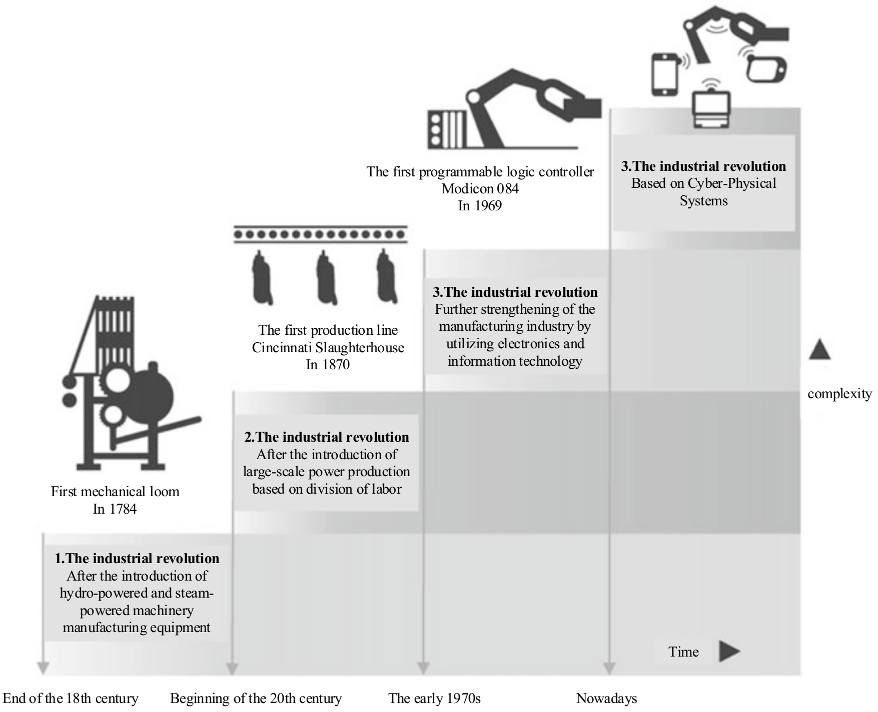

Fig. 1.3 Industrial 4.0 based on CPS

comes from the market. And customer consumption culture has changed from product demand to personalized and experiential demand. Product homogeneity is becoming more and more serious. Manufacturing companies urgently need to provide products and services to overcome product homogeneity and meet customer needs. For complex high-tech products, this trend is becoming increasingly prominent. In order to ensure the normal function of the product, it is necessary to provide corresponding auxiliary services, such as professional installation, commissioning, maintenance and repair, health management and other services. Obviously, good hexability is the support for the profit and competitiveness of service-oriented manufacturing enterprises.

Today, hexability is not only a peripheral activity of an engineering discipline or design company but also has gradually grown into a new industry. For example, the global market value of maintenance of civil jets and propeller aircrafts in 2014 reached as high as 56.3 billion US dollars. The development of maintenance technology has made GE a service-oriented manufacturing company. Another example is that in 2011, the global car ownership exceeded 1 billion, and the global car production reached 89 million in 2014. In the entire automotive industry chain, the automotive service industry accounts for 60% and maintenance is the core of automotive services, creating hundreds of billions of dollars in value every year and absorbing millions of employed people.

1.1.3 Challenges Faced by Hexability in China and Demands for Leap-Forward Development

1.1.3.1 Status Elevation of Hexability in China by the Galf War

In China, the domestic engineering design field is weak, and the equipment manufacturing industry has long been dominated by imitation. From the 1950s in which a relatively complete industrial system was established to the early stage of Reform and Opening-up, the systematic hexability design was almost blank. The typical manifestation was that designers lacked the consciousness of hexability design, the army did not require it, and the design lacked corresponding standards, difficult to advance, no assessment for acceptance. From 1980s, most of the self-developed equipment in China had many problems, such as a long development cycle, low combat effectiveness and many failures in use. However, at that time, no one realized that the main factor to cause these above-mentioned issues is the lack of hexability analysis.

In the Gulf War that took place in early 1991 and lasted 43 days, within 53 h after receiving the order, 45 of the first 48 US F-15C air superiority fighters from the 1st Tactical Wing appeared in Saudi Arabia. This shows an extremely high combat readiness and rapid deployment capability. During the war in Iraq, the F-15C was mainly responsible for providing air protection for the troops and equipment deployed in Saudi Arabia, and used as the main aircraft for the competition of air supremacy. The 120 F-15C deployed in southwest Asia have flown a total of 5906 sorties, with an average flight duration of 5.19 h per sortie and a mission rate of up to 93.7%. Of the 39 Iraqi fighter jets shot down by the US Army in air combats, 34 were shot down by the F-15C. In contrast, only one of the F-15C fighters was lost, demonstrating outstanding combat readiness and strong combat capability of the US Army. This high effectiveness of the US military equipment has awakened the Chinese people. Since then, people have realized that the equipment "can fight and win wars" not only needs excellent combat performance, but also excellent hexability.

The outstanding reliability, maintenance, and support ability of US military equipment is not naturally existent, but comes from the high attention and investment in the design of hexability. Regarding the formulation of standards and specifications, referring to US military standards and other international standards, a relatively complete hexability specification system was initially formed in light of China's national conditions. In terms of supporting means, a part of RMS design analysis, testing technical tools and equipment were imported, to achieve remarkable results and solve the urgent needs for equipment development. In terms of key technology breakthrough, key technologies such as computer-aided RMS design and analysis technology, integrated (temperature, humidity, low pressure, vibration) reliability test systems, electronic equipment component screening systems, mechanical and electrical product reliability integrated stress test technology, reliability test profile design technology, embedded software reliability simulation test technology, small sample reliability evaluation technology are tackled, and a large number of the three integrated (temperature, humidity, vibration) reliability test systems, fault analysis equipment and environmental test equipment were introduced. These above achievements and technical methods have been widely promoted and applied in high-tech equipment, providing key technical guarantees to the successful development and stable operation of these advanced constructions.

1.1.3.2 Challenge Faced by the Hexability Technology

Affected by its industrial foundation and design culture, it is always faced with the challenge of systematically and comprehensively implementing hexability design in China. Problems can be summarized such as: imperfect organizational model, irregular work process, inconsistent technical status, difficulty in accumulating design experience, insufficient synergy, system integrated without means, weak information foundation, and poor control on the overall status. These issues are caused by not only technical reasons, but also management factors, and deeper design cultural issues. The development of China's hexability technology cannot completely copy the experience of the United States. It must develop its own theoretical and technical system based on China's industrial foundation, management model, and cultural background, and take a path with Chinese characteristics.

From a theoretical perspective, effective ways to ensure the realization of RMS and performance design requirements are based on the idea of reliability system engineering, overall planning performance and RMS design activities, coordinating standard performance and RMS engineering methods, and synchronizing control performance and RMS work processes. But different from the performance design requirements, the RMS requirements cannot be directly used as design parameters in the equipment development. The RMS characteristics need to be applied in large quantities and for a long time before they can be accurately measured. Therefore, in the process of equipment development, it has always been a difficult problem to develop the RMS design in a way that is easy for designers to understand and to adopt its implementation to gradually realize RMS requirements.

After more than half a century of development in RMS engineering technology, a variety of methods and technical means have emerged and have been tested in engineering practice. These different RMS engineering methods do not exist in isolation but in extensive connections not only in between themselves but also between them and product function/performance design activities. These connections determine various further types of RMS design activities and their relationships with function/performance design activities, which cannot be independent to each other but must be integrated and coordinated in accordance with certain rules. This book refers to this collaborative design process as function/performance and RMS integrated design. Due to the particularity of the RMS engineering technology, in the whole process of product development, the control of the implementation process of the RMS characteristics is often achieved through adequate application of management regulations and documents, the use of management and design review and other qualitative means, rather than "naturally to be achieved" in product design. There is a great risk of re-doing the product development due to RMS issues. Therefore, it is urgent to develop a method that can integrate the RMS design into the function/performance design to achieve "precise" control. In this book, it is believed that in order to solve the problems systematically, improvements must be made in both technology and management, given in the following three aspects:

(1) Achieve sharing of function/performance and RMS design information. There should be a unified source of information for performance and RMS design. Public information sources should be unified and traceable. Changes in product technical status should be reflected in the RMS design analysis in time, and the results of the RMS design analysis should be updated in time according to changes in the technical status and affect product design. At present, in the field of performance design, an accurate and unified model can be established and the sharing of design information can basically be realized. However, RMS design lacks a standardized and unified model, and RMS design and analysis are still at the initial stage with self-enclosed and one-way features, and lack of control.
(2) Achieve the organic connection between function/performance and RMS design method. RMS and performance design have the same target object in a natural connection. Many RMS design analysis methods are carried out on the basis of performance models. Most RMS design methods can be incorporated into the performance design process, and the iteration of performance design can also be directly promoted by the RMS design conclusions; that is, an organic connection should be established between related engineering methods. However, due to the large differences in analysis purposes and modelling angles, the connection between RMS and performance design analysis is often implicit and vague, and it is very difficult to achieve interoperability.
(3) Achieve precise control of function/performance and the RMS design process. The design of RMS is an integral part of product development, and the implementation process of the RMS design requirements should be integrated with the implementation process of the performance requirements. However, there is a lack of technical interoperability between the RMS engineering method and the performance engineering method, and there is also a lack of a unified control mechanism for the process of implementing RMS characteristics in terms of management. Therefore, the RMS design process cannot be organically integrated into the performance design process, resulting in two parallel ways. The consequence is that the RMS design is only a link that has to be done in the design process, and it is difficult to have a substantial impact on the product design, and it is easy to produce the so-called phenomenon of "two skins". The traditional engineering process is mainly based on management to realize coordination and control between performance design and RMS design. It requires

highly experienced designers and managers, and the process is difficult to accurately control, prone to repetitive work, long work cycles, and high costs. At the same time, it is difficult to establish a unified digital integration platform that includes RMS design and cannot scientifically plan and effectively integrate various tools and means to support the efficient and coordinated development of performance and RMS integrated design. Therefore, the integrated design of performance and the RMS design cannot be discussed.

1.1.3.3 Requirements for Leap-Forward Development of the Hexibility Technology

There are two main obstacles to achieve the above improvements. One is that there is a big difference between the expression of functional performance design and various types of RMS design, which makes it difficult to automatically share and transfer information between performance and RMS; the other is that it is difficult to communicate and coordinate smoothly between performance and RMS design methods, so it is difficult to establish a scientific and reasonable unified process to control the entire process of design activities. For this reason, it is necessary to establish a unified hexability model through which the bridge between performance and various types of RMS design can be established to realize the unification of performance and RMS technology and management process.

In addition, in order to achieve the precision, automation and intelligence, the hexability work should be transformed from a documentation-driven work flow to a model-based work flow. This also requires the establishment of a complete hexability design model system, which is consistently connected with the various models and on the other hand—seamlessly connected with product design process. However, the unified hexability model has not been systematically studied all over the World, and the model-based hexability design is in the development stage as well. This provides an unprecedented development opportunity to bring China to the forefront of the World in the field of reliability engineering. It also meets the needs for the rapid development of equipment research in China.

1.2 The Concept of Reliability System Engineering

1.2.1 System Engineering

1.2.1.1 Summary of Complex Engineering Systems

As Carl Marx said, "when numerous workers work together side by side, whether in one and the same process, or in different but connected processes, they are said to cooperate, or to work in cooperation", "All combined labor on a large scale requires, more or less, a directing authority, in order to secure the harmonious working of the individual activities, and to perform the general functions that have their origin in the action of the combined organism, as distinguished from the action of its separate organs", "A single violin player is his own conductor; an orchestra requires a separate one".

With the continuous development of science and technology, modern engineering has become increasingly complex, and large engineering systems such as aviation, aerospace, and nuclear engineering have emerged. The engineering system herein refers to a system that transforms demands into engineering products, including the practice of integrating science, technology and related elements by taking the value as the orientation, to achieve specific goals in an organized manner. These emerging projects are large in scale, multilevel, and complex in structure. They contain a large number of interactive components in terms of technical methods, personnel organization, and project management. They have the characteristics of complex internal correlation, uncertainty, and dynamics. This leads to the overall behavior of strong non-linearity of the system, which is therefore called a complex engineering system. The research and development of these large-scale and complex systems face many challenges, both from the system itself and the engineering process. And the essence of these challenges is to solve the various complex issues existed in an engineering system.

These above complexity issues can be divided into three categories:

(1) Object complexity of the engineering system refers to the inherent complexity of the engineering product itself, such as the diversity of value elements, the huge number of components, the intensity of interaction coupling, and the complexity of the expected use environment.
(2) Subject complexity of the engineering system refers to the artificial complexity brought by the participants of the project, including the complexity of cognition and the complexity of behavior. The complexity of cognition is the source of the uncertainty of the engineering system, and the complexity of behavior may lead to various intentional, non-standard, naive, and even wrong engineering behaviors.
(3) The environmental complexity of the engineering system is reflected in the impact of the increasing complexity of the various environments of the engineering system on the engineering system. The environment here is the sum of the resources that the engineering system may obtain and the constraints. The management factors affect the value, scientific, and technical elements of the engineering system. It can usually be divided into scientific and technological environment, cultural environment, social environment and natural environment.

Prof. Xuesen Qian summarized the basic issues faced by complex engineering systems as: "How to gradually turn the relatively general initial development requirements into the specific tasks of thousands of participants in the development task" and

"How to finally integrate these tasks into a practical system that is technically reasonable, economically cost-effective, has a short development cycle, and can coordinate calculations, and makes this system an effective component of the larger system to which it belongs".

1.2.1.2 Engineering Methodology for Complex Systems

As Bertalanffy said, "We are forced to use the concept of 'whole' or 'system' in all areas of knowledge to deal with complexity". The complication trend of modern engineering systems has developed to use only consciously system concepts and principles to effectively deal with the complexity of the project. With the development of the system-based idea and methods in natural sciences, social sciences, engineering technology, and other fields, systems and their mechanisms are used as objects to study system types, properties, and rules of systems science gradually formed and began to mature.

According to the opinion by Prof. Xuesen Qian, system science can be divided into three levels, including basic science, technical science, and engineering technology, respectively. The level of basic science is a discipline that studies the basic attributes and general rules of the system and is the basic theory of all systems research. At present, the basic science level system is still being established and perfected. The technical science level includes informatics, cybernetics, operations research, affair theory and other theories, which can provide direct guidance for engineering technology. The engineering technology level is the knowledge that directly transforms the objective world, and the most typical representative is the engineering of systems.

In the development process of complex systems, the fundamental and technical scientific researches mainly play the guiding roles, and the solution of specific engineering issues require the support of engineering technology. According to the different roles in the development of complex systems, the engineering technology level can be refined into three levels, including the concept and methodology level, the engineering method level, enabling technology and the supporting environment level, respectively. These three levels interact with each other and together provide support for complex systems. The influence among them may be positive or negative. For example, design concepts or methodology may produce new engineering methods which will promote the development of corresponding enabling technologies and supporting environments; conversely, the development of enabling technologies and supporting environments may also change engineering methods, or even produce new ones.

At present, the most representative viewpoints in the engineering methodology of complex systems include system engineering concepts, concurrent engineering concepts, and integration concepts. Among them, systems engineering researchers first took the engineering object as a system in their research. In the 1940s, the Bell Telephone Company of the United States firstly proposed the term "system engineering". On the other hand, operations research gradually matured in World War II and was used in operation and management after the war, laying the foundation for the importance of system engineering. In 1957, the first book on "system engineering" was published, and then in the early 1960s, systems engineering gradually matured and officially became an independent discipline. The ideas and methods of systems engineering come from different industries, and its core role is to organize and manage the scientific ideas and technologies of engineering activities in accordance with the principles and methods of system science.

Concurrent engineering, as a systematic idea, was first proposed by the Defense Advanced Research Projects Agency (DARPA) in 1986. Later, in 1988 the Institute for Defense Analysis (IDA) of the United States released the famous R-338 report, which clearly put forward the idea of concurrent engineering, and at the same time gave the most influential definition of concurrent engineering: "Concurrent engineering is a systematic working mode to provide parallel and integrated design for a product and its related processes (including manufacturing process and support process) [2]. This working mode strives to enable developers to consider all the elements of the product life cycle from the beginning, including quality, cost, schedule, and user needs". The core idea of concurrent engineering is to organize product-centric and interdepartmental integrated product teams (IPT) for product development and to achieve rationalization of the product development process through the improvement and reorganization of the process.

In 1990, Prof. Xuesen Qian named the method of dealing with open complex giant systems for the first time as integration method. The integration methodology clearly advocates to combine qualitative and quantitative research, combine scientific theory with empirical knowledge, and also combine multiple disciplines to conduct an integrated research based on the system idea. To unify the macro and micro researches of complex giant systems, it must be supported by a large-scale computer system, and the system is required not only to have functions such as information management and decision support, but also to have integrated functions.

These three concepts were put forward by different advocators in different generations, so they focus on different aspects. As Gardiner pointed out, "Concurrent engineering and systems engineering focus on different aspects of the same object, and the two methods should be integrated to solve the issues". Compared to the former two, the focus of the integration method is the complex large-scale system, which can be regarded as the inheritance and development of the two in a sense.

It is noted that these three methodologies all follow the basic idea of system science, emphasizing the combination of reduction analysis thinking and comprehensive thinking, ensuring that the overall understanding is based on a detailed understanding of its parts, so as to break the existence issues of the modern engineering which using reductionism as the basis. In addition, although the three concepts have similar or overlapping parts, in fact they are still evolving continuously on their own, and have not yet formed a completely unified methodology.

1.2.1.3 Practical Applications of Engineering Methodology for Complex Systems

Complex system engineering concepts represented by systems engineering, concurrent engineering and integration, and related methods and technologies have been successfully applied in large-scale engineering systems and have achieved significant application effects.

System engineering was first successfully applied to the "Apollo" moon landing program, which is a large-scale R&D project. During its implementation, hundreds of prime contractors, tens of thousands of companies, and enterprises participated in the development work. The entire project has a total of more than 15 million parts and components, costing more than 20 billion US dollars, lasted 11 years and finally achieved success. The idea of concurrent engineering and its theoretical methods were first applied in companies such as Boeing and Lockheed Martin. For example, Boeing has adopted the new concept of "parallel product definition" and new project management methods in the development of the new 767-X aircraft, thereby achieving the goal of a successful flight test within three years. The thought of "integration" proposed by Prof. Xuesen Qian was first successfully applied to the quantitative study of several complex weapon systems in China.

In recent years, concepts such as concurrent engineering, systems engineering, and integration have been continuously applied in some major engineering system fields all over the world. People have been exploring in application to promote the development, enrichment and perfection of the relevant theories. Such as China's manned spaceflight project and the Joint Strike Fighter (JSF) project jointly developed by the United States, United Kingdom and other countries. In these projects, the boundaries of various engineering methodological concepts are becoming more and more blurred, and their application is often a comprehensive manifestation of multiple concepts. The ideas and methods of system engineering were used not only to organize and manage the overall process of the entire project, overcome a series of difficulties and obstacles caused by the complexity and uncertainty of large-scale engineering systems, but also in various elements of the product's life cycle were was considered to reduce the cost in product design early stage, according to the idea of concurrent engineering. At the same time, the project also contained the idea of integration.

The engineering methodology, engineering methods, and enabling technologies of complex systems are driven by the requirements of engineering system projects. Along with the successful experience and the failure lessons of engineering practice, new ideas, methods, and technologies are continuously emerging. With the increasing complexity of modern engineering systems, the solution of engineering problems will inevitably move towards the dialectical unity of "reduction theory" and "system theory", that is, to solve the complexity of engineering systems through the viewpoint of "system theory".