The rise of systems engineering in China
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Simplifying complexity

*Systems engineering focuses on optimizing individual work processes, as well as the coordination of those processes.*

### Systems engineering in China

This publication is dedicated to a comprehensive discussion of the emergence, origin, formation, development, and future of systems engineering in China.

It is difficult for the human mind to comprehend the vastness and complexity of the world in which we live. We have trouble fully grasping complicated networks of interactions, such as the interactions of hundreds of organisms in a forest ecosystem or the interplay of weather patterns across the globe. Reductionist thinking, which breaks down complex systems into smaller, more easily digestible parts, seems to be the most natural and comfortable way for us to intellectually ingest our environment. However, this paradigm can only get us so far, and it is unsuitable for either understanding or managing highly complex systems.

Take, for instance, the creation, management, and realization of a complex task such as building a spacecraft or developing an entire program for the security and defense of a sovereign nation. These undertakings are so complex as to confound the application of reductionist analysis, and require a different approach.

Enter systems engineering, a system of thought and research that analyzes a problem holistically and on a system-wide level. Systems engineering focuses on optimizing individual work processes, as well as the coordination of those processes.

Chinese-born scientist Hsue-Shen Tsien (Xuexen Qian) is regarded as the father of systems engineering in China, and provides the anchor for this latest Science supplement. It follows his life and work, both in China and the United States, as he developed his theories and applications for systems engineering. Although Tsien grew up in China and completed his undergraduate education there, much of his formative education took place in the United States, where he attended both the Massachusetts Institute of Technology and the California Institute of Technology, later taking teaching positions at both institutions.

Tsien played a critical role in the growth of the U.S. missile and space rocket program in the 1940s before returning to China in 1955, where he spent the remainder of his life leading that country into the modern age in space exploration and missile defense, even playing a role in the development of its nuclear weapons.

Tsien retired in 1991 and died on October 31, 2009, leaving a vast legacy of work in systems engineering and many other fields that has improved our understanding of complex systems, how they work, and how to manage them. China is undoubtedly a stronger world power today because of Tsien’s research and influence.

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Science/AAAS

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**Overview**

This publication is dedicated to a comprehensive discussion of the emergence, origin, formation, development, and future of systems engineering in China. It follows the life and work of Hsue-Shen Tsien, the father of systems engineering in China, and provides an anchor for this latest Science supplement. It follows his life and work, both in China and the United States, as he developed his theories and applications for systems engineering. Although Tsien grew up in China and completed his undergraduate education there, much of his formative education took place in the United States, where he attended both the Massachusetts Institute of Technology and the California Institute of Technology, later taking teaching positions at both institutions.

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Editor, Custom Publishing

Science/AAAS
The first systems engineering research base in China

China Academy of Aerospace Systems Science and Engineering (CAASSE)

China Aerospace Science and Technology Corporation Software Evaluation & Testing Center

The emergence of systems engineering theory in China

China Academy of Aerospace Systems Science and Engineering (CAASSE)
China has a long history and culture, including a rich history of systematic thinking, which is present in many ancient philosophical works. The theory of yin and yang, the “five elements” theory, and the “divinatory symbol diagram,” which emerged in the Western Zhou Dynasty over 2,000 years ago, are all clear evidence of this. According to the theory of yin and yang, the universe is formed of these two basic elements. Yin and yang interact strongly, rather than being isolated from each other, through the constant development of matter, energy, and information. The five elements theory holds that the universe consists of wood, fire, earth, metal, and water, and that natural evolution can be attributed to the motions of connected and interactive elements as opposed to static and isolated ones. The book Huang Ji, Jing Shi Shu, by Yong Shao of the Song Dynasty (960–1279), advanced the theory of a layered and constantly evolving universe. Yong believed the universe was derived from the evolution of taiji or tai chi, which consisted of two elements and four states (tai yang, tai jing, shaoyang, and shaoyin) as represented by the “eight diagrams.” Such systems were not only representations of the natural world outside, but also were expressed in many major projects in ancient China, which aimed to transform nature. For instance, the Dujiangyan Irrigation System, initiated in 256 BCE, consists of three major parts: the Minjiang River water-separation project, known as the “Fish Mouth Levee,” the flood-separation and sediment-disposal project (the “Flying Sand Weir”), and a water-diversion project (the “Bottle-Neck Channel”). Together, this intricate combination of irrigation networks successfully resolved irrigation and flood control problems in the Chengdu plain. During the reign of Zhenzong in the Song Dynasty, minister Wei Ding was tasked, under tight time constraints, with restoring the royal palace. He put in place a planning system that adopted integrated processes including “digging ditches, kilning bricks, diverting the Bian River, transporting gravel, disposing of sewerage, and covering ditches” (2). By employing scientific organization principles and rigorous logistics, he achieved swift progress at a far lower cost than was previously possible.

Numerous examples of such projects can be found throughout Chinese history, including the Great Wall, the Beijing-Hangzhou Grand Canal, and even the legendary tale of Emperor Yu taming the flood. All of these stories are examples of the astute application of systems engineering theory.

Ancient Chinese philosophers have also hypothesized about how the human body system came to be. The theory of traditional Chinese medicine and pharmacy was developed using yin and yang and the five elements as its theoretical basis. A classic work of Chinese medicine, Huangdi Neijing, was written during the Eastern Han Dynasty (25–220 CE) and still has tremendous value today. It uses the theories of yin and yang and the five elements to highlight the interdependence and interconnection between human organs, physical and mental phenomena, and the status of both the body and the natural environment. It does this by treating the human body as a microcosm of nature and an organic whole. Natural phenomena, physiological phenomena, and mental activities are combined in order to find the source of disease. Traditional Chinese medicine has developed a treatment principle that incorporates the “harmony between heaven and man” and seeks to balance the needs for maintaining health with the rules of nature. As described in Huangdi Neijing, the human body is an organically integrated and closely interacting system of tissues and organs.

Laozi, a philosopher who lived at the end of the Spring and Autumn Period (770–221 BCE), believed that nature is a complete system; as a result, its phenomena should be observed and explained systematically. Similar to Laozi’s thinking, the ancient philosophy of naïve materialism also emphasized the unity and integrality of nature. For example, it was believed that the overall effect of geographical location, climate, environment, and natural resources exerted great influence on people’s lifestyle and productivity. Therefore, we believe that all these factors need to be taken into consideration when seeking to improve people’s quality of life.

During the Eastern Han Dynasty, Heng Zhang put forward the “Theory of Spherical Heavens,” Ilya Prigogine, the founder of dissipative structures theory, pointed out in the preface to the Chinese version of his book, From Being to Becoming: Time and Complexity in the Physical Sciences, that “China’s traditional academic thought focuses on the integrity and spontaneity of systems so as to look into coordination and cooperation.”
Engels in his book Dialectics of Nature: “For the Greeks, whose ideas were not developed enough to dissect and analyze nature, nature was still perceived as a whole, where general connections between natural phenomena were not proven in the details.” It was not until the second half of the 19th century that the boom in modern science yielded suitable analytical methods, that natural details could be extracted from general connections. Figure 1 shows the development of ideas in systems and systems engineering thought during this period in China.

2100 BCE–Mid-1800s
Evolution of ancient systems thought—Pre-Qin Period to the birth of Marxist philosophy.

200 BCE–Mid-1800s
Systems engineering in China has seen significant breakthroughs recently thanks to the solid foundation laid by the first generation of systems engineering ideas, embodied by H. S. Tsien (Xuesen Qian). Determined to pursue a career in science from a young age, Tsien went on to study and work in the United States for 20 years before returning to China, where he played a vital role in the establishment and growth of China’s aerospace industry. He brought a strong theoretical background and extensive experience, coupled with a unique scientific perspective, to the creation of the discipline of systems engineering in China and he also developed a theoretical system and methodology for systems engineering.

The first stage

The emergence and maturation of Tsien’s systems engineering theories were influenced by his rigorous domestic education and the political, economic, and social environment of his time.

At an early age, Tsien received a comprehensive education from his parents. Jinfu Qian, Tsien’s father, studied in Japan when young and was exposed to the advanced concepts of Western education and ideas popular at that time. He applied these ideas, integrated with a traditional Chinese education, in the education of his own children. This had a tremendous impact on Tsien’s early growth and development. Under his father’s tutelage, Tsien not only studied science and engineering, but also literature and the arts. In this way, when at home he received training both in logical thinking and in how to harness his imagination. Tsien had broad interests, encompassing painting, photography and music. He often attended performances of the Boston Symphony Orchestra while studying at the Massachusetts Institute of Technology. His wife, Ying Jiang, was a well-known vocal music educator who both encouraged and intellectually challenged Tsien, enabling him to expand his thinking. “An innovative scientist must not only be scientifically knowledgeable but also culturally and artistically cultivated,” Tsien said.

Tsien’s childhood coincided with a critical time in Chinese history. When the Qing Dynasty was toppled and the Republic of China founded in 1912, the first president, Sun Yat-sen, introduced the “Plan for National Reconstruction,” advocating the idea of “rescuing the country through railroad construction.” Deeply influenced by Confucianism and the movement to save the nation through industrialization, Tsien made his first major career choice after graduating from senior high school. He decided to study railroad engineering. Two years after his enrollment in the railroad mechanical engineering course at Shanghai Jiao Tong University, on September 18, 1931, the Mukden Incident took place, and Shanghai was subjected to severe air raids by Japanese forces throughout the following year. Shocked by the apparently helpless Chinese army and the lack of any means for the average citizen to fight back, Tsien realized that China badly needed an air force and a more advanced aviation industry to better safeguard the nation. Achieving this goal would require research in aviation theory and technology. In response to Sun Yat-sen’s call to “save the nation through aviation,” Tsien was determined to contribute to China’s aviation industry, making his second major career choice: to study aeronautical engineering.

Although he did not receive the highest grades at Shanghai Jiao Tong University, Tsien developed good scientific habits, such as seeking the underlying truth in facts and always using a meticulous approach to his work. Upon graduation, he continued his aviation studies at Tsinghua University and then, in order to study advanced aviation theory and technology, he applied to study in the United States as a state-funded student. Tsien was not only accepted with excellent grades but also received a Boxer Indemnity Scholarship, a funding scheme that allowed Chinese students to study in the United States. His studies at the California Institute of Technology (CalTech) “enlightened me in every aspect,” wrote Tsien, thanks in large part to the innovation-oriented education he received under the tutelage of Professor Theodore von Kármán. It was during this time that Tsien gradually developed his academic independence. His friendship with von Kármán (who was also his mentor) deepened, and they worked together to develop the mathematical formula known as the Kármán–Tsien formula. Von Kármán spoke very highly of his former student: “I found him very imaginative, very talented in mathematics, as well as being extraordinarily skillful, with precise insights into physical images through his imagination. Still a young student, he helped me refine some of my own ideas, achieving a clear and thorough approach to strenuous propositions and questions” (3). Guided by his innovative spirit, Tsien constantly expanded his knowledge and became an authority in mechanics, applied mathematics, and aerodynamics, laying the foundation for his later achievements in aerospace.

Building a foundation of ideas

Tsien arrived in the United States in 1935. Upon completion of his aeronautical engineering training at the Massachusetts Institute of Technology, he shifted focus from engineering toward aviation theory, the third important career choice of his life. He felt that aeronautical engineering at that time was guided more by experience than theory, and that studying theory would yield twice the results with half the effort. This was a time of propeller-driven aircraft; supersonic aircraft and jet propulsion technology were still in their infancy. The solid...
In 1941, together with von Kármán, Tsien cooperated with the U.S. military and successfully built the first supersonic wind tunnel laboratory capable of continuous operation. This achievement laid a solid foundation for the support, testing, and design of supersonic aircraft in the United States. Throughout a series of research and publications, Tsien demonstrated his deep understanding of the aerodynamics and design requirements for high-speed aircraft travel, thus earning him worldwide acclaim as an aerodynamics expert who had overcome many obstacles. The global aviation industry’s entrance into the supersonic era. Even while still in college, Tsien had been deeply interested in the latest developments in rocket technology. He maintained this interest throughout his studies in the United States, recognizing the great potential of this technology for the military. Although U.S. rocket technology in the 1930s was still in an experimental stage, Tsien and some of von Kármán’s other students created an informal interest group called the “Rocket Club” in 1936. Tsien derived new theoretical calculations that modeled rocket flight. Although it was created by students, the Rocket Club made several important advances, doing pioneering research that drew attention from all quarters. Many of its members later became pioneers in the field of spaceflight, and all made significant contributions.

In a 1938 report about the Rocket Club, published in a CalTech campus newspaper, Tsien explained his vision of future rocketry: “The planned rocket will have three independent parts. A great deal of energy will be needed. The rocket will be propelled into space. It will be launched from the earth into space.”

Prior to the 1940s, it was widely thought to be impossible for aircraft to achieve supersonic speeds. In 1941, together with von Kármán, Tsien cooperated with the U.S. military and successfully built the first supersonic wind tunnel laboratory capable of continuous operation. This achievement laid a solid foundation for the support, testing, and design of supersonic aircraft in the United States. Throughout a series of research and publications, Tsien demonstrated his deep understanding of the aerodynamics and design requirements for high-speed aircraft travel, thus earning him worldwide acclaim as an aerodynamics expert who had overcome many obstacles. The global aviation industry’s entrance into the supersonic era. Even while still in college, Tsien had been deeply interested in the latest developments in rocket technology. He maintained this interest throughout his studies in the United States, recognizing the great potential of this technology for the military. Although U.S. rocket technology in the 1930s was still in an experimental stage, Tsien and some of von Kármán’s other students created an informal interest group called the “Rocket Club” in 1936. Tsien derived new theoretical calculations that modeled rocket flight. Although it was created by students, the Rocket Club made several important advances, doing pioneering research that drew attention from all quarters. Many of its members later became pioneers in the field of spaceflight, and all made significant contributions.

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used comprehensive and systematic thinking to create holistic, strategic plans, while always keeping the needs of the nation in mind.

In November 1944, U.S. Army Air Forces Commander General H. H. Arnold wrote a memorandum entitled “U.S. Research and Development Plan for the Immediate Post War Period and the Next War,” in which he suggested that scientists serving in the U.S. military during World War II should form “an independent research institute between governmental and non-governmental sectors for objective analysis” to “avoid future national disasters, and to win the next war.” Accordingly, in 1946, the U.S. Army Air Forces signed a $10 million R&D project contract [the famous “RAND (research and development) Project”] with the Douglas Aircraft Company.

On February 13, 1946, General Arnold wrote a letter praising his work on Toward New Horizons, and for the outstanding contributions he had made. In 1948, with a $1 million donation from the Ford Foundation, General Arnold, then retired, separated the RAND Project from the Douglas Aircraft Company and established the independent RAND Corporation, which was first and foremost a think tank. It became famous for research on advanced military science and technology, and later emerged as a world-class institution dealing with a comprehensive array of subjects.

In 1948, Tsien began his research into lunar exploration, making a bold prediction that human beings would fly to the moon in less than 30 years, and that the trip would take only one week. In 1950, he introduced the concept of the “rocket airliner” at the annual meeting of the American Rocket Society. Far ahead of its time, the rocket airliner was the forerunner of the space shuttle as we know it today. With many of his hypotheses and bold predictions becoming reality years later, Tsien was acknowledged in the U.S. press for his vision. The New York Times called him a “valuable Chinese scientist” and “the most talented rocket scientist in the U.S.” The New Angeles Times described him as “one of the most authoritative rocket experts in the world,” among many other accolades. At the time, he enjoyed a high social status, with access to the formulation of plans and information about U.S. national defense projects.

Tsien’s theories, forward-thinking ideas, and scientific predictions, as well as his insightful reports on postwar development of aircraft, rockets, and missiles established him as a leading figure in the field of mechanics and jet propulsion during the first part of the 20th century.

**Physical Mechanics and Engineering Cybernetics**

In 1950, Tsien wrote the acclaimed works *Physical Mechanics* and *Engineering Cybernetics*. Physical mechanics is not a subdiscipline of classical physics, but rather a new branch of applied mechanics. Tsien established this new science by combining atomic and molecular structure theory, quantum mechanics, and statistical mechanics. In 1953, he published the paper “Physical Mechanics—A New Field in Engineering Science,” which officially introduced the concept of physical mechanics, marking the emergence of the new field of high-temperature and high-pressure hydron mechanics (13). Later, Tsien developed the physical mechanics program at CalTech and formulated a physical mechanics textbook with contents drawn from his teaching and research in the subject.

In 1955, Tsien returned to China and began to vigorously advocate for advanced research into physical mechanics, bringing the latest content and ideas to Chinese researchers and students. In 1956, he created the Institute of Mechanics at the Chinese Academy of Sciences. Then in 1958, he established a physical mechanics major at the University of Science and Technology of China, where he lectured. That same year he wrote that “physical mechanics was introduced to meet the requirements of new technology. Therefore, it is a new discipline, which means that there aren’t many people working on it even in countries possessing advanced science and technology. In our country, it is only a bud and requires tremendous support to achieve fast development and meet the demands for new technology” (14).

After World War II, a paradigm was developed to objectively study the world, utilizing the structure and function of systems (including coordination, control, and evolution). Systems theory, operational research, cybernetics, and information theory emerged in the 1940s. These were the early theories upon which systems science was based. Systems engineering, systems analysis, and systems management science emerged in the same period, at a time when the engineering applications of systems science were becoming commonplace.

Norbert Wiener’s book *Cybernetics* was published in the 1930s and 1940s, when automatic control technology and statistical mathematics were booming. The birth and development of cybernetics held great significance for systems science, in that cybernetics allows the principles and rules of a large collection of systems to be extracted, including biological and artificial systems. All the collected systems were in fact the main objects of study in systems science research. Using Wiener’s original work, *Cybernetics: Or Control and Communication in the Animal and the Machine* (13), as a guide, Tsien wrote *Engineering Cybernetics* (16). The book, three years in the making, was first published in 1954 in English in the United States, and was later translated into several languages, with versions published in the Soviet Union, East Germany, and China in 1956, 1957, and 1958, respectively.

*Engineering Cybernetics* concerned those aspects of cybernetics that could be applied directly in engineering in order to design controlled systems. It extended Wiener’s ideas to the engineering field and combined general theories with practical engineering. As a brand new science, engineering cybernetics contributed significantly toward the development of both automation and systems science. Tsien had long held the opinion that Wiener’s Cybernetics was based on a technological theory that embodied systems science and played an important role in the formation and development of systems ideas and concepts. Cybernetics was a collection of design principles and testing methods frequently used in engineering practices. Furthermore, the concept put forward in *Engineering Cybernetics* that a reliable system could be achieved by decomposing its components, and the idea that the overall performance of components would be improved through the optimization of the whole system, reflected Tsien’s systems engineering thinking in a more direct way. By generating scientific theories based on common properties (such as integrality, coordination, resilience, and reliability), scientists and researchers could be empowered to see technological problems more systematically. This understanding, in turn, enabled these researchers to more fully understand and exploit new technology to direct different engineering practices and drive the development of systems engineering.

*Engineering Cybernetics* was an important theoretical source for Tsien’s systems engineering ideas, and a direct catalyst to the development of systems science. According to Guozi Xu et al., writing in the preface of Tsien’s book *On Systems Engineering*, “From the perspective of the development of modern science and technology, *Engineering Cybernetics* was way ahead of general objects of study of automatic control theory at the time.”

**From the perspective of the development of modern science and technology, Engineering Cybernetics was way ahead of general objects of study of automatic control theory at the time.**
science toward systems science. It studied the relations between objects and movements of matter as well as system control, which are the system properties of these relations” (17).

For the first time, Engineering Cybernetics put forward theories, concepts, and methods for controlled engineering systems that were directly applicable to engineering designs and experiments. It was a classic monograph that creatively discussed control and guidance, and revealed the influence and significance of cybernetics on science and technology through a more broadminded and systematic method. Weimin Bao, an academician of the Chinese Academy of Sciences, called Engineering Cybernetics “a classic book on control and guidance, which revealed creatively the implication and significance of cybernetics to the automation, aerospace and telecommunication fields,” adding that it was the reflection and extension of Wiener’s Cybernetics (18).

Engineering Cybernetics offered readers a universal theory that they could use to solve engineering challenges, enabling a more systematic approach to solving engineering control problems, and brought cybernetics into the field of engineering technology. It was pivotal in the development of automation science and technology theories. In particular, Tsien’s discussion of the construction of highly reliable systems using unreliable components reached far outside current research into automatic control theory, applying this concept to the field of systematics. Therefore, this work was considered a milestone in the development of systems science.

In 1948, Tsien wrote in “Engineering and Engineering Sciences” that “modern science and technology research is no longer unplanned individual activities. The government of every major nation has realized that such research is the key to national strength and people’s welfare, which must be organized and strictly controlled” (19). For this reason, he recommended that the U.S. government establish a Department of Jet Weapons that would lead the development of rocket and missile technology. In 1955, following discussions with colleagues, Tsien proposed the idea of combining operational research and socioeconomic development.

Tsien’s ideas on systems engineering were directly linked to his early education. It was his experience of frequently shifting focus, changing from railroad engineering to aviation studies, moving from China to the United States, then changing from aerospace engineering to aviation theory, and finally to the emerging fields of rocketry and missile technology, that gave him the ability to assimilate multidisciplinary knowledge at a high level. Through this environment of constant learning, Tsien gradually honed his systems engineering ideas while also laying the foundation for his unique academic vision and for the development of systems engineering in China.

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On September 17, 1955, the SS President Cleveland left San Francisco, California, carrying H. S. Tsien back to China. He disembarked in Hong Kong on October 1, and a week later reached Beijing, arriving at a time when the country was devastated by war and poverty and besieged by economic, military, and political ills. In short, China’s national security was in dire straits.

**Systems engineering in defense**

Tsien did not expect that his fate would be so closely tied with China’s national defense industry, specifically its missile and rocket program. On February 17, 1956, he submitted a document titled “Proposals on Establishing China’s National Defense and Aviation Industries” to the Chinese State Council (1), which outlined his ideas for developing China’s missile industry. The document comprised four parts:

1. **Sectors required by the aviation industry.** Tsien pointed out that in addition to manufacturing plants, a sound aviation industry should also have a sector that can provide design research and testing services, as well as a sector carrying out broad, long-term research. Tsien detailed the differences between these two sectors with respect to the nature of the research, the tools to be used, and the research staff to be employed.

2. **Organization of the aviation industry.** This section included details about aviation industry leadership, scientific and design research, and manufacturing facilities.

3. **Current state of domestic research.** China’s shortcomings in the aviation industry were laid out, such as the lack of materials, research capacity, and manpower.

4. **Development plan.** Here, Tsien suggested that research, design, and production should be given equal priority, with no one area advancing more rapidly than the others.

In his proposals, Tsien systematically delineated his thoughts regarding the development of China’s rocket and missile technology. He provided a detailed analysis of the current state of the domestic aviation industry and related talent pool, suggesting organizational solutions, implementation plans, and specific measures for developing missile technology. He also proposed a long-term development plan for short-range and medium-range missiles, as well as for intercontinental ballistic missiles (ICBMs).

Furthermore, he spelled out the urgent necessity for establishing the research, design, and production sectors of China’s national defense and aviation industry. Specifically, he made the following suggestions:

- Setting up an aviation bureau under the Ministry of National Defense with the authority to undertake comprehensive planning and leadership;
- Establishing national aviation organizations with nationwide recruitment capabilities; and
- Seeking international support from other governments.

Tsien’s proposals provided the first blueprint for China’s missile program. They immediately drew the attention of decision-makers from the Chinese Communist Party and the state alike.

Tsien was subsequently appointed head of the drafting group for the government’s National Long-Term Plan for the Development of Science and Technology (1956–1967). He supported the central government in establishing atomic energy and missile defense as top national priorities. He insisted that missile technologies be developed prior to focusing on aviation, and as such played an important role in prioritizing China’s weapons programs and ensuring the country’s national strategic security. The foresight and far-reaching implications of this approach became increasingly apparent in the ensuing years.

Tsien excelled at strategic planning and top-level design, using his expertise to guide the development of national defense-related science and technology. On July 10, 1959, Tsien sent a letter to Ding Ai, the Party Secretary for the Shanghai Institute of Mechanical and Electrical Engineering (formerly the Rocket Engineering Institute), suggesting the creation of the Department of Integrative System Design (DSD) to ensure the successful manufacture of large launch vehicles. “Designing and manufacturing large rockets is a very complex task,” he stated in his “Proposal on the Development of the Shanghai Electrical and Mechanical Design Institute,” adding, “It is a highly integrated project, requiring a huge and highly skilled technical team,
as well as massive national investment. Therefore, setting up two design and manufacturing systems simultaneously will be the first thing to consider for China, with its underdeveloped science and technology. Only the National Ministry of Defense is presently capable of undertaking the design of large rockets” (2).

The aerospace engineering system features complexity, intense technological demands, high reliability, high integration, high risks, and a long development cycle. Nevertheless, when the nation called for me to do it, I had no doubt in my mind about the wisdom of doing it without thinking twice. It was only after I started that I realized how difficult it was and how much energy it required. I was under extreme pressure since the nation could afford to spend very little, due to its dire economic condition.

Large-formation warfare refers to engagements of thousands of people, which was a massive organizational feat. Furthermore, during testing, the "two bombs" project required the coordination of several thousand people, which was a massive testing environment. Based on their experience with large-formation warfare, Chinese leaders had established DISD and initiated the development of cutting-edge technology for defense. This experience was a defining factor in the development of China’s national defense policy and strategy. Tsien remarked, “The entire development project of missiles, atomic bombs, hydrogen bombs, and satellites in China was conducted under the leadership of Premier Enlai Zhou, with Marshal Rongzhen Nie responsible for specific implementation. There had never been such a challenge facing China before. I think Premier Zhou and Marshal Nie took advantage of the experience gained while organizing the PLA and leading revolutionary wars. Fortunately, it worked. Methods developed for organizing and leading the ‘two bombs’ project remain relevant in the new era” (6). Large-formation warfare refers to engagements involving large numbers of soldiers on both sides, complex and fast-moving combat, and flexible and changeable tactics. Tsien offered an excellent grasp of strategy and tactics, particularly when one side is outnumbered or facing a better-equipped enemy. The only hope of defeating such an opponent lies in integrating combat thinking, command, and flexibility.

Large-formation warfare emphasized a combination of unified command, administrative management, and combat technique management, which had previously provided a model for the development of China’s aerospace engineering projects. By applying their systems engineering knowledge, the older generation of aerospace pioneers, such as Tsien, created comprehensive designs that incorporated prototype requirements, design principles, technological systems, and possible solutions. This work strengthened the technical foundation and reinforced the role of administrative management, creating an interactive and flexible management workflow that integrated a unified command system. In this way, military wisdom laid a methodological foundation for the development of China’s national defense industry. When it comes to collective labor, tasks or functions are divided among individuals or groups. In all large-scale engineering projects there is a department of general design, which effectively coordinates the various parts within the complex whole, enabling the entire system to perform as required. The department needs to direct specific components in order to guide design decisions and ensure the smooth operation of the whole. The “two bombs” project required the coordination of thousands of engineering projects in a highly organized fashion. Furthermore, during testing, almost half of the nationwide communication network was needed. The manned spacecraft project included several hundred units that were directly involved in the project, several thousand supporting units, and some 400,000 participants. Guided by systems engineering principles
advocating the concentration of nationwide resources to ensure national security, China's large-scale coordination of science and technology research was implemented. The application of this coordination to the service of national defense not only played a key role in advancing the aerospace industry, but also provided support for the development of systems engineering in China in terms of stimulating ideas, theories, methods, technologies, and projects.

**Promotion of systems engineering ideas in China**

On July 12, 1961, Tsien submitted a proposal to Marshal Nie to establish a Science and Technology Commission for the Fifth Academy. It was to be staffed by senior technological experts and would be tasked with, among other issues, studying the technical feasibility and workflow for the development of rocket prototypes, and with providing suggestions and advice to the Communist Party Committee and administrative leadership based on their findings. The Science and Technology Committee was founded on February 2, 1962, with Tsien as the director. Subordinate to the Science and Technology Commission, 16 professional teams were established, with the deputy directors also serving as team leaders. Each team developed its own plans and prioritized preliminary research projects in accordance with the requirements of each task in the workflow for the development of the rocket prototype. One hundred and forty-nine experts and scholars from both inside and outside the Fifth Academy were hired as members. They regularly gathered to discuss and design the development plans and preliminary studies for aerospace technology in the short, medium, and long term. The research work of the Science and Technology Committee enabled government leaders to make more effective scientific decisions.

On April 2, 1963, at the first annual meeting of the Science and Technology Committee, developmental approaches for building ground-to-ground missiles, ground-to-air missiles, and coastal defense missiles were discussed. These findings were ultimately incorporated into the plan for the Fifth Academy and were later implemented. The goals of training the best researchers and realizing research breakthroughs were fulfilled, as a large number of skilled experts were hired. These researchers had experience in the design, manufacture, and testing of aerospace prototypes. Two researchers, Yongzhi Wang and Jiadong Sun, later won the State Supreme Science and Technology Award.

Ultimately, the number of people elected as academics outnumbered those in any other industrial sector.

In the early 1980s, following instructions from Aiping Zhang, the then-director of the National Defense Science and Technology Commission, the Science and Technology Committee of the Ministry of Aerospace Industry (under the Ministry of Defense, and a different committee than that discussed above) hired senior experts from various aerospace academies as its standing members to help establish the general direction of the research and the specific requirements for designing and building rocket prototypes. In order to make full use of these experts' experience and ensure the effectiveness of their decisions, all major planning and decisions were required to achieve consensus among the standing members, and then to gain approval from the Ministry's leadership before they could be reported to the National Defense Science and Technology Committee. This model has now been copied in other research institutions and laboratories involved in R&D, and even in government departments and enterprises.

Tsien played multiple roles in the development of the aerospace industry in China. He was a planner, an implementer, a leader, and a tutor. Under his leadership, despite the difficulties, many advances were made. The “four bombs in eight years” plan (1965–1972) was a long-term program to develop four launch-vehicle prototypes in eight years. It was also the first of such plans with clear aims and milestones. With the full support of then-Premier Enlai Zhou and the Communist Party leadership, milestones were successfully developed.

Through his vision as a strategic scientist, Tsien thought big, but nevertheless showed great attention to detail, meticulously planning, organizing, and implementing China's aerospace program. Taking the success of the first generation of missiles in China as an example, Tsien eloquently stated that the strategy for the development of cutting-edge technology in China must be transformed from “catch-up” to “catch-up and surpass.” In the former case, the path of the follower is always determined by the leader, he explained; the follower can narrow but never eliminate the gap between them. But, when the follower overtakes the leader, they can create a new path and destiny of their own. It was Tsien's hope that China might transition from follower to leader, and thus advance to the forefront of aerospace and missile defense.

**The systems engineering-based management of the Chinese aerospace program**

Tsien drew valuable lessons from his broad experience. He applied theories from engineering cybernetics, a field he established, to solve management difficulties in simple systems. Influenced by the concepts of large-formation warfare seen during his time with PLA, and taking into account the rapid expansion of China's space industry and workforce, he advanced an innovative management strategy called “one headquarters and two lines of command,” which incorporated technical and administrative management into one command structure (Figure 1). This strategy enabled improvements in engineering management, allowing breakthroughs in the aerospace industry to be made in a more rational and orderly way than previously done.
The role of the Department of Integrative System Design

The concept denoting DISD as the “one headquarters” originated from the organization and management of large-scale scientific and technical projects for the development of missiles and atomic bombs, which took place in the late 1950s. Methods developed during that time were innovative not only in terms of organization and management, but also from a systems engineering perspective.

The experience gained by Tsien while working with PLA was applied to scientific research and the development of cutting-edge defense technologies. He drew on his engineering experience to establish DISD, which allowed him to advance his strategy.

The aerospace systems engineering approach

The development of rockets, missiles, and spacecrafts calls for an integrated approach to a large-scale aerospace project, which, by definition, requires considerable manpower as well as material and financial support. The final product is a complex system comprising many instruments and modules, each of which has many units and parts. These elements are closely linked, constituting a truly integrated system. The development of each component demands several steps, including prototype research, design, and manufacturing: design testing, finalization, and production; and finally delivery. Multiple disciplines and specialties are involved and new technologies required. Workshops and prototype production are also required. The entire development process includes three phases—preliminary study, prototype development, and formal production—and typically, as the first-generation prototype goes into production, second- and third-generation prototypes are already in the pipeline.

Given the size and complexity of aerospace projects, the challenge is how to organize and manage a project so as to generate products that are technically advanced, reliable, and cost-effective within a given period of time.

From the very earliest phases of development, China's aerospace leaders devised and implemented a unique organizational and managerial strategy, which became known as the "aerospace systems engineering approach." It included the following elements:

1. Scientific and technological management was carried out by DISD. Specialized workforce who were familiar with large-scale engineering systems were organized, while experts with broad background knowledge (chief designers) led the project. DISD was responsible for designing technical solutions for the entire system and coordinating their application. Technical issues were handled at a subsystem level, but coordination occurred at a higher, whole-system level. When conflicts arose between subsystems, or between subsystems and the system as a whole, DISD considered the overall system requirements and chose the optimal solution, using analyses and simulations as a guide.

2. Management authorities used specialized information systems to develop, implement, and adjust aerospace engineering plans. Plans were based on available techniques and technologies to ensure feasibility, and the techniques used were implemented in accordance with the schedule. Human, material, and financial resources were distributed in such a way as to ensure successful completion of the missions.

Utilizing a new organizational and managerial paradigm, all activities were directed by two lines of command. One line involved scientific and technical decision-making using a systems engineering approach, while the other ensured appropriate resource allocation and prioritization, leading to realization. This paradigm supports the adoption of a systems engineering approach, which enables decision-makers or decision-making authorities to integrate knowledge and power in a manner that promotes project success (for more details, see page 24).

As shown in Figure 2, the two systems under the supervision of decision-making authorities performed different roles and functions, but operated collaboratively. DISD supported scientific decision-making; it took a holistic approach to understanding problems, and applied systems engineering to develop technological solutions. The data and information systems provided support to DISD and the implementing agencies such as production departments.

Systems engineering theory and DISD

The establishment of DISD, together with the associated research institutes and test bases, was guided by the principles of systems engineering. The process of setting up DISD and the managerial principles developed during its tenure contributed extensively to forming technical and managerial practices in China’s aerospace program, and were considered key to the aerospace industry’s success. Some of DISD’s key features were:

1. DISD management

DISD was the technical headquarters for prototype development. It was responsible for prototype development approval, technical command, coordination, integration, and performance optimization. Aerospace engineering R&D should adhere to the latest advances in weapon design, and DISD played an essential role in promoting independent technological innovation and the development of new prototypes to meet this goal.

The DISD management model had a significant and positive effect on the success of aerospace prototype development. It helped to establish clear definitions for the duties and obligations for this type of managerial model, including optimization of organizational structures and responsibilities, and integrating the needs of the various Chinese science academies, rocket launch bases, and contractors involved. DISD was an independent legal entity, responsible for managing its own budget. It enjoyed managerial autonomy and retained the authority to enter into support and collaboration contracts with the army and the other entities involved, pending supervisory authorization.

(2) DISD responsibilities

Apart from overall system management, DISD was also responsible for basic, exploratory, and preliminary research into the development of aerospace prototypes. It undertook studies on the performance of various designs of components and subsystems and new technologies, including feasibility analyses, tracking of key technological issues, and technical demonstrations. DISD also participated in the construction of quality control systems and acted as a technical support, consulting, and coordination center.

DISD was also the center for strategic planning of aerospace prototype development and marketing, and as such was responsible for tracking and updating the research and technical requirements of the prototype program both at home and abroad. DISD’s rapid response to prototyping and implementing various subsystems, signing related subcontracts, and ensuring the veracity of proposed solutions and evidence of their tactical and technical performance, as well as managing inter subsystem technical coordination and interfacing. DISD also provided technical support for decision-making and prototype development during overall optimization of the technological program.

DISD and prototype development

Work at DISD focused on the system under investigation’s engineering design, including the interfaces between subsystems and their performance.

During a project’s planning phase, prior to initial approval, DISD was responsible for developing a project roadmap that described technical requirements and took into account technology development trends and national political and military strategic objectives.
In the exploratory phase, DISD conducted system requirement analyses and research, providing a general system-level design proposal. During the discussion and confirmation phase, DISD provided details on optimization and integration, system requirements, and functional analyses, and validated the system's draft design. These details enabled top-level technical requirements to be transformed into specifications for subsystem hardware and software. DISD also carried out computer-based proof-of-concept analyses and preliminary analysis of the system's draft design. Once a design had been fully developed, DISD carried out the overall technical design management, dissemination of design requirements, testing and evaluation of products and systems, and whole-system testing and assessment.

Finally, during the production and application phase, DISD tracked production approvals and ensured that technical documents were current and user manuals were properly prepared. In short, as the headquarters in the “one headquarters and two lines of command” strategy, DISD played an essential role in all facets of prototype development, control, and implementation. It enabled systems to go from conceptualization to reality through an iterative process of analysis, decision-making, and revision.

A new paradigm for Chinese aerospace management: two lines of command

The “two lines of command” part of the “one headquarters and two lines of command” strategy represented a new management system that assured timely project completion. It involved the coordinated management of both technology and planning through delegation of DISD’s ideas and procedures, guaranteeing rational prototype design and effective resource allocation.

The past, present, and future of the two lines of command theory

The research and development of aerospace prototype systems was exploited as an opportunity to refine the two lines of command management system through multiple rounds of testing, revision, and optimization. In the early days of China’s aerospace industry, insufficient attention was paid to the role of systems design due to a lack of relevant managerial experience and innovation. As a result, only the administrative line of command was initially adopted.

That organizational system was finally exposed as deficient. In 1962, after the failure of the maiden flight of a short-range carrier rocket—the first to be independently designed by China—it was acknowledged by aerospace researchers and leadership that prototype development was very different from other engineering challenges. In November of that year, the Ministry of National Defense issued a directive stating that a system-design strategy was to be implemented that ran parallel to the administrative strategy. The two lines of command management system continued to evolve, eventually becoming an essential organizational component of many engineering projects. It introduced definitions of technical responsibilities, improved efficiency, and accelerated development. And in April 1984, it was codified into widespread practice when the State Council and CMC issued regulations on the development and administration of command systems for weapons research that required application of the two lines of command strategy. These regulations played an important role in strengthening technical accountability, improving management efficiency, shortening the development cycle, lowering costs, ensuring quality, and accelerating the construction of modern weapons and equipment. In addition, they clearly defined the composition of the design and administrative command systems, as well as their respective responsibilities and working relationships. As a result, the two lines of command structure gained popularity in the national defense sector.

In the early stages of the two lines of command strategy, administrative leaders were technologically inexperienced and focused mainly on ideological politics and logistical support, while the technical staff took care of planning, scheduling, and command tasks related to prototype development. But as the aerospace industry developed, a growing number of scientists assumed administrative leadership posts and moved into command positions at all administrative levels. Through increased international exchange, managers at all levels gained experience in the project management methods used by other countries, and these methods have been incorporated into China’s system. This exchange has led to the further expansion and strengthening of the scope and responsibilities of the administrative command, and a commander-in-chief-centered project management model has gradually taken shape. The paradigm has also been widely adopted by aerospace programs around the world.

In the future, the current commander-in-chief administrative model will likely prevail in aerospace systems engineering development, and the two lines of command strategy will gradually find wider application in the management of other government departments. Below, we will detail the composition of the two lines of command strategy to clarify its functions.

Structure of the two lines of command

(1) Organizational structure of the two lines of command

As described above, the two lines of command strategy encompasses both administrative and technical command. To improve quality and process control in this model, two subsystems—quality control and process management—were introduced. However, management relationships vary from organization to organization. In some cases, the two subsystems fall under the supervision of the administrative command system; in others, they are placed under the technical command system (see Figure 3).

(2) Relationships between the two lines of command systems

The administrative and technical command systems work in harmony under the supervision of their respective leaders. In order for the two command lines to work successfully and adhere to proper systems engineering principles, it is important to pay attention to their many interdependencies. Some examples include:

(i) Relationship between the subsystems and whole systems. A rocket is an immensely complex system comprising multiple parts and components. Subsystems need to be interconnected in such a way so as to realize the full functionality of the entire system.

(ii) Relationship between design and final product. Product development involves research, design, and prototype manufacture, as well as multiple rounds of testing and refinement to achieve a final product. Each phase should strictly adhere to the development procedures and plans, and work on the next phase should not begin until the current phase has been completed. The realization of the final product, which has been verified as globally feasible and in which subsystems or products meet the required design specifications, should be determined and fixed. Interface parameters between the product as a whole and its various subsystems, and between subsystems in their respective components and parts, should not be modified arbitrarily. If necessary, approval procedures should be adopted. In principle, a finalized design should never be changed. In cases where there is a limited supply of raw materials or components, for example, necessitating the use of alternative parts, additional components and parts, should never be modified. If necessary, approval procedures should be adopted. In principle, a finalized design should never be changed. In cases where there is a limited supply of raw materials or components, for example, necessitating the use of alternative parts, additional validation will be needed prior to any potential change to ensure full compatibility.

(iii) Relationship between “technological democracy” and “technological centralization.” When formulating design plans and addressing
The concepts of technological democracy and technological centralization should also be applied to issues concerning interface design and decision making. Any potential design changes should be reported to senior designers for approval. The chief designer should have the final say (adhering to a more hierarchical structure of technological centralization management), and all levels should follow his or her instructions and decisions. These concepts are scientifically feasible and effective.

A core feature of systems engineering is to conduct systematic analysis and evaluation. Simulations are widely employed in aerospace engineering, including those for initial concept design, systems development, engineering analysis, and technical indicators and development plans should not be changed unless both parties approve the proposed changes. Any military department, namely the Department of Integrative System Design, was needed, which was a high-tech team whose members had rich development experience in many supporting disciplines and various specialties. DISD originated from China’s “two bombs and one satellite” strategy and played a crucial role in its success. DISD’s proven track record shows that similar modern systems, mechanisms, and methods of organization, management, and decision-making are scientifically feasible and effective.
Tsien’s legacy

Over the past several decades, China’s aerospace science and technology industrial management system has witnessed tremendous changes in terms of mission requirements and institutional reorganization. However, as the core of the overall design, systems engineering has remained unchanged; it has been applied to guarantee the successful launch of missiles, rockets, satellites, and spacecraft. The success of China’s aerospace industry has proven the effectiveness of systems engineering. Tsien’s theory was inspired by his experience in China’s aerospace industry, and in turn advanced the industry’s progress.

After his return to China in 1955, Tsien devoted himself to the construction of China’s aerospace industry, applying his theories and ideas to a number of practical engineering issues. Tsien not only improved engineering practice in a broad sense, but also offered key insights into China’s social structure, managerial structure, and technological development. Among other achievements, Tsien:

- established China’s first rocket and missile research institution and the country’s first aerodynamics research institution;
- guided the design of China’s first liquid-fuel sounding rocket;
- assisted Nie in organizing China’s first short-range ground-to-ground missile launch test;
- jointly organized and commanded China’s first improved medium- and short-range ground-to-ground missile flight tests;
- assisted Nie in organizing and implementing China’s first “two-bombs integration” test (i.e., the integration of a missile and atomic bomb/hydrogen bomb);
- organized and implemented China’s first man-made satellite launch;
- organized and completed the Practice No. 1 satellite launch test, and obtained data from China’s space environmental probe for the first time;
- directed the design and manufacture of China’s first nuclear-powered submarine;
- commanded the successful launch of China’s first recoverable satellite; and
- organized and directed the first full flight of a Chinese ICBM as well as the launches of the first submarine missile and first geostationary orbit test communications satellite.

Tsien refined the discipline of aerospace systems engineering, transforming it into a general systems engineering field. “Systems engineering is a scientific method of organizing and managing the planning, research, design, manufacture, testing, and use of systems, and is also a scientific method, having universal significance for all systems,” said Tsien in the Chinese newspaper Wenhui Daily. It has been applied not only to simple systems, simple megasystems, and complex megasystems, but also to social systems. “The systems engineering approach was developed from a large-scale science and technology development project, which used modern organization and management techniques,” explained Tsien. “Its application scope is more extensive. It can be applied in large-scale scientific experiments, in the planning of national economy and social development, and even in the national affairs of the whole country” (8).

References

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Differing historical contexts have resulted in significant variations between China and the West as regards the creation, propagation, and evolution of modern systems engineering. It could be argued that reductionism, which has flourished over the past 300 years, especially in the West, is now being surpassed by systems theory. In China, the concept of “systems” has a long history and began to develop before reductionism was firmly rooted in the country, even though both concepts were introduced from the West at about the same time. The evolution of systems engineering in China was thus not influenced by reductionism as it was in the West. Instead, constant exploration of systems engineering theory drove the creation of a unique Chinese school of thought on this subject, from which significant advances have come in terms of both theoretical research and social applications. As Dongchuan Sun and Kejun Liu wrote, “Formed under the leadership of academicians Hsue Shen Tsien and other well-known scholars in the 1990s, the school of systems engineering in China is of global significance and its implications in the world will manifest increasingly over time; China is a big and powerful country as far as systems engineering is concerned, thus the school of systems engineering in China maintains a leading position in the world” (1).

Supporting the development of systems engineering in China

The term “systems engineering” was introduced in China in the early 1940s, but did not become an academic discipline immediately due to a lack of evidence for its applicability at that time. Initial exploration and practice of the theory gradually started to emerge in China, laying a foundation for the future development of systems engineering as a discipline. One of Tsien’s major achievements in the 1950s, the creation of “engineering control theory,” played a vital role in advancing the development of systems engineering. In his writings, Tsien stated: “Even today, the scientific thinking, theoretical approaches, and applications embodied by engineering control theory still have a profound effect on the development of subjects such as systems science and engineering, control science and engineering, as well as the disciplines of management science and engineering” (2).

Shortly after Tsien returned to China in 1955, he devoted his efforts to expanding China’s aerospace industry. Jingyuan Yu, a researcher from the China Academy of Aerospace Systems Science and Engineering (formerly the No. 710 Academy) wrote: “During the pioneering phase of China’s aerospace industry, Tsien developed a set of systems engineering management approaches and techniques which combined universal scientific theory with Chinese characteristics” (3). To develop a trusted and valued school of thought, a foundation based on solid disciplinary architecture and good operational research was needed. In the case of systems engineering, these elements were developed throughout the 1960s and 1970s, generating a strong theoretical foundation for this discipline. Outlined below are descriptions of operations research, automation technology, and Tsien’s aerospace research, factors which helped to promote the rise of systems engineering in China.

Providing a theoretical foundation for systems engineering

While the goal of systems engineering is to achieve system optimization, operations research describes the study of optimization. Thus, advances in operations research form a theoretical basis on which systems engineering can be created and developed.

Operations research grew out of efforts during World War II to find resolutions for certain tactical issues, such as force deployment and operational command. It was extensively developed in the West during the 1950s and was primarily aimed at providing a scientific foundation for decision-making. Operations research was able to assist in mapping strategies to win a victory thousands of miles away by facilitating effective management and well-informed tactical choices (4). Tsien was prescient enough to envision the huge potential and wide application of the discipline. In 1981, he deemed operations research to be a form of technological science in his proposed paradigm of systems science. He argued that operations research could be used to define mathematical models and find solutions, elements that are at the core of the field and its applications. Methodologically speaking, it is necessary to analyze all possible causes from which a problem may have arisen and establish a mathematical model to test these causes. The process of finding a solution to the model is also the procedure for addressing the real problem. In practice, it is almost impossible to model all factors, since even a small problem could be the result of multiple interactive factors. Therefore, practically speaking, a solution can only be found by analyzing the most important factors.

While in the United States in the early 1950s, Tsien addressed a letter to Chinese scholars in which he proposed applying operations research methodology to large construction projects of national interest. When Tsien arrived back in China, he immediately recommended its application to economic construction and, alongside Guozhi Xu, an academician of the Chinese Academy of Engineering, established an operations research group within the Institute of Mechanics. In 1959, a second operations research department was set up.
up at the Institute of Mathematics of the Chinese Academy of Sciences (CAS). The following year, the two operations research groups merged to form a research office under the aegis of the Institute of Mathematics. This new group focused on queuing theory, nonlinear programming, and graph theory. Dedicated researchers were also assigned to the study of transportation theory, dynamic planning, and economic analysis. In 1963, the group offered a systematic operations research course to first-year graduates majoring in applied mathematics at the University of Science and Technology of China in Beijing. This course was the first of its kind in China. Since then, tremendous achievements and huge economic benefits have resulted from the application of operations research in the fields of transportation, construction engineering, equipment maintenance and repair, and production organization. Automation provides technical support for systems engineering

In the mid-to-late 1960s, automation technology was already being widely applied in research-related to various human activities. This technology still faced a number of challenges, in particular its application in enterprise production processes, in which both the stability of process parameters and optimal process control needed to be guaranteed. Product manufacturing requires optimal conditions that conserve energy, demand the fewest raw materials, and entail the shortest production cycle. Most production processes are not simply a combination of one or more subprocesses, but rather a system consisting of multiple interrelated processes. Furthermore, global optimization of the production process is more than the sum of the optimization of each individual subprocess. The process of pursuing the maximum production output uses the same underlying principle as systems engineering, namely system optimization. Advances in automation technology thus laid a solid foundation for the birth of systems engineering. Automation technology also played a vital role in the ongoing development of systems engineering in China. Many systems engineering researchers had backgrounds in automation technology, and systems engineering was studied as a subdiscipline of automation control.

The aerospace industry’s role in the birth of systems engineering in China

When Tsien returned to China, he worked in the Chinese aerospace industry. Aerospace engineering is characterized by its huge scale, technological complexity, high standards of quality and reliability, tremendous cost, and long R&D cycle. It is closely tied with national politics and defense security, and may indirectly provide socioeconomic benefits. In developing an effective missile, Tsien faced the challenge of organizing numerous people and units, and of making appropriate trade-offs between the whole system and its integral parts. This challenge was the driving force behind his idea to apply systems engineering to the organization and management of the aerospace industry. In the late 1970s, Tsien decided to shift the focus of his work from guiding the construction of aerospace engineering to academic research. Based on intensive research into the early practices of the aerospace industry and extensive discussion with other aerospace experts, Tsien published “Technology for Organization and Management: Systems Engineering,” together with experts Guozhi Xu and Shouyun Wang. In this essay, he clearly described the primary concept of systems engineering in China: “Systems engineering is a scientific approach to the organization and management of the planning, research, design, manufacture, testing, and application of systems” (5). The article gained national attention and marked the beginning of the rapid development of systems engineering in China. In 1978, following approval by the Ministry of Education, systems engineering institutes and similar organizations were established at Tsinghua University, Tianjin University, Xi’an Jiaotong University, Huazhong University of Science and Technology, East China University of Science and Technology, and Dalian University. These universities were the first Chinese research institutes to offer training in systems engineering. As a systems engineering symposium was organized in Beijing in 1979, Tsien proposed an initiative requesting that a “system of systems science” be established as soon as possible. In 1980, the Systems Engineering Society of China was officially established in Beijing. Its aim was to unite both researchers and managers from across the country in the pursuit of scientific research into systems engineering.
Designing and building a systems engineering discipline in China

Exploring and developing an education system

In the early 1980s, the Ministry of Education began to pay more attention to teaching and research in systems engineering, focusing on widening the scope of the field and advancing in-depth research into artificial intelligence. Previously, automation research had emphasized technology, with less concern for economic and societal factors; this focus changed when a number of systems engineering researchers recognized the importance of these factors in advancing and applying automation research. Furthermore, automation control researchers began to use systems engineering to analyze large-scale systems already in operation; the results of their analysis became a critical part of the fields of control science and engineering.

In 1979, the Ministry of Education sent a delegation to the United States and Japan to investigate systems engineering practices. The delegation returned with two primary insights: China needed to strengthen its basic theoretical research and to focus more on the application of systems engineering.

That same year, with the authority of the State Commission of Science and Technology for the National Defense Industry, Tsien traveled to Changsha to preside over the transformation of the Changsha Institute of Technology into the National University of Defense Technology (NUDT). To achieve this, he drew on his experience running the Mathematics Teaching and Research Office, as well as others representing a wide variety of disciplines, including flight vehicles, information science, Dongsheng Miao added new disciplines such as communications technology, informatics, and computer science. Tsien argued that philosophy, in particular Marxist philosophy, sits atop the hierarchy of sciences. In 1981, Tsien elaborated on the “system of systems science” in the journal Systems Engineering—Theory and Practice (7).

In 1981, Tsien published “Discussion on Quality Management Systems Engineering” in the weekly academic seminar (Figure 2). The updated structure he proposed is illustrated in Figure 2. In 2009, nearly 50 years later, he published “Discussion on Quality Management Systems Engineering” in the weekly academic seminar (Figure 2).

In 1981, Tsien introduced the Systematology Seminar, a weekly academic symposium on systems engineering, which was launched at the No. 710 Academy. Under his guidance, the seminars attracted famous scholars from a variety of fields and laid a sound foundation for the creation and evolution of systems engineering. They provided an arena for the popularization and development of systems science and systems engineering in China.

Research achievements in systems engineering

Systems engineering theory and methods have been widely applied in China since the late 1970s, spurred on in large part by the advancements of Tsien and others. Notable achievements are described below.

Professor Zhongtuo Wang, an expert in the theoretical analysis of decision-making processes and knowledge systems engineering, assisted in establishing the system of systems science in China. In 1960, he entered the Shih research and doctoral degree-granting laboratory. In 1970, he published “Discussion on Quality Management Systems Engineering” in the weekly academic seminar (Figure 2).

Ting Chen devoted himself to researching large-scale systems theory and decision-making analysis, and compiled The Bibliography of Giant Systems Theory and Its Applications, 1963–1978 (12), contributing to the field of mathematical modeling in systems engineering.

Wenjun Wu devised Wu’s method, a mathematical equation that offers the most complete method for solving nonlinear algebraic equations, providing an important reference point for finding solutions using mathematical modeling.

Weimin Zheng explored the new field of modeling and automation control for crop breeding by combining systems engineering with bioscience and rice breeding, using mathematical modeling and analysis to study the life cycle of rice crops. In 1980, with the support of Luogeng Hua, Minyi Yue opened the Operations Research Society of China. This organization was later approved by the state as the leading association of its kind. Yue also founded the *Journal of Operations Research*, now a key journal in the Chinese mathematics community.

Litong Xie described the hull construction manufacturing process using mathematical expressions, which led to improvements in the accuracy of hull manufacture modeling. Xue Baoqing proposed increase investment in China's ecosystem, prioritizing flood and drought control and backing projects to prevent desertification and alkalization, in order to boost agricultural development laws. These efforts have contributed greatly to the formulation of future agriculture policies for China. Finally, several scholars have applied the theories and approaches of systems engineering to studying and solving a broad range of critical practical problems in China, from optimizing economic policies to managing large-scale construction projects. As a result, a number of important achievements have been realized in a variety of fields, as outlined below.

**Studies on financial subsidies, prices, and wages**

Starting in 1979, a rapid increase in prices for above-quota purchases, as well as growing financial subsidies coupled with a better than expected annual agricultural harvest, contributed to a steadily increasing central budget deficit in China. Moreover, financial revenue—including taxes such as customs and value-added tax, and special revenue such as pollution discharge fees from businesses—failed to keep pace with national revenue, and the percentage of national revenue contributed by financial revenue decreased year over year, impairing investment in key national projects and restraining the rate of economic development. The problems arising from financial subsidies caused great concern among the central leadership, leading to suggestions of subsidy policy reform. However, no consensus could be reached regarding price and wage reform. Bin Ma, then deputy director-general of the Energy Research Center of the State Council, gave great importance to addressing this issue to Jingyuan Yu, who applied systems engineering to find a solution. Yu and others studied financial subsidies, prices, wages, and all other direct and indirect elements of the economy, treating them as an integrated, interdependent whole. A set of parameters, state, policy, and observational variables were used to define the boundaries, which provided the qualitative foundation for modeling and functionality design. Later, based on real statistical data and modeling, the researchers simulated 105 policies, applying different national capabilities (environmental variables), prices and wages (regulatory variables), starting points, and methods, and ranges of adjustment (one-time adjustment or gradual adjustments), market equilibrium, currency circulation and savings, and income levels of urban and rural citizens. Using these measures, (evaluation indicators), the scholars' goal was to quantify the impact of different economic policies on the problems caused by financial subsidies, investigating, for example, whether the simultaneous adjustment of prices and wages could solve these problems, how effective the adjustment was, and when the adjustment should be implemented. After consulting with management experts and economists, five policies were ultimately proposed to the state government.

Comprehensive research on the issue of financial subsidies, prices, and wages was highly valued by the central government leadership and offered a good example of systems engineering in practice. Tsien attached great importance to this achievement, using it to further refine and improve his theory and approach. This study also formed an important foundation for the refinement of his principles describing complex giant systems.

**National and regional energy planning**

Energy exploitation and utilization is one of the most important issues affecting China's social and economic development. In the late 1970s, Bao Liu and others applied systems engineering approaches to research energy issues and energy planning problems. They formulated energy development in parallel with economic development and established the Systems Engineering Committee of the China Energy Research Society, responsible for guiding energy development and exploitation in China. Having studied the energy economy and national energy models, Liu and colleagues made a series of proposals. Notably, they argued that energy conservation measures could ensure that China's development goals were achieved by the year 2000, providing a powerful scientific basis for formulating national energy policy and enabling the State Development Planning Commission to move confidently forward with their energy planning.

Based on this work, the China Energy Research Society conducted a preliminary analysis for formulating national energy development and industrial policies and published the "Research Report on Energy Policies in China," which supported China's economic development goals. Test models of these policies were set up in Tianjin by Liu and Shubai Xu, and in Shanghai by the Shanghai Energy Research Institute. These efforts provided the theoretical basis for energy planning and industrial
restructuring in these two cities. In addition, Zongxin Wu and colleagues offered a preliminary discussion on agricultural energy planning and validating government energy production policy.

In order to advance energy planning studies in China, Liu organized training in this area. The Tianjin Training Center of Energy Planning was founded at Tianjin University as part of an agreement signed by the Chinese government and the European Community in 1982. Since then, international cooperation and information exchange in this field, and in systems engineering more broadly, has included extensive cooperative research into energy planning and management.

Economic development simulations

Based on a comprehensive study of financial subsidies, prices, and wages undertaken in 1979, and with the support of the Development Research Center and the State Commission for Restructuring the Economic System (both under the State Council), in 1984, the No. 710 Academy under the leadership of Bin Ma initiated research into forecasting and development planning for the national economy. In the late 1970s, with strong support from the National Health and Family Planning Commission, the National Bureau of Statistics, and the Ministry of Public Security, Jin Song, Jingyuan Yu, Zhenghua Jiang, and a group of other scholars began quantitative research into population development in China. This work resulted in the creation of population systems science, a new type of interdisciplinary science with distinctively Chinese characteristics.

This new science was applied to the population problem in three ways: (1) Systems engineering principles were applied in concert with computer technology to create a complete set of population forecasting methods and software packages specific to China; (2) by combining modern control theory, systems engineering, and demographics, various population control and systems engineering theories were established, including those for population system modeling, parameter identification, controlling population upper limits through population planning, and control optimization, as well as dynamic analysis of the population system; and (3) modern functional analysis theory was applied using a distribution parameter model to create a general theory for controlling the birthrate.

This quantitative research into population systems and its application to the population problem in China provided a concrete example of systems engineering theory put into practice. The results became an official source of data for the Chinese central government when setting population policy. In 1987, the study won first place in the National Science and Technology Progress Award.

Applying quantitative analysis to population research

Since the 1970s and 1980s, overpopulation has been recognized as a serious problem globally, particularly in China. Had China not controlled its birthrate, which by the 1970s was outpacing national economic growth, the country would have remained undeveloped for decades to come. The urgent population problem required an effective method of quantitative control and the regulation of the birthrate.

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Systems analysis of talent planning

The appropriate quantity and quality of national human resources, in particular professional talent, are necessary for the national economy to flourish and for progress to be made in science and technology. Yingluo Wang and others applied systems engineering theory to the national talent planning program formulated by the State Council during the 1980s.

Guided by systems engineering approaches, the general structure of the talent planning model— including submodels for the national economy’s future talent needs, education planning, and adult education planning—was developed to quantitatively describe the relationships between workforce supply and demand; the availability of qualified workers, funding, and teaching resources; and socioeconomic development and its impact on the demand for talent. Based on socioeconomic development trends as well as trends in scientific and technological advances, the demand for talent in different fields was forecast for the year 2000.

The supply-demand balance was analyzed in terms of educational background, age, professional title, and worker experience. Furthermore, student enrollment numbers were projected for a variety of educational institutions for the same year. An analysis of the effect of different policies was conducted, using variables such as workforce professional qualifications, supply and demand of professional talent, and funding and teaching resources. The results identified the level of professional talent needed each year over the next 17 years. Funding, teaching resources, and policy measures were proposed that were in line with these findings.

The cultivation, utilization, and optimization of human resources are part of the complex theory and practice of social systems engineering. Through systems engineering approaches, Yingluo Wang and others qualitatively and quantitatively analyzed the intricate correlations between talent development, future socioeconomic development, and progress in science and technology. They also examined the correlation between talent development and changes in the national economy. This research contributed significantly to the deployment of China’s talent strategy.

The Three Gorges Project

The Three Gorges Hydroelectric Project on the Yangtze River was an extensive and extremely complex construction project. It not only offered comprehensive benefits in terms of flood control, power generation, and shipping, but also accelerated the development of the national economy and spurred social and economic reforms in the Three Gorges area. Nonetheless, the Three Gorges Project faced unfavorable financial challenges and risks due to the large-scale investment required, the lengthy construction period expected, and the potential for significant impact on the environment, among other issues. Therefore, demonstrating the feasibility of this project could not be based solely on its practical potential for creating hydroelectric power—various additional factors had to be taken into consideration as well. Consequently, an evaluation to demonstrate...
the feasibility of the Three Gorges Project was initiated in 1986, under the leadership of Zengyuan Qian. The Three Gorges Project was an elaborate systems engineering project, divided into 14 special subsystems: geology and earthquakes, hub structures, hydrology, flood control, sediment, shipping, electric power systems, electromechanical equipment, migration, ecology and environment, comprehensive planning and water levels, construction, investment estimation, and a comprehensive economic analysis. These subsystems were divided into four subcategories: (1) foundational: geology and earthquakes, hydraulic structures, and sediment; (2) functional: flood control, electric power generation, and shipping; (3) physical factors: water level, structures, construction, equipment, and infrastructure; and (4) costs: investment, migration, and ecology.

A special group was established to conduct a comprehensive feasibility assessment in two phases. In the first phase, construction plans were designed for water levels of 150 m, 160 m, 170 m, and 180 m. The preliminary findings were presented. Based on feedback from stakeholders and special interest groups, the planning group completed their analysis and recommended the construction plan that was most acceptable to all parties. During the second phase, alternative plans with equivalent or similar benefits were studied and compared to the plan presented in the first phase. These alternative plans were proposed by experts on flood control, electric power systems, and shipping. They were analyzed by the economic evaluation group, who looked at two key elements: whether the project should be implemented, and if so, the optimal timing for construction to begin.

The Three Gorges Hydroelectric Project on the Yangtze River was an extensive and extremely complex construction project.

Application of the national agriculture input–output table in grain yield forecasting

Xikang Chen of the Institute of Systems Science at the CAS, together with Jinliang Hao and Xinwei Xue, successfully completed their study on the theory and application of an agricultural input and output table for calculating the return on investment in agriculture. This project was achieved with the support of the former Rural Policy Research Office of the Secretariat of the Central Committee of the Communist Party of China, the Rural Development Research Center of the State Council, the Agriculture Bureau of the State Development Planning Commission, the Agriculture Department of the National Bureau of Statistics, the Planning Department of the Ministry of Agriculture, and the Department of General Grain Affairs of the Ministry of Natural Resources, and with funding from the National Science Foundation, the agricultural economy, and the energy table. This research resulted in the creation of the national agricultural input-output table, which showed a statistical analysis of the consumption of resources and production of agricultural products (both commodity and noncommodity), providing a reference point for the government to formulate agricultural development policies.

The input-output table not only attained international recognition for its unique method and theory, but was also of great practical value, as outlined in the two examples below.

Purchase pricing for pigs

From 1980 to 1984, the grain yield in China increased from 320.6 million tons to 407.3 million tons, while the number of pigs grew from 305.4 million to 306.8 million. The national agricultural input-output tables for 1982 and 1984 revealed that profits from pig husbandry were negative. For this reason, Xikang Chen and colleagues suggested increasing the pig purchase price, passing this information to the Rural Development Research Center and the Rural Policy Research Office. In 1985, the pig purchase price was increased, and the number of pigs grew rapidly along with the pork output.

Forecasting national grain yield

Government agencies involved in developing food resources policy applied the national agricultural input-output table to national grain yields from 1981 to 1986. The predictions directly impacted policy formulation on the production, distribution, sale, and export of grain, as well as imports and exports. The input-output table is not only an important research tool for Chinese economics—it is also an excellent example of applied systems engineering. The entire agricultural input-output system can be considered as a large system consisting of three subsystems: the agricultural economy, the energy table, and the energy table. The physical table includes 40 primary products, 16 byproducts, 10 nonagricultural inputs, and 16 fixed assets; the value table comprises 24 agricultural departments; and the energy table lists the energy generated by 47 types of agricultural products. The research also considered the relationships between subsystems in order to facilitate the accuracy of grain yield prediction.

Systems research for "China in 2000"

In the 1980s, Huijiong Wang and others conducted research for the "China in 2000" program, in order to create a blueprint for future development and accumulate evidence-based data to aid in decision-making and planning. Research for the program played a vital role in China's economic development and in expanding the application and development of systems engineering.

The researchers established a variety of models using qualitative and quantitative analysis, employing systems engineering-based approaches. Based on these models, a roadmap for the country was put forward. It predicted that if the roadmap was implemented, the population would stabilize at about 1.25 billion, living standards would rank in the mid-level compared to other nations, the Chinese economy would be the fifth or sixth largest in the world, the value of industrial output would reach the level of that of the United States, and agriculture would satisfy the needs of economic development and personal consumption. To ensure the roadmap's proper implementation, the researchers included certain policy suggestions, including a strategy for quadrupling the scale of the national economy, enforcing strict pollution control measures, improving transportation and communication conditions, and adjusting the industrial structure in rural areas, based on an integrated analysis of trade, industry, and agriculture.

Research into China's human spaceflight development strategy

In March 1986, Chinese statesman Xiaoping Deng remarked: "We need to strive for high-tech development, otherwise we will be left behind and pay a high price. That is why we need to do this thing right now." In response to this statement, the National High Tech R&D Program of China (or 863 Program) was launched in March 1986.

Human spaceflight was an important part of the 863 Program, but no conclusions were reached as to whether this goal was a necessary part of China's growth, particularly as a developing country. It was also unclear exactly how a human spaceflight program could be put in place. For these reasons, research into human spaceflight development strategy was commissioned. It was conducted by the aerospace strategy group, which included Zhenye Qian (director of the No. 710 Academy), Guangyao Yang, and Desen Wei.

Human spaceflight systems engineering challenge involving political, economic, military, scientific, technological, social, and diplomatic variables. It was decided by the aerospace strategy group that systems engineering theory and approaches should be applied. The four-year-long, in-depth, comprehensive analytic research examined the issue from multiple perspectives.
perspectives while still adhering to national strategic policies. It addressed issues such as why and how to develop spaceflight in China, and what development strategies, overall objectives, and technological approaches should be adopted. This research helped China to find the best way to explore outer space independently.

Further applications of systems engineering techniques
When systems engineering first began its evolution in China in the 1970s and 1980s, the approaches used were chiefly imported from the West. Arthur D. Hall's methodology for systems engineering was spoken of particularly highly by most Chinese experts and scholars, as described by Jifa Gu: “Since 1978, Professor Hsu-Shen Tsien and others have disseminated systems engineering throughout China. As CAS academician Jian Song elaborated in 1982, “Research into the characteristics of various social phenomena, their occurrence, and their developmental pathway through quantitative description, with the help of mathematical tools, has recently become a trend” (19).

At the core of Hall’s methodology for systems engineering is optimization. Many problems in social development can be treated as systems engineering problems that can be addressed through quantitative analysis. Some Chinese systems engineering experts have emphasized the value of quantitative methods in their research as a means to develop satisfactory solutions through analysis, simulations, and system modeling. Tsien and others had already begun to explore the “metasynthesis approach”—which combines qualitative and quantitative analysis—in the 1970s and 1980s, even though the term was not in common use at the time. Tsien first used it in a 1981 speech to government leaders titled “On Scientific Thinking, Achievements, Experience, Knowledge, and Wisdom, as well as various other data to provide a detailed, qualitative description of an academic problem.

In 1992, Tsien proposed a metasynthesis workshop to discuss and refine this discipline. Making reference to Chinese cultural tradition, he described the metasynthesis technique as “Metasynthesis through Wisdom Engineering” (22). During the boom in quantitative research, many new systems engineering approaches emerged. In particular, a number of important mathematical models were established, among them the network diagram that represents the various forms of energy, prices, and wages conducted by Bin Ma, Jingyuan Yu, and others discussed previously (see page 36) is considered to be an early application of metasynthesis. Metasynthesis was more explicitly described in Yu’s 2002 article, “Metasynthesis—A Case Study” (21).

In essence, metasynthesis combines data from experts, information systems, and computers to form a highly integrated human-machine-network system. Metasynthesis can integrate human thinking, achievements, experience, knowledge, and wisdom, as well as various other data to provide a detailed, qualitative description of an academic problem.

The challenges in energy planning are many, including determining how to achieve the best return on investment and how to find and utilize energy resources responsibly. Energy planning involves numerous variables. In the coal industry, for example, variables might include the locations of the mines in a particular region and the types of transportation solutions available to move coal from the mines to the power stations where it is consumed. In addition, decision-making at multiple levels must be taken into account, including choices about which development options are best for a particular region and for the mines within that region. Further, the construction parameters, size, and time required for a mine to start production all play a role. Research into available choices, as well as consultation with decision-makers and energy experts on the ground, is vital.

The sheer number of factors involved makes it difficult to find a complete solution. For this reason, a model for gradual energy optimization was proposed by the research team of the China Aerospace Laboratory of Social System Engineering; the model deconstructs this single, large problem into smaller subproblems. Then a stepwise optimization process is started, and the decision-maker is invited to make certain choices at each step. Based on these choices, various subsolutions for optimization can be proposed, which lead to further choices in the next step. This process is repeated until the most optimal solution is found. This kind of gradual optimization makes calculations easier and can facilitate the conversation with the decision-maker.

Comprehensive model for financial subsidies, prices, and wages
A comprehensive model for application to financial subsidies, prices, and wages was created by Bin Ma, Jingyuan Yu, and others (see page 36). This model focuses on market equilibrium and consists of two parts: (1) national income distribution and the retail market, and (2) the input-output relationship in each industrial sector. The former is described by 115 variables and equations. There are 14 environmental variables (for example, the output value of light industry and the cost-of-living price index) and 6 regulation variables (namely the state-listed retail prices of grain, the total wages of employees of state-owned enterprises, the clothing price index, the daily supplies price index, the agricultural production goods price index, and the listed retail price of goods price index, and the listed retail price of
edible vegetable oil). These variables can be used as proxies for fluctuations in financial subsidies, prices, and wages, and including them in a model can improve that model's accuracy. The latter input–output relationship model measures the utilization efficiency of 237 industrial sectors so that new financial policies can be instituted.

The model can be used for policy simulations and economic forecasting with an error tolerance of within 3%, satisfying the accuracy requirements for this type of research.

Building an organizational foundation for systems engineering

At the 1978 military operations research symposium held by the Chinese Society of Aeronautics and Astronautics, a number of scientists proposed the establishment of the Systems Engineering Society of China. In October 1979, at the systems engineering academic conference co-organized by the Commission for Science, Technology, and Industry for National Defense and other units in Beijing, 21 scholars including Tsien and Zhaozhi Guan submitted a joint proposal for the establishment of this same society. The following August, after more than a year of preparation, the society was officially established in Beijing. Guan was elected president, while Tsien and Muqiao Xue were elected as honorary presidents. The participation of Tsien as well as other experts in automation and mathematics, and members of the CAS, created a perfect mix of interdisciplinary knowledge in the systems engineering field.

Since its inception, the Systems Engineering Society of China has continued to expand (see page 72). Many famous Chinese scholars are or have been members, including Shouyang Wang, Guoqing Chen, and Zengru Di, and others. These scholars come from a range of fields including automation control, mathematics, finance, management engineering, and social economics. The society remains an active arena for interdisciplinary academic exchange.

The establishment of the Systems Engineering Society of China brought together diverse science technicians and managers throughout the country in the pursuit of research into major issues affecting social progress in China. It has contributed greatly to the scientific research community.

References

THE RISE OF SYSTEMS ENGINEERING IN CHINA

Satellite view of China

H.S. Tsien, an academician at the Chinese Academy of Sciences (CAS) and Chinese Academy of Engineering, spared no effort in promoting and popularizing the field of systems engineering. During its early development, systems engineering grew mostly in line with traditional ideas and theories. In recent years, researchers have conducted in-depth studies into systems engineering and science, resulting in important and innovative advances.

New explorations into systems engineering in modern China

Tsien and other scholars performing work in systems engineering and systems science have established a general framework of study within these disciplines. However, even today, many systems engineers say that the field is so broad and complex that the subjects of systems engineering and systems science themselves are not well organized. Many scholars are unsure of what precisely constitutes the core of systems engineering theory, how it and other theories are interrelated, and what its future development might entail. It is therefore important to unravel the complexities of systems engineering and gain a solid understanding of its basic components so that continued development can be assured.

Through academic lectures and seminars, Tsien and other experts strengthened the systems engineering field both domestically and internationally. From its establishment, the China Aerospace Laboratory of Social System Engineering (CALSSE) has adopted a tradition of advancing research through symposia. Huifeng Xue, director of CALSSE, together with a number of his students, has conducted research into developing systems engineering architecture (Figure 1). This work has led to the publication of several books on this subject, including a new text by Xue and his team, Theoretical Systems Engineering, which is yet to be published.

Systems engineering is an open, integrative, and multidisciplinary field. These characteristics ensure that it is dynamic in nature and is constantly evolving and being improved upon.

Systems engineering methodologies in modern China

In parallel with the rapid socioeconomic development of China in recent years, systems engineering has witnessed an equally fast evolution. In his paper, “Evolution of Systems Engineering Methodology,” Ji Fa Gu divided the evolution of systems engineering methodology into three stages: hard systems methodology, soft systems methodology, and Eastern systems methodology. Gu wrote, “Various systems engineering methodologies proposed by Western scholars were dominant in the systems field both at home and abroad from the 1940s to 1980s.”

Various systems engineering methodologies proposed by Western scholars were dominant in the systems field both at home and abroad from the 1940s to 1980s."
The core of WSR is to consider physical objects, optimization principles, and human resources to provide a comprehensive, integrated result that aligns with all three WSR principles. When using this approach, different WSR principles are emphasized depending on the characteristics of the system under investigation.

The WSR systems approach has been applied to research on urban development (4), environmental security (5), and energy safety in the manufacturing sector (6). Studies have also examined the application of this approach to knowledge management (7), quality assessment (8), and enterprise culture in the building industry (9). An empirical study of the application of the WSR systems approach to the management of large construction projects has also been conducted (10).

The SPIPRO principle

Using the so-called “Self-Increasing Difficulty System” (SIDIS)—the idea that the difficulty in dealing with a system increases over time as the system develops—a collaborative innovation system, Wang proposed the Spiral Combining Propulsion (SPIPRO) principle in his paper, “A Type of Systems Methodology—The SPIPRO Principle” (11). The SPIPRO principle advocates the concept of using the SIDIS process to create an “ideal” target for the dynamic tracking of system goals. Different approaches can then be used jointly or individually to maintain the system as near to the goal as possible. As the system evolves, the approach can be adjusted. In this way, limited and gradual system optimization can be realized.

In 1997, Wang proposed models and criteria under the SPIPRO principle that were applicable to completely deterministic random-information systems as well as state-dependent systems. These models and criteria enhanced the applicability of the SPIPRO principle and were also applied to problem-solving as tools for system optimization.

Today, the SPIPRO principle has applications across numerous different technical fields. For example, Yuanhua Liu and colleagues at the University of Shanghai for Science and Technology designed a SPIPRO strategy for the sustainable development of the enterprise cluster innovation system (12). It was a collaborative innovation system utilized in the manufacturing chain, with the aim of advancing compatibility and complementarity among different enterprises within the chain.
TABLE 1. The Wuli-Shili-Renli systems approach.

<table>
<thead>
<tr>
<th>Objects and content</th>
<th>Wuli</th>
<th>Shili</th>
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<td>Laws and rules of the</td>
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<td>Focus</td>
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<td>Coordination, efficiency</td>
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<td>Shili</td>
<td>Renli</td>
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<td>Humanity, harmony, success</td>
<td>Humanity, harmony, success</td>
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<td>Principles</td>
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**Basic principles in the evolution of the complex adaptive system**

In 2002, Guangzhou Zhou, the former vice president of CAS, introduced three basic principles for the evolution of complex adaptive systems in his paper, "The Complex Adaptive System and Social Development." He argued that "there are several basic laws that play critical roles as a complex adaptive system evolves . . . The three most important of these laws are: the conservation principle, open systems theory, and evolutionary theory" (13).

The conservation principle reflects the first law of thermodynamics: A system contains a certain constance in its properties, and energy is never created nor lost. This principle is a precondition for analyzing the operational laws and formulating optimization measures for systems.

With respect to open systems theory, Zhou further stated that closing a system would lead to it becoming more disordered, while naturally occurring ordered systems or physical matter, such as crystals, living organisms, and social organizations, were derived from a disordered but open state. Only open systems are able to accept inputs that increase their order.

The third basic law that plays an important role in complex adaptive systems is evolutionary theory. According to Zhou, the wide acceptance of evolutionary biology as applied to nonhuman organisms has led to these concepts being further expanded and applied to both human beings and to inorganic elements of the natural world. It follows that the concepts of biological evolution can further be applied to human origins from an anthropological perspective and to social progress under the aegis of sociology. Studying complex adaptive systems not only helps to characterize objective structures, but reveals their composition and evolution, making systems theory applicable in the fields of physical science, biological science, and socioeconomics.

**J-structure theory**

Based on an in-depth study of the causes and mechanisms behind economic growth, Fukang Fang of Beijing Normal University proposed the "J structure" of a complex system in his paper "J Structure and Complexity of Economic Growth" (14). The J structure or process describes models of economic growth. The process of developing and marketing a new product is a three-step process that generally takes the form of a "J" when plotted as economic impact over time.

During the first phase, development, trial production, and evaluation are conducted on a small scale for testing and validation purposes. Limited investment is required, and little or no economic returns result. On a curve of economic impact, this is demonstrated as a gentle descending trend.

In phase two, the new product is launched in the market. This entails heavy investment and uncertainty in terms of acceptance of the new product. This phase is characterized by the continuous decline in economic returns.

During the final application and promotion phase, a tremendous return on investment is obtained if the product is well received by consumers, illustrated as a sharp rise in terms of economic benefit.

In essence, the J structure describes the way in which a system can reach a different stationary state from an initial stationary state by overcoming certain barriers. This structure can be used to identify relationships between macrovariables in a macroeconomic system and to describe how these variables interact in a nonlinear way. The structure is applicable in different fields, including international trade, finance, human resources, and ecology. However, due to system complexity, the J structure and corresponding processes or effects can often be hidden in the “noise.”

**The multiscale method**

CAS Academician Jinghai Li and colleagues proposed a multiscale method for application in chemical engineering in "Complex Systems and the Multiscale Method of Chemical Engineering" (15).

“Scale” in this case refers to the depth at which research investigates systems engineering problems, with analysis ranging from the macro to the molecular or even atomic level.

The method Li and colleagues proposed consists of five basic steps: (1) Deconstruct the system into subprocesses of different scales; (2) research the subprocesses; (3) investigate the interconnections between subprocesses; (4) identify the optimal control methods for each subprocess; and (5) integrate all of the subprocesses to optimize the system.

The multiscale method was first successfully applied in particle fluid systems research, when the Energy Minimization Multiscale (EMMS) model was established. This model was subsequently expanded to the studies of single-phase turbulent flow, three-phase flow, and emulsion systems. The multiscale method is an effective approach when examining correlations between different modes of complex systems, as it can integrate both reductionist and holistic models.

**An artificially intelligent decision-making support system**

Jian Chen and Yan Zhu from Tsinghua University have attempted to create methods that support decision-making using artificial intelligence based on neural networks and qualitative reasoning, and have established an intelligent decision-making system that combines qualitative and quantitative research. The system provides a framework for defining and solving complicated decision-making problems.

During the development of this system, input from decision-makers was sought, decision-making efficiency was optimized, and neural networks were applied to improve support for decision-making. The methodologies used included a variety of optimization techniques, such as qualitative analysis, decision-making analysis, optimization of network architecture, and improvement of mathematical algorithms.

From a theoretical perspective, this system has reached an advanced level and has been applied to the development of decision-making support systems for complex problems. Among those systems is the Qingdao Macroeconomic Decision-Making Support System, a research project on virtual enterprises and supply management that took second place in the 2001 National Science and Technology Progress Awards.

**Measuring engineering**

The idea of "measuring engineering" was first proposed by Kunsheng Wang, a researcher at the China Academy of Aerospace Systems Science and Engineering, in his paper "Measuring Engineering—Preliminary Research on Methods and Techniques of Fine Management" (16). Measuring engineering refers largely to theoretical methods and techniques for establishing a quantitative evaluation system and optimizing it for engineering use. It comprises two aspects: quantitative evaluation and optimization of system components. Systems engineering focuses on a system's overall operation, the key to which is establishing a clear design and properly coordinating all system components. By contrast, measuring engineering emphasizes the "unity of opposites," that is, determining the actual state of the system components (during the implementation phase) are needed to develop a comprehensive understanding of the system, provide effective optimization, and complete all systems engineering tasks.

Following completion of the systems engineering design, the important states (whether the timelines and milestones set in the original schedule have been achieved), nodes (measurable outputs), and factors (the main elements that will affect the program, such as investment, technical level, and staffing) should be quantitatively evaluated. Based on the results, specific improvements and upgrades can be made to improve the system operation and increase the prospect of overall success. This closed-loop process of system construction, evaluation, and improvement, or "evaluation-optimization-upgrade-evaluation," makes sustainable improvement possible.

Measuring engineering involves the integration
Feedback is a core concept in the systems and control field, and a basic principle used when analyzing control systems. In an automation control system, the main function of feedback is to manage internal and external uncertainties. For nonlinear random systems with uncertain variables, Guo found that the feedback system's sensitivity depended on the degree of nonlinear growth experienced by the system itself and the number of unknown parameters involved. In instances where only one uncertain parameter exists, a critical value for nonlinear growth exists and can be handled by the feedback system. When nonlinear growth drops below this critical value, the feedback system can ensure system stability and optimize its functionality. When nonlinear growth is greater than or equal to this value, the feedback control can no longer stabilize the system.

Vector optimization
Optimization is a standard part of operations research and a component of systems engineering. It is an important approach that is useful when solving problems with multiple objectives. In the 1980s, Guangya Chen and Shouyang Wang conducted in-depth research into the Multiobjective Optimization Problem (MOP), in which there might be multiple and sometimes conflicting objectives. For example, industrial development not only aims for the rapid growth of gross domestic product (GDP), but also tries to minimize environmental impact. Moreover, due to limited availability of resources, such as manpower, materials, and funds, it is usually impossible to realize all development objectives without trade-offs. Thus, the only option is to optimize resources in order to maximize the utility of the configuration and thus best satisfy the objectives.

Another approach that can be used to study vector optimization is the so-called “alternative theorem,” which is used to solve mathematical formulas consisting of multiple equations or inequalities. Wang and Chen proposed using the alternative theorem to find the optimal conditions for both extremal optimization (i.e., determining optimal solutions for a mathematical model) and the Lagrange duality theory (a method used to map mathematical variables). Their research was a catalyst for further studies in this field by other scholars around the world (17).

Research on feedback effects and abilities
Lei Guo, president of the Academy of Mathematics and Systems Science at CAS, undertook some of the first studies on system feedback under complex conditions.
Xianhao Xu performed research on management and control of compact storage systems, focusing on optimizing strategies for storing and retrieving goods inside compact storage centers. Supply chain modeling, optimization, and coordination in the low-carbon era were the focus of research by Jian Chen, who measured the distribution of carbon emission costs in industrial supply chains.

Xiaoguang Yang analyzed the short- and long-term impact of wage increases on price fluctuations during China's twelfth Five-Year Plan by employing a cost-driven input-output price model and structural decomposition analysis, a method used for analyzing the interactions and comparisons among the elements of an economic system.

Wenbin Wang has used statistical and mathematical models to explore the accuracy of evaluations and predictions concerning the state of complex engineering systems.

To facilitate the development of systems engineering modeling and simulation, Ren'an Jia conducted in-depth research into mathematical modeling of feedback loops, using computer emulation and operations research methods such as matrix analysis and vector analysis.

Studies carried out by Shouyang Wang into complex circumstances examined basic decision-making theories and methods in various decision-making contexts and modeled feedback loops, using computer emulation and operations research methods such as matrix analysis and vector analysis.

Xiaohong Chen's research on the theories and applications of flexible decision-making in complex circumstances examined basic decision-making theories and methods, including group decision-making behavior, group decision-making strategies, and optimization algorithms, as well as approaches and platforms for the development of decision-making support systems.

Xiania Wang conducted a series of experiments in regional economic development research, resource exploration and utilization, and enterprise management, with the aim of studying the metasynthesis macroeconomic decision-making support system proposed by systems engineering researchers.

The metasynthesis macroeconomic decision-making support system

The No. 710 Academy of the Aviation Industry Corporation of China, the Institute of Automation at CAS, and Huazhong University of Science and Technology jointly developed the metasynthesis macroeconomic decision-making support system (MSMEDSS) research program in 1994, as part of China's 863 Program, launched in March 1986 by the central government to advance technology development. MSMEDSS, which utilizes the metasynthesis method as its foundation while adopting hi-tech and systems engineering methods, created an artificial intelligence decision-making system utilizing human-computer interfacing as well as an artificial intelligence system 

MSMEDSS can be applied as an efficient supplement to macroeconomic analysis, forecasting, planning, and evaluation. It consists of five subsystems: the modeling, expert, information, parameters, and methods database subsystems. The modeling subsystem includes various models developed for different practical applications. The expert subsystem collects and categorizes individual experiences to provide interactive consultation, while the information subsystem provides multidisciplinary information, such as data files, with near real-time updates. The parameter and system records manage problem-solving. The MSMEDSS prototype system integrates these three components in a cohesive, intelligent, human-computer problem-solving system. For example, when performing macroeconomic forecasting of the national economy, multiple solutions are generated that can be analyzed by the expert system; then the optimal one is chosen. The expert system is composed of experts from diverse fields, including economics, sociology, natural sciences, and engineering technology, ensuring that all possible facets of the issue are addressed.

The short term objective of the HWMSE system is to provide a theoretical basis for evidence-based decision-making. The HWMSE prototype system is an important basis for evidence-based decision-making and is now ready (from a software/hardware system and organizational structure perspective) to be applied to researching and performing complex problem-solving.

Exploring new systems engineering applications

CHINA'S POST-TSIEN ERA: SYSTEMS ENGINEERING MOVES TOWARD A NEW HORIZON

The No. 710 Academy of the Aviation Industry Corporation of China, the Institute of Automation at CAS, and Huazhong University of Science and Technology jointly developed the metasynthesis macroeconomic decision-making support system proposed by Tsien to study the forecasting, early warning, and assessment of China's macroeconomy by applying control engineering methodology to the decision-making process at a national level. This prototype system was unveiled at the International Institute for Applied Systems Analysis Conference on September 11, 2003, attracting widespread attention.

The HWMSE system comprises a panel of experts (the "expert system"), a knowledge/information content system, and a computer system. The experts participate in seminars and, as the main component of the HWMSE system, use their own intelligence (or wisdom) to solve complex problems. Wisdom is essential to problem-solving and is impossible to acquire from computers. The computer system provides high-performance data and logical operation capabilities, while the knowledge/information system contains a wide variety of data related to both problems and problem-solving.

Shouyang Wang has initiated research that explores and analyzes challenges in the real-time economic monitoring and forecasting of conditions in global financial markets. He also is investigating innovations and logistical management principles that promote integrated economic, social, and environmental development, as well as conducting in-depth research into how global logistics networks are created and evolve.

Huifeng Xue has conducted in-depth research into the optimal types of aerospace engineering research centers, including the launch of a multisatellite, multimode, intelligent, microwave fiber transmission system, and the application of aerospace technology to the construction of intelligent cities.

Kanliang Wang studies how the design of interactive interfaces impacts customer behavior online. His research focuses particularly on
technology used in the design of interactive online systems that provide customized services.

Xiaohong has focused on behavioral finance and specializes in researching psychological biases and their influence on investor behavior. This research provides an effective tool for analyzing the performance of different types of investment portfolios.

Changyong Liang has analyzed the growth of different industries under the constraints of limited resources and environmental challenges, and how growth might be improved by reengineering management information systems. An exploration of the basic theory of enterprise parallel management systems, including system construction and analysis, has been undertaken by Feiye Wang, and has been used to optimize the configuration of the human resources and fixed assets of enterprises.

Guoqian Chen's research explores how an organization can better distribute limited resources among individuals and teams in a complex business environment.

Shanlin Yang is conducting research into rural resources management, and has focused on modeling the series of activities that an entity carries out—with each one adding economic benefit. In the basic theory of Aerospace Systems Engineering (22), Enjie Luan elaborates on the basic concepts behind systems engineering and advances the concept of a national engineering culture.

Baozhu Guo has worked to identify, promote, and develop essential concepts and technical methods from aerospace systems engineering to aerospace engineering management.

In addition, many systems engineering scholars, such as Yingmi Wei, Guowu Zhang, Defang Li, and Jianhao Yang are conducting in-depth research into the applications of systems engineering. Systems engineering has found wide application in the field of knowledge systems engineering, social systems engineering, traffic systems engineering, and military systems engineering.Military systems engineering, agricultural systems engineering, traffic systems engineering, economics, communication and transportation, military exploration, and agricultural planning, among others. These applications have advanced the fields of knowledge systems engineering, social systems engineering, traffic systems engineering, engineering, process systems engineering, and rule-of-law systems engineering, and have gained wide attention from leaders in all sectors of Chinese society.

Some of systems engineering's most important applications are discussed below.

Human spaceflight

China's human spaceflight program is a century-long project of national importance. It is a massive undertaking and involves the most complex system needs, the highest technical difficulty, and the most stringent requirements for quality, reliability, and safety. The application of systems engineering in this field has set a good example for the country and provides a model for other organizations.

A system to manage the human spaceflight program has been established, involving the government, users, contractors, and supporting third party activities. The China Manned Spaceflight Project Office was created to manage and coordinate more than 110 research institutes and 3,000 collaborating manufacturers. Two lines of command were put in place for this project: a commander-in-chief and a chief engineer. These individuals hold joint meetings to discuss and make decisions on issues arising from the project. A technical system was established led by the Department of Integrative System Design (DISD). Its main responsibilities include developing, implementing, and coordinating the projects and models for the project, and confirming that the seven different subsystems comprising the project are coordinated in an optimal manner and that all technical specifications are satisfied.

A technical system led by DISD, was put forward to coordinate the human spaceflight project. Since the project was complex, with many input and output points, a robust and carefully implemented coordination system was essential. Short, medium, and long-term objective planning was formulated to ensure that all aspects of the project were closely aligned and all scientific planning well integrated. In accordance with the tasks to be undertaken, the human spaceflight project was divided into five parts: R&D, production, testing, launch, and recovery. In terms of operational procedures, the project also included five segments: system, subsystem, single unit, raw materials, and components and parts. Each part and segment was equally important, as every single component could potentially have a direct impact on the success of the mission. The quality of R&D was therefore equally as important as that of coordination and support. By the same token, the quality of both the hardware and software developed for the project was given equal weight according to best practices for systems engineering management. Quality was a priority in every area, with leaders and administrative authorities making certain that the quality culture was adhered to. Furthermore, there was a focus on maintaining quality with respect to parts and components, raw materials, design, and manufacturing. Quality control checkpoints were assigned to each system, unit, and work post, ensuring that every worker was aware of and responsible for standardizing systems and performing the proper checks at all levels of the workflow.

Systems engineering principles and theories were fundamental in establishing the project's organizational management system, including a technical system led by DISD, a comprehensive planning and coordination system, and a systematic and standardized quality management system.

Since the establishment of the aerospace industry in China, its management system has undergone continuous change, and related products and technologies have been constantly updated. China now has decades of experience in developing aerospace systems engineering methodologies and has made significant practical advances.

Xingrui Ma, former director of the State Administration for Science, Technology and Industry for National Defense, summarized the core practices in Chinese aerospace systems engineering in “Management and Practice of Aerospace Systems Engineering in China” (23).

He wrote, “In particular, the function of DISD is highlighted. The task of command and design have been created specifically for the development of launch vehicle prototypes, including the implementation of overall quality control systems and procedures. All of these efforts have contributed to the success of human space flight.”

Jiajun Yuan, former deputy general manager
of the China Aerospace Science and Technology Corporation (CASC) points out in his article, "Research on Elements and Key Aspects of Chinese Space System Engineering and Project Management," that "undertakings in aerospace owe their success to the application and development of systems engineering and project management.

The development of the Chinese aerospace program has happened in concert with that of aerospace systems engineering and project management. Chinese aerospace grew out of nothing and moves forward through exploration, flourishing in the wake of reform and the opening up of the nation. This exemplifies a unique way of implementing scientific management using systems engineering, which has laid a sound foundation for the further development of the aerospace industry" (24).

Baozhu Guo, deputy director of the CASC Science and Technology Committee, points out that "China’s aerospace industry has created a set of effective systems engineering approaches for researching and developing manned rockets, man-made satellites, spacecraft, and missiles. These include the establishment of a management system, the creation of research and development procedures, among others" (25). All these achievements reflect the application of systems engineering theory in China’s aerospace industry.

Knowledge-intensive grass and sand industry

In 1985, Tsien noted that in looking at the problem from a historical perspective, it seemed possible to create a knowledge-intensive grass and sand industry that would benefit the economy, ecology, and society as part of the government’s West China Development program.

It seemed possible to create a knowledge-intensive grass and sand industry that would benefit greatly from high-quality pasture, husbandry, forestry, fishing, commerce, and tourism, among other locations. Such efforts have enabled many rural areas to develop their own programs for sustainable development.

Understanding China’s current economic and social situation

It is important to properly grasp the reality of China’s economic and social condition in order to formulate principles, policies, and development strategies that will support modernization and reform. Under the chairmanship of Lisan Zhou, the CAS National China’s Social Analysis Research Group published three reports on domestic conditions, in 1989, 1992, and 1994 (“Survival and Development,” “Tapping New Sources of Income and Reducing the Exposure of ‘C’ and ‘City and Village,’ respectively). All of these reports have received considerable scrutiny and attention both in China and abroad.

In 2000, the same group conducted systematic research on China’s population growth, resources, environment, energy issues, grain production, and economic development. They published a new report, Chance and Challenge—Research on the Economic Development Objectives of Moving Towards the Socialist Market Economy, and put forth the Basic Development Strategies (26).

This latest report provides a series of scientific calculations and forecasts for long-term economic development in China using qualitative research and quantitative analysis. The report addresses issues such as population growth, resources, and environmental challenges. It also discusses China’s advantages and potential opportunities, and offers suggestions regarding training, coordinated development in rural and urban areas, and nontraditional pathways to modernization.

Fostering sustainable development

The establishment, development, and promotion of systems engineering has essentially fulfilled the directive of Chinese Premier Enli Zhou to apply the experience gained from research into atomic weapons and man-made satellites to other fields. In China, social management and development has always been a core concern of the country’s leadership, its state administration, and its people. Systems engineering moves toward a sustainable development and boosting social development and management, and can play a role in reforming certain negative cultural and social attitudes, such as hubris.

In their public addresses, Chinese leaders frequently mention that state governance requires the application of systems engineering methods. China’s leadership thus appreciates the value of this field in managing state affairs. “Improving the party’s leadership is a complicated issue, entailing a systematic and down-to-earth way of solving these problems,” said late Chinese statesman Xiaoping Deng (27). Moreover, Jintao Hu, former president of China, once discussed systems engineering theory with Tsien, stating: “Your theory emphasizes that when we develop a comprehensive and overall consideration for factors of each aspect is a must, which is a creative idea. Currently our emphasis on scientific development is focused on innovation, planning, all around consideration, and realizing sustainable development” (28). The current president, Jinping Xi, said that “comprehensive reform is a complex systems engineering problem, so top-level design and development planning are necessary to properly research the relationships, integrity, and feasibility of each reform measure” (29).

The central government has adopted systems engineering to help develop socioeconomic development plans, implementing scientific and technological institutional and educational reforms, planning new rural construction, promoting regional reform, and increasing the transparency of socioeconomic development. These processes are aided by the strengthening of the comprehensive governance of societal security and the creation of a rigorous punishment and prevention system for corruption.

Systems engineering concepts have become an important tool used by the Chinese government and state leadership when formulating policies and promoting the betterment of the economy, politics, culture, society, and ecology. They have become a guiding principle for realizing sustainable development. For instance, at the 2008 National Science and Technology Education Leadership Group meeting held in Beijing, it was argued that the "Outline of the National
Medium and Long-Term Educational Reform and Development Plan” was in fact a complex social systems engineering project. This plan later became the programmatic document for educational reform and development in China. At an economic meeting of the central government in December 2012, President Xi pointed out that reform in China required practical, top-level design and comprehensive planning based on current conditions. He said this reform should also reflect the importance of systematic, integrated, and coordinated action in advancing the sustainable development of China’s economy.

Social systems engineering practice in Yulin
Prior to 2002, economic development in Yulin lagged behind other cities in the region, with its GDP ranking last in Shaanxi Province. The party secretary of Yulin determined to kick-start development using social systems engineering, with the aim of transforming Yulin into an economically powerful city with a distinctive culture and strong, environmentally friendly credentials.

Toward this end, a group of social systems engineering experts was established, led by Yuan Chang, a professor at the China Aerospace Social Systems Engineering Laboratory. They undertook a series of in-depth surveys in order to produce a general development strategy for Yulin. At the time, Yulin struggled with a high poverty rate. The region had therefore begun developing its abundant coal resources in concert with the adoption of national environmental strategies, and saw remarkable economic benefits over a short period. However, such development provides only a short-term benefit, as coal is a nonrenewable resource and coal mining is an unsustainable driver of economic growth.

The expert group suggested an approach that involved coal mining that provides coal for power generation, which in turn produces fly ash that can be used in the building materials industry. Additionally, carbon dioxide emissions, wastewater, and energy consumption have been brought under control. As a result, Yulin’s GDP ranking in Shaanxi Province has been rising year over year.

Research on environmental resources in Shaanxi Province
The use and protection of environmental resources is an issue of great concern around the world and an ongoing problem for China due to the country’s rapid development. Environmental protection is seen as a complex systems engineering problem requiring the integration of environmental management, research, and the adoption of both qualitative and quantitative methods. Systems engineering principles have been applied to the issue of environmental resources in Shaanxi province, for example, in a research project led by Huikun Xue that examined the carrying capacity of particular environments (a measure of the capacity to accommodate a particular biomass, including people, organisms, and plants, over a given time period), and the strategies used to protect them.

In their research, Xue and others systematically analyzed the history of environmental protection in Shaanxi and the deep-seated environmental issues—such as the discharge of industrial waste water into rivers and serious air pollution—underlying the current socioeconomic development plan. The researchers focused on how to establish a balance between economic development and environmental protection. The calculation and evaluation of the environmental carrying capacity of Shaanxi was used as a standpoint for forecasting future development. Simulations and predictions of the effects of future development were then produced using dynamic system modeling, and the most appropriate optimization scheme was determined. This scheme provided a framework for decision-making and a reference point from which to devise relevant economical and sustainable development strategies.

This research has for the first time systematically reviewed the path that Shaanxi’s environmental protection sector has traversed over the past three decades. The study included an in-depth analysis of the province’s most prominent environmental problems and the main factors at play in the province’s development, in order to evaluate the current situation and determine how environmental resources have been utilized and developed. To carry out this analysis, a system of 31 indicators was created that assessed the environmental carrying capacity of three regions and 10 cities across Shaanxi between 2001 and 2007. The results provided an accurate picture of the current environment, allowing for a system dynamics model to be constructed that could identify the key factors influencing environmental carrying capacity. Based on the quantitative analysis, the research group forecast changes in Shaanxi’s environmental carrying capacity (up to 2020) and predicted the influence on the environment, economy, and society in the coming decade based on five different development scenarios. The research sets forth comprehensive theories, strategies, countermeasures, and guarantees for the environmental protection strategy being implemented in Shaanxi for the next two decades, and provides support to help the province adjust to industrial changes and to formulate its twelfth five-year environmental protection plan (2007-2012). The plan gained positive attention from the Shaanxi Province Party Committee and the Shaanxi provincial government, also winning Shaanxi a special award for its contribution to environmental science and engineering.

Systems engineering has also been applied to many other fields. Xue has initiated several programs that are heavily dependent on systems engineering for their success, including a cooperative agreement between China and Nigeria, and a program to establish a computer-based information system that records the history of the Chinese Communist Party (CCP) for the central government. These activities involve the service industry, international cooperation, and computer-based management.

Research geared to smart cities
The “National New Urbanization Plan,” a strategic plan for urbanization in China published by the central government, designates the “smart city” as a new type of development. The concept of the smart city evolved in response to public demands to improve standards of living, enhance environmental protection, public security, and city services. The smart city harnesses information technology to measure, analyze, and integrate vital information regarding the city’s operations, in order to improve city development and encourage modernization. The CPC Central Committee and the State Council have expressed their intention to implement the strictest water resource management policy.
China is one of the countries that have fully understood the significance of systems science.

However, there is little data regarding water usage rights, usage monitoring, and quality analysis. The new water resource data, which has helped to establish requirements for smart cities, makes it essential to track these variables and necessitates the establishment of a standardized water resource data management system.

The National Natural Science Foundation of China is funding a project (headed by Xue) that explores how water resource data from multiple sources can be aligned and combined to generate a model specifically for smart cities. From the analysis of national water resource management data, three core data-related issues were identified: data completeness, data authentication, and data collection efficiency. Using Tien’s comprehensive integration theory, advances were made in data integration and knowledge management. For water resources management, including data processing and relevance analysis, data mining, and data integration. Improvements were also made to decision-making processes in accordance with the technical methods employed. Both domestic and global data were used, together with research on key technologies applied in this field, with the results reflecting the multidisciplinary, multidimensional nature of water resource data.

These data were applied in Guangdong Province. The theoretical and technical validation of water resources data management practices in Guangdong have been conducted, and indicates that many previous practical problems have been solved. The solutions and the data management practices used to reach them have been applied to refine the systems engineering theory specific to these types of projects. This theory can now be effectively applied to water resource data management issues facing the Ministry of Water Resources, the Pearl River Water Resources Commission, and the Water Resources Department of Guangdong. This work will undoubtedly improve decision-making regarding water resources and may be applicable to problems beyond water resource management that are currently faced by smart cities.

Attention from the international academic community

As systems engineering has grown and matured in China, the country has gained more recognition from the international community. For example, G. F. Gu, X. D. Xu, and L. Bian have been recognized by Engineering for Technology for his outstanding contributions to systems engineering, including his work in raising the profile of the field.

In 1994, SESC became a member of the International Federation for Systems Research (IFSR). In 2002, Jifa Gu, the first president of SESC, became chairman and then deputy chairman of IFSR. His tenure at SESC ended in 2006. In 2003, China became a member state of the International Institute of Applied Systems Analysis (IIASA). Many of China’s systems engineering workers have participated in research done by IIASA, and some have also visited the Santa Fe Institute, a U.S. organization known for its engineering research. Domestically, China has hosted many international academic conferences on systems engineering. While the examples provided in this chapter show that systems engineering is widely known in China, the application of systems engineering thought and principles has a far broader reach. For instance, systems engineering research is now spreading throughout Asia. Japanese scholar Yoshikazu Sawaragi, Hirotaka Nakayama, and Yoshiteru Nakamori proposed the Shinayakana method for decision making, which has spread throughout Asia. Japanese scholars have also visited the Santa Fe Institute, a U.S. organization known for its engineering research. Some have also visited the Santa Fe Institute, a U.S. organization known for its engineering research.

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In 1937, Ludwig von Bertalanffy first advanced his general systems theory, focusing on the potential operational laws of complex systems. Twenty years later, Harry H. Goode and Robert E. Machol published the book *Systems Engineering: An Introduction to the Design of Large-Scale Systems*, which was recognized as a defining moment in the formation of the discipline of systems engineering. The success of the Apollo program in particular led to the wide acceptance of systems engineering and its application in a variety of fields. Furthermore, with the emergence of important theories stemming from research into complex systems by luminaries like Arthur D. Hall, Ilya R. Prigogine, Hermann Haken, and Manfred Eigen, systems engineering and systems science have been greatly enriched.

Today, systems engineering is used in fields as diverse as industry, agriculture, national defense, education, enterprise operation management, Internet management, and diplomacy, and it has become a popular topic in China, now discussed by political leaders.

Since the 1970s, systems engineering has been applied in ever-widening fields. From communications network engineering at Bell Labs to the Apollo program, and from military engineering to domestic infrastructure development, systems engineering methods have achieved successes in mathematics, operational research, management, and computer science. This rise has not been without its challenges. The discipline has met a number of obstacles to its practical application, particularly in the social arena. Nonetheless, systems engineering remains an excellent scientific approach to dealing with complex problems.

Looking ahead, with the rapid development of knowledge-based economies as well as improvements in computer power, bioscience, and other technologies, systems engineering theory will continue to evolve by incorporating concepts and methods from other disciplines, and thus continue to find new applications.

Building a systems engineering discipline
Taking the experience learned in one systems
The definition of systems engineering varies between professional fields, but there is just one theoretical system.

There are still no effective methods and models available to describe the behaviors of many complex systems, especially those involving people and society. This is because certain issues arising from social change are not resolvable using a single theory or method. For example, solving an energy system problem might involve such fields as politics, economics, society, ecology, and climatology, all of which should be given due consideration when seeking a solution. Embracing this process will lead to improved guidance for addressing challenges with broad societal impact in the future.

Multidimensional development of systems engineering theory

Systems engineering theory has evolved in different ways in the East and West (see page 30). Enhancing global communication about the underlying tenants of systems engineering will contribute positively to the development of the field. The sections below discuss the development of systems engineering theory, and how input from both East and West, as well as from related disciplines, has impacted this process.

In-depth research into the theory of systems engineering

Systems engineering has found a wide range of applications. However, its precise definition differs between research fields and depends on the tasks involved and the understanding of the problem. A variety of definitions for systems engineering have been offered, as outlined in the essay “Technology for Organization and Management: Systems Engineering” (2), which also proposes studying the laws governing its evolution in order to create a single, unifying theory. As Jisun Lu, former executive vice-president of the China Academy of Launch Vehicle Technology, explained: “The definition of systems engineering varies between professional fields, but there is just one theoretical system. The proper application of systems engineering is inseparable from the scientific theory; without a clear principle to explain [its] function, its validity will come into question” (3). H. S. Tsien, as already noted, conducted an in-depth investigation of systems engineering theory and its philosophy, as discussed by Hongsen Wei in his article “The Basic Concepts of Tsien Hsue-Shen’s System Construction Theory” (4). Systems engineering is a discipline in and of itself, even though it has—and still does—rely upon the foundational theories of other disciplines. Its theoretical system is able to stand on its own. Maintaining a strong theoretical architecture is necessary to keep the growth of systems engineering on the right track.

Systems engineering is a powerful tool for solving complex real-world problems. Systems engineering can potentially provide insight into intractable questions such as where life began and how it thrived, evolved, and grew in complexity. To continue to be of benefit, systems engineering must itself continue to develop and evolve through continuous study and modification of its theoretical foundations, and perfection of its theory and application.

Communication between the East and West

Western scholars of systematics and related fields have been paying increasing attention to ancient Eastern traditions in recent years (see page 6). The Tao of Physics: An Exploration of the Parallels between Modern Physics and Eastern Mysticism, a book by physicist Fritjof Capra, became an international bestseller when it was published in 1975 and has been translated into over two dozen languages, selling more than a million copies. In China, the book was translated as Modern Physics and Eastern Mysticism (1983). For its fourth edition in 1999, Capra added an epilogue titled “The Future of the New Physics.” In it he discussed six perspectives, the first of which concerned his understanding of the relationship between a system and its subsystems (5). “Once knowing the whole system,” he wrote, “you can at least speculate on the interactional nature and prospects of its subsystems in principle, which is quite obvious in the Eastern traditional culture.” The second perspective addressed different interpretations of structure and process. “The more one studies the texts of the Hindus, Buddhists, and Taoists, the more it becomes apparent that in all of them the world is conceived in terms of movement, flow, and change,” wrote Capra. Furthermore, he continued, “classical scientific concepts treat the knowledge system as a mansion in which fundamental law is its basement. The basic view that knowledge is established on a stable foundation has been used for 2,000 years in Western science and philosophy. Eastern traditional thought treats the universe as a relationship network without any basement. Capra believed that certain Eastern cultures could be utilized by those in the West without the need for adaptation. Rhee Yong Pil, a Korean systematics scholar, introduced Laozi’s Tao Te Ching in a 1997 article and used it to explain many phenomena in society and perspectives in modern physics theory, even describing Laozi as the first theoretical physicist. Furthermore, he wrote detailed analyses of many books and articles by Capra and compared them with the Tao Te Ching, which had previously been used by sociologists to observe the dynamic processes of social systems (6). Indeed, Todd...
Pressman proposed that the synthesis of systems methodology and Eastern ideas could result in the formulation of a new methodology (7).

Research into systems engineering in the East has not been restricted to within China. In the late 1980s, Yoshikazu Sawaragi, a Japanese expert on systems and cybernetics, put forward Shinayakana systems methodology. This method emphasizes the operability of technology and the fusion of multiple disciplines. In terms of its application, it stresses honesty, harmony, humanity, interaction, intelligence, and integration. Sawaragi and his students used this methodology to formulate decision-making support systems and to analyze environmental and other problems confronting modern Japan (8).

In 1990, Tsien, Jingyuan Yu, Ruwei Dai, and others put forward the concept of open complex systems—systems containing a large number of components connected in relationally complex ways—drawing on a comprehensive study of the latest achievements both at home and abroad (9). This research was an important milestone in the development of systems science in China.

FIGURE 1. Contemporary Western systems movement.

The convergence of different cultures around the world has popularized the development of systems engineering. As globalization has progressed, this tendency has become more obvious.

Interdisciplinary integration

Hong’an Che, professor at the University of Shanghai for Science and Technology, wrote that “the developmental tendency of science and technology in the 21st century is interdisciplinary integration, which gives us a deep recognition of objective rules as a whole. This tendency is clearly highlighted in the development of systems science” (10). Systems engineering is an achievement of interdisciplinary research, and other disciplines are now being built atop its foundation. The contemporary Western systems movement (Figure 1) also uses systems engineering theory as a tool to analyze, organize, and manage its academic research activities. Currently, the majority of systems sciences rely on at least one other science. For example, economic cybernetics is based on general systems theory, and uses modern control theory and approaches to model, simulate, and analyze the laws governing the evolution and optimization of economic systems.

Scientific study in one area is often complementary to another. When functioning in the context of the rapid development of a knowledge-based economy, systems engineering can be enriched and improved by theories and methodologies from other disciplines. New achievements in science and technology in different fields provide the raw material for progress in systems engineering, and its interdisciplinary nature will benefit future development. Scientific disciplines with particular potential for the application of systems engineering include ecology, mathematics, geography, history, linguistics, philosophy, and physics.

Systematization of systems engineering methodology

In general, two methodologies—“hard” and “soft”—are applied to address real-world systems engineering problems. Hard systematic thought addresses issues with clearly defined objectives, while soft systematic thought is applied to more ambiguous management and social problems, the objectives of which are often unclear and difficult to identify and describe. A main difference between the hard and soft approaches is that there is a comparison phase in the latter. Hard methodological investigation can start with questions such as “what kind of system should be designed to solve this problem?” or “what kind of system will meet this need?” This method addresses given problems and needs. When a soft systematic method is applied, unexpected answers may arise that are typically addressed in the comparison phase. Notwithstanding this key difference, it is considered appropriate to apply soft methods to common situations and hard methods to special situations.

Typical soft system methods include social system design, strategic assumptions analysis, interactive programs, and soft operations research. These methods represent complex and systematic investigation into cognitive systems, value systems, motivation systems, and interest systems between social peers and organizational members. They examine and coordinate behaviors and interactions between managers and their staff by applying principles and methods taken from hermeneutics and phenomenology, which focus on methods for understanding and analyzing the objective world from the perspective of modern Western philosophy, emphasizing the study of process and mutual understanding, and thus realizing feasible requests, objectives, and plans.

After twice participating in the UK-China-Japan International Conference on Systems Methodologies, Jifa Gu, an academician of the Chinese Academy of Sciences, argued that the “softening” of systems engineering should proceed along two lines: (1) methodology and (2) modeling and computer sciences (Figure 2) (11).

The methodology branch can be divided into...
three tracks. The primary track is soft systems methodology, developed by Peter Checkland and based on systems thinking and systems methodology. The other two tracks are Wuli-Shili-Renli (WSR), advanced by Jifa Gu and benefiting from Western social science; and Total Systems Intervention, put forward by Robert L. Flood and Michael C. Jackson.

Information technology is vital for identifying the requirements, main parameters, and planning and application methods needed when addressing interconnected systems engineering problems or complex research tasks. In addition to theoretical advances, peripheral and computer science has provided strong support for systems engineering; and training of technical staff is improved. The modernization and integration of those tools can effortlessly complement systems engineering to benefit society through the assimilation of the knowledge of the discipline in order to support decision-making.

Currently, these soft systems methodologies and techniques are still maturing. With an in-depth study of systems methodology and advanced modeling and computer science, the soft methods will likely become even more useful, moving systems methodology gradually toward maturity.

Modernization of peripheral systems engineering tools

In addition to theoretical advances, peripheral tools, including modern computers, and networking and communications technology, have also provided strong support for systems engineering. The emergetics of various instruments and innovative approaches created by Tsien during the so-called “Fifth Industrial Revolution”—epitomized by information technology—has undoubtedly advanced systems engineering.

Information technology is vital for identifying the requirements, main parameters, and planning and application methods needed when addressing interconnected systems engineering problems or complex research tasks. For example, these technologies for be used to draft and test a general system formula before a real system is configured, as well as to evaluate the mutual adaptability of all elements of a system, and to investigate the system’s reactions to real or simulated external elements. To achieve this, the system must be connected to a quantitative or qualitative model that can emulate the performance of the system’s mechanisms. This allows the problem to be analyzed and solved, and the solution optimized.

New practical tools for systems engineering are constantly emerging. Computers have been introduced; and, for instance, led to the creation of building information modeling (BIM) as well as other technologies. BIM has provided a means for data analysis and visual representation of physical characteristics and functional information in construction engineering. BIM can be applied in several different phases of engineering projects, including planning, on-site investigation, design, construction, operation, and maintenance. BIM can facilitate data sharing with diverse parties involved in various construction phases via a single multidimensional construction information model. In addition, it supports the analysis of systems engineering. BIM provides a foundation for scheme optimization and decision-making throughout the design process, also supporting teamwork between sectors and enabling virtual construction and project management refinement.

The practical tools of systems engineering play an irreplaceable role in driving its progress, and in turn, its advancement will also improve those tools. The modernization and integration of those tools will undoubtedly continue: thus, their application will broaden further when standard systems are perfected, domestic application software matures, and training of technical staff is improved.

Broadening systems engineering applications

It is thought that systems engineering was first utilized by the American Bell Telephone Company in the 1940s. Its effectiveness for solving complex, large-scale engineering problems was further demonstrated in the major engineering projects and military equipment in the United States in the 1950s. Systems engineering developed rapidly, finding application in missile development and the American Apollo moon landing project. In the 1960s, China utilized this technology for missile development (see page 17). From there, systems engineering began filtering into Chinese society, economics, ecology, and other areas throughout the 1970s and 1980s, and has become an effective tool for studying complex systems. It also fragmented into subdisciplines, covering such areas as regional planning, the environment, energy, water resource management, agriculture, population research, and more.

One of the advantages of systems engineering is that it can easily incorporate the achievements of other fields. Through the assimilation of the theories and methods of both established and emerging disciplines, systems engineering can grow stronger and become more effective. One example is information science and big data, which can effortlessly complement systems engineering goals. Zhongtuo Wang argued, “If systems engineering wants to broaden its application field and scope, it should focus on big data, and on solving problems using data. The combination of systems engineering and big data could be a pathway for its future development” (12).

Hong’an Che held a similar view: “As an important strategic asset, big data has seeped into varied industries and departments to different degrees. Not only will businesses benefit from its application, but also advanced national economic development. Big data is a hot area, so to speak, in today’s society. We must grasp this opportunity. Although big data has been studied in all walks of life, we, as researchers of systems engineering, should take advantage of social systems, because big data is a system. Perhaps we can achieve a breakthrough for systems engineering by studying the design and management of social systems” (13). Yong Shi claimed that “the combination of systems engineering and big data is a trend. The uniqueness of cloud computing lies in proving a special kind of organizational thinking, that by organizing resources to serve, organizing technologies to realize, and organizing workflows to meet a need” (14).

With the rapid development of economic globalization, scientific and technological progress is currently flourishing and the global economy continues to grow. These factors provide development opportunities and enable systems engineering to benefit society through the widespread adoption of its applications and the improvements in efficiency that it brings.

References
13. H. A. Che, Journal of the University of Shanghai for Science and Technology 34, 204 (2012).
The Systems Engineering Society of China has made tremendous contributions to systems engineering development in China. Currently, SESC comprises six working committees: the SESC office and academy committee, the international academic communication committee, the education and publicity committee, the editing and publishing committee, the youth committee, and the consultation committee. Furthermore, a total of 21 professional committees have been created, covering areas such as society, economics, finance, education, forestry, medicine, and municipal planning. Also, SESC runs a number of influential periodicals, including Systems Engineering—Theory & Practice, the Journal of Systems Engineering, Fuzzy Systems and Mathematics, the Journal of Transportation Systems Engineering and Information Technology, the Journal of Systems Engineering and Electronics (in both English and Chinese), the Journal of Systems Science and Systems Engineering (in English), and the Journal of Systems Science and Information (in English). Detailed information on the various professional committees is presented below. Provincial systems engineering societies are each unique and have contributed significantly to the development of systems engineering in China. Due to the space constraints, these societies are described only briefly in Table 1.

### Table 1. The 21 professional committees established by SESC.

<table>
<thead>
<tr>
<th>Name of professional committees</th>
<th>Research fields</th>
</tr>
</thead>
<tbody>
<tr>
<td>Military Systems Engineering</td>
<td>Theory and practice of noncombat military operations and operation experiments, military training, and future warfare, among others</td>
</tr>
<tr>
<td>Systems Theory</td>
<td>New theories, methods, and applications of systems science, management science, and information science, among others</td>
</tr>
<tr>
<td>Socioeconomic Systems Engineering</td>
<td>Organizational management systems, social economics systems, and social collective behavior, among others</td>
</tr>
<tr>
<td>Fuzzy Mathematics and Fuzzy Systems Engineering</td>
<td>Studies of fuzzy measurement, fuzzy probability statistics, fuzzy information, fuzzy planning and optimization, and fuzzy image processing, among others</td>
</tr>
<tr>
<td>Agricultural Systems Engineering</td>
<td>Agricultural development, safety of agricultural products, and rural development, among others</td>
</tr>
<tr>
<td>Educational Systems Engineering</td>
<td>Education planning and management, talent training, teaching assessment, and quality assurance, among others</td>
</tr>
<tr>
<td>Information Systems Engineering</td>
<td>Internet of Things, cloud computing, and reconstruction of information management and cloud management systems, among others</td>
</tr>
<tr>
<td>Science and Technology Systems Engineering</td>
<td>High-tech industrialization, operational models, and key techniques in emerging ecommerce, among others</td>
</tr>
<tr>
<td>Transportation Systems Engineering</td>
<td>Integrated management systems for traffic and transportation, traffic and transportation systems layout, and coordination of national resource and transportation development strategies, among others</td>
</tr>
<tr>
<td>Process Systems Engineering</td>
<td>Green process development, environmental problems, and processing and product design in process engineering, among others</td>
</tr>
<tr>
<td>Decision-Making Systems Engineering</td>
<td>Artificial intelligence decision-making support systems, and theory, methods, and applications of decision-making science, among others</td>
</tr>
<tr>
<td>Forestry Systems Engineering</td>
<td>Interaction between forestry and ecology, economy, and society</td>
</tr>
<tr>
<td>Praculture Systems Engineering</td>
<td>Praculture theory, industrialization of agricultural and pastoral areas, and management and operation of grassland biological environments, among others</td>
</tr>
<tr>
<td>System Dynamics</td>
<td>Application of system dynamics, trends in international system dynamics, and developmental trends in system dynamics in China, among others</td>
</tr>
<tr>
<td>Medical and Health Systems Engineer</td>
<td>Medical systems, including quality of medical care, service quality, and social benefit; and health care reform decision-making, among others</td>
</tr>
<tr>
<td>Finance Systems Engineering</td>
<td>Financial risk control and oversight, agent-based computational finance, and asset pricing and finance innovation, among others</td>
</tr>
<tr>
<td>Energy Resources Systems Engineering Branch</td>
<td>Energy demand forecasting, energy transformation and economic growth, energy efficiency, energy conservation, and emission reduction, among others</td>
</tr>
<tr>
<td>Service Systems Engineering Branch</td>
<td>Studies of dynamic distribution, deployment, and computer software design, among others</td>
</tr>
<tr>
<td>Logistics Systems Engineering</td>
<td>Logistics innovation, modern and urban logistics management, planning, and management and control of logistics systems, among others</td>
</tr>
<tr>
<td>Ships and Marine Systems Engineering</td>
<td>Shipbuilding design methods, and performance testing and quality control, among others</td>
</tr>
</tbody>
</table>

### Scientific research institutions involved in systems engineering in China

In recent years, China’s systems engineering community has focused on establishing key laboratories and research institutes. The areas of investigation include systems theory, information theory, and cybernetics, among others. Selected institutions and laboratories, together with their specific research fields and directions, are listed in Tables 2 and 3.

### Table 2. Provincial-level research institutes.

<table>
<thead>
<tr>
<th>Research Institute</th>
<th>Supervised by</th>
<th>Research field</th>
</tr>
</thead>
<tbody>
<tr>
<td>China State Shipbuilding Corporation</td>
<td>China State Shipbuilding Corporation</td>
<td>Electronic information systems, aviation systems, and ship platform systems, among others</td>
</tr>
<tr>
<td>Academy of Mathematics and Systems Science, Chinese Academy of Sciences</td>
<td>Chinese Academy of Sciences</td>
<td>Mathematics, systems science, bioinformatics, and statistics, among others</td>
</tr>
<tr>
<td>China Academy of Aerospace Systems Science and Engineering</td>
<td>China Aerospace Science and Technology Corporation</td>
<td>Overall strategy for national space industry development, theoretical structure of systems engineering, and innovation in application technology, among others</td>
</tr>
<tr>
<td>Systems Biomedicine Institute, Shanghai Jiaotong University</td>
<td>Systems Biomedicine Institute</td>
<td>Complex diseases and modern biology, among others</td>
</tr>
<tr>
<td>Institute for Systems Biology, Jiangnan University</td>
<td>Jiangnan University</td>
<td>Complex diseases of plants and humans, and systematic biology, among others</td>
</tr>
<tr>
<td>College of Global Change and Earth System Science, Beijing Normal University</td>
<td>Beijing Normal University</td>
<td>Global change and earth system science, among others</td>
</tr>
<tr>
<td>Realizer Beijing Institute of Social System Engineering</td>
<td>China Central Leadership Institute of Politics and Law and others</td>
<td>Social systems engineering, talent systems engineering, life systems engineering, and systematic leadership thinking in China, among others</td>
</tr>
</tbody>
</table>

### Table 3. Provincial-level key laboratories.

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Supporting organization</th>
<th>Research field</th>
<th>Research direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>China Aerospace Laboratory of Social Systems Engineering</td>
<td>China Academy of Aerospace Sciences and Engineering</td>
<td>Social systems engineering</td>
<td>Aviation information, decision-making support systems, and resource and environment engineering, among others</td>
</tr>
<tr>
<td>Key Laboratory of Management, Decision-Making, and Information Systems</td>
<td>Academy of Mathematics and Systems Science, Chinese Academy of Sciences</td>
<td>Management systems engineering</td>
<td>Theory and practice of systems engineering, computer science and its application, and complex social systems, among others</td>
</tr>
<tr>
<td>Key Laboratory of Systems Control, Chinese Academy of Sciences</td>
<td>Academy of Mathematics and Systems Science, Chinese Academy of Sciences</td>
<td>Control systems engineering</td>
<td>Stochastic systems, nonlinear systems, distributed parameter systems, and discrete event dynamic systems, among others</td>
</tr>
<tr>
<td>Key Laboratory of Systems Bioengineering, Ministry of Education</td>
<td>Tianjin University</td>
<td>Biology systems engineering</td>
<td>Systems biotechnology, biosynthesis technology, biobased resources, and production and industrialization of chemical products, among others</td>
</tr>
<tr>
<td>Key Laboratory of Metallurgical Industrial Process Systems Science in Hubei</td>
<td>Wuhan University of Science and Technology</td>
<td>Process systems engineering</td>
<td>Differential equations and dynamic systems, theory and application of probability and mathematical statistics, and mining dynamics, among others</td>
</tr>
<tr>
<td>Key Laboratory of Complex Systems and Intelligence Science, Chinese Academy of Sciences</td>
<td>Institute of Automation, Chinese Academy of Sciences</td>
<td>Complex systems engineering</td>
<td>Theory and practice of complex systems, and theory and application of artificial intelligence science, among others</td>
</tr>
<tr>
<td>Key Laboratory of Systems Biology, Chinese Academy of Sciences</td>
<td>Shanghai Institutes for Biological Sciences, Chinese Academy of Sciences</td>
<td>Biology systems engineering</td>
<td>Omic and big data, tumor systems biology, metabolic regulation, and systems biology, among others</td>
</tr>
<tr>
<td>State Key Laboratory for Manufacturing Systems Engineering, Xin Jiaotong University</td>
<td>Wuxi Jiaotong University</td>
<td>Manufacturing systems engineering</td>
<td>Manufacturing theory and techniques, manufacturing information and systems engineering, control and integration of manufacturing systems and equipment, and management and decision-making in manufacturing systems, among others</td>
</tr>
</tbody>
</table>
Institutions offering systems engineering training in China

According to the classification criteria announced by the Ministry of Education, systems engineering has been categorized as a subdiscipline of control science and engineering. In 2012, 43 of 51 Chinese universities with the authority to grant doctoral degrees participated in an assessment of control science and engineering training (Table 4). Some universities with the authority to grant secondary doctoral and master degrees were also involved, bringing the number of participating universities to 83. These universities classified systems engineering as one of the research focuses within the top-level Management Science and Engineering doctoral program. (Note that the systems engineering research institutes and universities that were not involved in the assessment are not included in the list, but may also offer top-level doctoral programs in management science and engineering.)

TABLE 4. List of some of the universities offering a systems engineering major degree, and their laboratories and research institutes.

<table>
<thead>
<tr>
<th>University</th>
<th>Laboratories and research institutes</th>
</tr>
</thead>
</table>
| Air Force Engineering University | • Communication Engineering Experimental Teaching Center  
• Air Traffic Control Operational Virtual Simulation Teaching Center |
| Beijing Institute of Technology | • Engineering Research Center for Complex Product Advanced Manufacturing Systems, Ministry of Education  
• Reliability Engineering Institute, Beijing University of Chemical Technology  
• Joint Research Center for Spacecraft Navigation, Guidance, and Control |
| Beijing University of Chemical Technology | • Engineering Research Center of Intelligent Process Systems Engineering, Ministry of Education  
• System Optimization Laboratory  
• Chemical Systems Simulation Engineering Technology Center  
• Systems Simulation Laboratory  
• Systems Simulation, Optimization, and Control Laboratory  
• Engineering Research Center of Chemical Safety, Ministry of Education  
• Intelligent Systems and Safety Engineering Laboratory  
• Process System Failure and Abnormal Operating Conditions Information Guidance System Laboratory  
• Computer Intelligence Systems Security Evaluation Laboratory |
| Beijing University of Technology | • Key Laboratory of Computational Intelligence and Intelligent Systems in Beijing  
• Key Laboratory of Embedded Systems  
• Digital Community Engineering Research Center, Ministry of Education  
• Institute of Intelligence Control/Intelligent Systems and Software  
• Institute of Intelligent Systems  
• Institute of Transportation Systems Engineering and Control  
• Institute of Communication Systems and Network Security  
• Institute of Network Systems  
• Institute of Network Evaluation Systems Engineering  
• Institute of Automation Engineering  
• Institute of Intelligent Control  
• Institute of Automation  
• Internet of Things R&D Center  
• Institute of Circuity  
• Key Laboratory of Advanced Chemical Process Control and Optimization Technology, Ministry of Education  
• Institute of Automation  
• Engineering Research Center of Process Systems Engineering, Ministry of Education |
| Central South University | • Institute of Automation  
• Institute of Intelligent Control  
• Institute of Automation  
• Internet of Things R&D Center  
• Institute of Circuity |
| Chongqing University | • International R&D Center of Micro- and Nanosystems and New Materials Technology  
• Key Laboratory of Low-Grade Energy Utilization Technologies and Systems, Ministry of Education  
• Key Laboratory of Optoelectronic Technology and Systems, Ministry of Education  
• New Technology Engineering Laboratory of Control and Intelligent Systems |
| Dalian University of Technology | • Institute of Automation  
• Institute of Intelligent Control  
• Institute of Automation  
• Internet of Things R&D Center  
• Institute of Circuity |
| Donghua University | • Key Laboratory of Advanced Chemical Process Control and Optimization Technology, Ministry of Education  
• Institute of Automation  
• Engineering Research Center of Process Systems Engineering, Ministry of Education |
| East China University of Science and Technology | • Key Laboratory of Advanced Chemical Process Control and Optimization Technology, Ministry of Education  
• Institute of Automation  
• Engineering Research Center of Process Systems Engineering, Ministry of Education |

APPENDIX
TABLE 4. continued

<table>
<thead>
<tr>
<th>University</th>
<th>Laboratories and research institutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shanghai University</td>
<td>Key Laboratory of Intelligent Manufacturing and Robotics, Key Laboratory of Power Station Automation Technology, Key Laboratory of Advanced Display, Ministry of Education, Sino-Swedish Microsystem Integration Technology Center</td>
</tr>
<tr>
<td>South China University of Technology</td>
<td>Institute of Systems Engineering, Advanced Control Technology Laboratory, Advanced Control Strategy Development Laboratory, Intelligent Detection and Control Technology Laboratory, Complex Systems Control and Information Technology Laboratory</td>
</tr>
<tr>
<td>Southeast University</td>
<td>Institute of Complex Systems Control</td>
</tr>
<tr>
<td>Southwest Jiaotong University</td>
<td>Automation Laboratory, Traffic Information and Control Laboratory, Traffic Information Engineering Laboratory, GE FANUC Integrated Automation Laboratory</td>
</tr>
<tr>
<td>The Second Artillery Engineering University</td>
<td>State Key Laboratory of Armament Launch Theory and Technology</td>
</tr>
<tr>
<td>Tianjin University</td>
<td>Key Laboratory of Systems Biology Engineering, Ministry of Education, Key Laboratory of Power System Simulation Control, Tianjin Power Distribution System Planning and Automation Technology Promotion Center</td>
</tr>
<tr>
<td>Tongji University</td>
<td>Institute for Advanced Study of Intelligent Transportation, Institute for Advanced Study of Intelligent Sensor Networks, Institute of Network Systems</td>
</tr>
<tr>
<td>Tsinghua University</td>
<td>Institute of Systems Engineering, Institute of Systems Integration, System Modeling Laboratory, System Monitoring Demo Center</td>
</tr>
<tr>
<td>University of Science and Technology Beijing</td>
<td>Key Laboratory of Advanced Steel Processing Control, Ministry of Education</td>
</tr>
<tr>
<td>University of Science and Technology of China</td>
<td>Communication and Electronic Systems Laboratory, Institute of Intelligent Information Technology, Laboratory of Integrated Circuits and Systems</td>
</tr>
<tr>
<td>Wuhan University of Science and Technology</td>
<td>Key Laboratory for Metallurgical Industrial Process Systems Science, Hubei Province</td>
</tr>
<tr>
<td>Xi’an Jiaotong University</td>
<td>Institute of Systems Engineering, Key Laboratory for Software Systems Engineering, Key Laboratory of Electronic Subsystem Integration Design, Institute of Information Science, Institute of Information Processing</td>
</tr>
<tr>
<td>Yanshan University</td>
<td>Institute of Industrial Control, Institute of Intelligent Systems and Control, State Key Laboratory of Industrial Control Technology</td>
</tr>
<tr>
<td>Zhejiang University</td>
<td>Key Coalition Laboratory for Embedded Systems Research, Zhejiang Province, Special Equipment Manufacturing and Advanced Processing Technology Laboratory</td>
</tr>
</tbody>
</table>

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AEROSPACE CHINA
A Brief Introduction to the China Aerospace Laboratory of Social System Engineering

The China Aerospace Laboratory of Social System Engineering (CALSSE) is an open laboratory with a flexible and progressive governance structure. It was co-founded in August 2009 by the China Academy of Aerospace Systems Science and Engineering (CAASSE) and three other professional organizations in the field of social systems engineering. It is also the first official think tank in the domain of social systems engineering. The first council members of CALSSE are Prof. Hui-Feng Xue, Prof. Hai-Cheng Yang, Prof. Kun-Sheng Wang, Prof. Yon Chung and Prof. Hai-Bin Liu. Prof. Hui-Feng Xue (President of CAASSE) was elected as first director of CALSSE.

CALSSE is tasked with honoring, developing, and promoting methodologies for handling complex systems that were first put forward by Qian Xue-Sen (Hsue-Shen Tsien), a strategic scientist and pioneer of social system engineering. This includes applying advanced systems science and systems engineering philosophies, theories, and approaches, especially specialized modeling methods and intelligent information support systems, based on transdisciplinary research in the exploration of civilization evolution laws that govern complex social systems. The overall intent is to provide solutions to significant and practical problems in China, and in human society more generally, which might include economic, political, cultural, environmental, workforce, and quality of life systems. Additionally, CALSSE offers technical support to various decision makers and think tanks in order to promote the excellent governance and sustainable safety and development (S&D) of the Chinese people and the whole of humanity in a complex worldization era.

CALSSE’s mission is to promote continuous positive change through globally sustainable integration and innovation. It played a leading role in initiating the International Research Project for Systems Thinking of Chinese Leadership as well as in Project Shangri-La. Its strategic partners include the World Institute of Social System Engineering; the Institute of Resources, Environment and Information Engineering of the Northwestern Polytechnical University; and the Realizer Beijing Institute of Social System Engineering. The predecessor of the latter institute was the Center of Legal System Engineering of the Central Leadership Institute of Politics and Law. CALSSE is making a conscious effort to increase its new strategic partners worldwide.

CALSSE is striving to become a unique, world-class think tank, applying advanced technology—including modeling, simulation, and artificial intelligence—to complex social systems. Furthermore, CALSSE aims to develop insight into the evolution of today’s civilizations and to promote the continuous development and improvement of civilizations worldwide through integration and innovation.