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Error Systems: Concepts, Theory and Applications

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To our family and friends who have been giving unselfish and generous emotional and material supports over the course of writing.

Preface

Jérôme Kerviel, ever a French trader working for Société Générale, was convicted for unauthorized trading resulting in estimated €4.9 billion loss for the company. In 1995, former Daiwa Bank trader Toshihide Iguchi pleaded guilty of covering up his 12-year loss estimated at $1.1 billion due to unauthorized trading. The fraudulent and unauthorized trading activities of Nicholas William Leeson, a former UK derivatives broker, caused the collapse of Baring Bank in 1995. Although there are still arguments on who were really responsible for the huge loss, all those events were caused by decision-making errors either in companies' staffing mechanism and performance evaluation or trading processes. The well-known research institute and think tank RAND Corporation indicated that the collapse of 85% large and medium companies was attributed to errors in decision making.

Errors permeate every corner of the world. The decision-making processes in different entities including state governments, for-profit enterprises, nonprofit organizations, and people are often susceptible to error. The occurrence of error does not differentiate the developed countries or underdeveloped countries, well-tuned organizations or under-performing organizations, those famous or infamous persons in history. Errors were often seen in scientific and technological fields whether they were in developed countries or developing countries. History has witnessed many different errors in either primitive or civilized societies. The causes for an error might result from multiple elements or a single element of the system in which the error is embedded. The consequences of the errors in an object, a case, a decision, or a theoretical system may lead to minor loss, catastrophic casualties, disbandment of organizations, dissolution of countries, or even the termination of human beings. For instance, the mid-air collision on July 1, 2002 between Bashkirian Airlines Flight 2937 (Tu-154 passenger jet plane) and DHL Flight 611 (Boeing757 cargo jet plane) was caused by a series of errors including problems of the arrangement for both personnel and equipment maintenance of SWISS air traffic control service and procedural errors of using Traffic Collision Avoidance System (TCAS). The disaster killed 69 passengers and crew members on Flight 2937 and 2 crew members of the Flight 611, which offered a thought-provoking lesson for relevant organizations and decision makers.

The generation on the idea of developing error logic, error theory, and error systems can be traced back to 1983 while professor Wen Cai and the first author of this book were attending workshop named "Value-mapping Engineering" in former Guangzhou Nitrogen Fertilizer Plant. During a noon nap time, noises coming from the dispute between two housekeeping ladies outside my room woke me up. One of them said "you are wrong." The other one argued that "I am not wrong, it is you who made the mistake." The first one replied "Would you please tell me where my fault is if you think I was wrong?" The other returned very rapidly "and where is my fault if you think I am wrong? On what basis do you judge if I went wrong?" "On what basis do you judge if I went wrong?" struck my mind while I was still in the hypnopompic state and it ignited my inspiration and passion in research of conceptualization, symbolization, and modeling of error over the past 30 years. Yes, indeed! On what basis does one judge if certain thing, matter, decision, action, etc., is erroneous and what caused the error? Is there any condition, measure or way to eliminate the error? More importantly, is there any condition or method to prevent error from happening. If there exist conditions or measures to prevent erring, one must figure out the laws of change, transformation, and transition of errors. Question then arose again. Are there laws in preventing, identifying, and consequently eliminating errors? While pondering these issues, I woke up, like what I used to do, and wrote them down on my notebook. From then on, I started my life-long studies in error-related theories and practices.

Thus far, many papers and books regarding the investigation of errors have been published. For sake of brevity, we mainly review some books and please refer to reference for other publications. Books are listed as follows: (1) *Malfunction Diagnosis*: diagnosing the causes and position or predicting the occurrence of malfunction; (2) *Enterprise Diagnosis*: figuring out discrepancies between standards and the results and corresponding laws for generating such errors by scanning the internal and external environments of organizations, identifying the laws and mechanisms for improving management; (3) *Enterprise Disaster*: risk management; (4) *Rand Diagnosis* and *Rand Decision-making*: conducting in-depth and extensive research on the causes of errors, countermeasures dealing with errors, and approaches in diagnosing errors. Rasmussen (Eds.) (1987) summarized the topics addressing various approaches to human error analysis in different fields, especially in the context of technological development. Reason (1990) identified cognitive processes to gain better understanding on mechanism of human error. Bogner (1994) presented those examples of human errors in medicine collected from various medical fields including psychology, medicine, engineering, cognitive science, human factors, gerontology, and nursing. Dorner (1997) proposed the "logic of failure" and analyzed the roots of catastrophes. Hollnagel (1998) put forward CREAM (Cognitive Reliability and Error Analysis Method) to offer an error taxonomy that incorporates individual, technological and organizational factors based on cognitive engineering principles. Reason and Hobbs (2003) systematically analyzed the types of error in maintenance and provided a well-organized guide to managing maintenance error accordingly. Dekker (2004) assessed two views of human errors with old view of looking at errors as the cause of an incident or accident and new view of deeming error as a symptom of deeper problem within the system. The author preferred to adopt the new view. Dismukes (2009) indicated that "*human errors in aviation industry are not root causes but symptoms of the way industry operates*". The book edited by Hofmann and Frese (Eds.) (2011) talked about the errors in organizations and future directions of related research. Hagen (2013), using aviation industry as an example, offered insights on how to exercise error management in organizations. Haselton and Galperin (2013) exhibited the application of Error Management Theory (EMT) in relation management for the purpose of reducing biases. Dhillon (2007, 2009, 2012, and 2014), in four books, discussed human errors in transportation systems, engineering maintenance related to aviation and power generation, engineering systems in general, and nuclear power plants, respectively. Blokdyk (2018) provided the essentials of error management theory and extensive criteria summarized from past projects. There are also many theories and methodologies for studying errors and mistakes in different fields and disciplines such as "reductio ad absurdum" in mathematics, clinical "misdiagnosis", "criminal psychology" in forensic science, "abnormal thinking" in thinking, and "theory of fault tolerance" in computer science.

Nevertheless, none of the above-mentioned research has conducted quantitative and holistic studies on errors in general, let alone the studies on the patterns and laws of error transformation and transition. Since 1983, our team started to build the theoretical framework and systems for error elimination where common errors are research objects and causes & mechanisms of erring, patterns and laws of error transformation and transition, and methodologies for preventing and eliminating error are the primary contents. In summary, the research done by our team includes the following 7 aspects:

1. Definition of error
   Suppose that U is the universe of discourse, G is a set of rules for judging error defined within U, if $\exists G \nRightarrow a$ (including the cases that a can not be completely or partially obtained by exercising G; or the case that a has nothing to do with G), a is erroneous defined within U under the rule of judging errors G. Based on the definition, we know that the error is relative. Its existence pertains to certain universe of discourse, a group of rules, and the implications manifested in the definition. Note: G is a set of predetermined and qualified rules for judging if an object is correct or not. Otherwise, $G \Rightarrow a$ holds if G is the rule for judging whether an object is erroneous or not.

2. Rules for judging errors
   Research contents in this area contain: (1) conditions for justifying the appropriateness of those chosen rules and their applicable factors such as fields and time; (2) relationships between chosen rules; (3) relationships between chosen rules and the object being investigated; (4) methods for screening and assessing rules.

3. Error function
   In order to quantitatively depict the scale and value of errors, error function is introduced. The particular formulation of error function should hold the principle that the obtained error value should reflect the degree to which the object violates the chosen rules. Scalar and vector functions are two relatively simple error functions.

4. Error set theory
   On the basis of classic and fuzzy set theories, the established error set is composed of classic error set, fuzzy error set, and error set with critical points. In error set theory, we investigate both static and dynamic relationships and interactions between subjects. We especially focus on the study of relationships between change and transformation of subjects. Six basic transformations, namely, similarity or equivalence transformation, displacement transformation, decomposition transformation, addition transformation, destruction transformation, and unit transformation are introduced for the purpose of studying change and transformation of subjects. Dynamic parameters are assigned to elements of error set to capture the change and transformation of subjects. Thereafter, by using 6 basic transformations, operations can be qualitatively and quantitatively conducted on elements of error set.

5. Error logic
   Built on the foundation of classic mathematical logic, fuzzy mathematical logic, and dialectic logic, the concept of error logic is proposed in order to identify the patterns and laws for transition and transformation of errors. In our error logic system, in addition to denotation connective, connotation connective, and individual connective, 6 more transformation connectives are created, namely, similarity transformation connective, displacement transformation connective, decomposition transformation connective, addition transformation connective, destruction transformation connective, and unit transformation connective as well as their inverse transformation connectives. More importantly, research in error logic covers many aspects including but are not limited to (1) principles and laws of operation of each newly created connective, operations between new connectives, and operations between each of the new connective and existing denotation connective, connotation connective, or individual connective; (2) truth table, normal forms, and valid reasoning methods in error logic; (3) concepts and parameters of error predicate logic; (4) semantic structure and interpretation of subject term (the variable), quantifier, predicate, etc.

6. Error system
   For convenience of judging error, concept of error system is introduced. By so doing, the subject being evaluated will be abstracted to be an object system which is composed of issue set, condition set, conclusion set, intrinsic features, objective features, and relation set. Under the influence of certain judging rules, error values are assigned to this object system. In a broad sense, all the object systems and those corresponding judging rules defined within universe of discourse form a general error system.

7. Application of error theory
   The motivation of conducting research on error theory originates from issues in the real world and the achievements from the theoretical research should be put into practice to help people to prevent and eliminate errors. Among all actual application cases of error theory, one worth mentioning is a project supported by China National Natural Science Foundation (CNSF) from 1991 through 1993, which was titled as "Research on Expert System Used for Judging and Examining Decision-making Errors in Fixed Asset Investment". Having completed the project, several valid methods for identifying, judging, and investing decision-making errors in fixed asset investment had been found. With appropriate summary, induction, and deduction, the "Fifteen", "Six", and "Three" methods for preventing and eliminating errors were proposed.

Since 1983, although the fundamental architecture for error theory has been established and has gained attention from scholars in different fields, the research on the theory system still remains at a relatively immature level. Many aspects and concerns in this architecture need to be fixed and consummated. Examples include: (1) refinement on particular structure need to done; (2) need to develop a systematic guidelines for defining steps, methods, and formats in building error functions; (3) the conditions and ways of using the 6 basic transformations need more extensive investigations; (4) the research on the laws of error transition and transformation only resides in logical analysis instead of systematic exploration; (5) the developed "Fifteen", "Six", and "Three" methods can only provide a guideline in helping predicting, preventing, and eliminating errors. Therefore, it is very necessary to develop more systematic, concrete, and valid methodologies to enhance the operability, applicability, and practical values in addressing emerging issues in real world.

This monograph, by putting error research in the context of a typical system, investigates the root causes and mechanisms of erring, transition and transformation of errors, and consequently the conditions and methods of preventing and eliminating error in such system.

The essence of systems science resides in the philosophy of holism. When talking about the state that system reaches optimal, it generally refers to global optimum of the whole system with respect to the objective features that are included in the intrinsic features of a system. The attainment of global optimum of a system must rely on the normal deployment of functions (features) of its subsystems.

The word "system" originates from Latin word *systēma* meaning whole made of several parts or members. Many different definitions have been made by scholars for system from different perspectives based on their particular research objectives. Let's give some examples of them. "System is a pre-given set composed of elements and their normal behaviors"; "System is a well-organized wholeness"; "System is an entity made of connected materials and processes"; "System is a body composed of ordered elements/factors working towards a common goal" are some popular examples for the definitions of system.

The development of systems theory and their applications in different fields were mainly attributed to the contributions of scholars such as biologist Ludwig von Bertalanffy (1901–1972), Norbert Wiener (1894–1964), Ross Ashby (1903–1972), John Henry Holland (1929–2015), and Murray Gell-Mann (1929–2019). Bertalanffy pioneered the general system theory by introducing models, principles, and laws that apply to it. Wiener and Ashby used mathematics to study systems. Holland, Gell-Mann, and others proposed the term "complex adaptive system".

General system theory attempts to provide a definition that can capture common properties of various systems. The definition for general system is a body composed of well-organized elements working toward attaining particular goals or features. This definition apparently includes 4 concepts and their relationships, namely, system, element, structure, feature, relationships between elements, relationships between elements and structure, and relationships between system and its external environment.

The purpose of system theory is to investigate form, structure, and laws of general systems, to examine the common properties of those systems, to capture and illustrate their features using mathematical methods, and consequently to identify the mechanisms, rules, laws, principles, and mathematical models that can be applied to general systems. And the ultimate objective of learning system theory is to use the understanding on the system to better manage, control, renovate, or change the current system structures (natural or man-made systems) to align them with the needs of our civilized world. With better understanding on the system structures, we can introduce all kinds of interventions or policies to enable the systems of interest to attain their optimal performance or outcomes. Moreover, by gaining better understanding on the dynamics of a system over time, decision/policy makers and practitioners can prevent policy-resistance (counter-intuitive behaviors). System theory is recognized a discipline that possesses both mathematical and logic characteristics. System theory proclaims that holism, connectedness, hierarchical structure, and dynamic equilibrium, time-dependence are common properties of all systems, which are both philosophies of system thinking and principles of using system approach. As a branch of scientific approaches, system theory helps identify the objective laws on how world is running and also offers human being a way of thinking about the world. Therefore, system theory is also called system approach since it can represent concept, view, model, and mathematical methods as well.

In Bertalanffy's masterpiece titled "General System Theory; Foundations, Development, Applications", he emphasized the concept of holism. System, as an organic body, is not mechanical combination or simple addition of its constituents but an organic combination of its elements working together towards a common goal. The system's features are its emerging behaviors, which can not be found in its individual elements or subsystems. By quoting Aristotle's "*A whole is greater than the sum of its part*", Bertalanffy opposed those mechanical philosophies that the wholeness (system behaviors) can be observed or inferred from the behavior of a particular element of the system. He also stated that each element of the system is in a particular location in the system hierarchy, which is also tightly coupled with other elements. The connectedness among system's elements renders system integral and holistic. The "should-be" function of a system's element will disappear once it is separated from the system structure. For example, having done the hand amputation due to traumatic injury, the removed "hand" would never function as it could have been doing when it is an integral part of a person.

The fundamental thoughts of system theory is to treat the object being investigated as a system and to analyze the structure, function, dynamic relationships between elements, system, and their environment. With better understanding on the dynamics, complexities, and uncertainties associated with the system, the ultimate goal is to find how it attains its optimal target and, consequently provide counter-factual analysis when interventions need to be implemented in the system. Systems are ubiquitous in the universe. From cosmos to the microscopic world, systems exist everywhere such as Milky Way, solar system, earth system, social system, transportation system, production system, human body system, bacterial system, cell system, and atom, etc.

For ease of studying system, many ways were used to categorize system: (1) natural systems and artificial systems (whether designed by human being or not); (2) natural systems, social systems, and thinking systems (according to research subject); (3) macrosystems, mesa system, microsystems, and microscopic systems (scale of the systems); (4) open systems, closed systems (whether there exists interaction with environment); (5) balanced systems (systems having equilibrium), non-equilibrium systems, near-equilibrium systems, and far-from-equilibrium systems (whether there exists equilibrium).

The emergence of system theory brought profound changes on the way how people think about the world. In conventional research practices, Descartes' philosophy of "reductionism" had been dominating the academic fields. Under such influence, the general practice in research is to divide a complicated issue or subject into multiple parts and investigate each part individually. Thereafter, the characteristics of those individual parts are then used to infer the behaviors of the original issue or object. The reductionism approach focuses on local substructures or elements and abides by the unidirectional causal-effect determinism. Although this approach had proved valid for centuries within certain confined ranges and had served as the most popular way of thinking in mainstream research communities, it can only handle simple issues or objects without being able to capture the wholeness, dynamic interactions, and circular causalities of complicated objects (i.e., systems in the language of system theory). With accelerated development in economy, technology, and society, human beings with traditional analytical thinking become incompetent in dealing with issues/objects with thousands or even millions of variables connected/networked in various ways. However, the emergence of system theory, cybernetics, and informatics paved the way for human beings to drive the rapid advancement of modern science and technologies. The widespread applications of system theory make it become basis for developing new theories in handling complicated system in the fields of politics, economy, military, culture, science, and society, etc.

Regarding the trend of system theory, the authors think it is moving towards the formation of unified framework that summarizes the achievements obtained from the empirical and theoretical research in different fields. System thinking ensued by system theory has become very powerful force to overturn the ingrained singular causation thinking.

In many occasions, people like to use the formula "system function $\neq \sum$ {functions of all subsystems}" to represent the relationship between system features and subsystem features, which is not a precise expression. First of all, we are not sure if there exists additivity among subsystem features. Secondly, the system features could be larger, equal, or smaller than the sum of its subsystem features since the complicated synergistic effects caused by interactions between subsystem renders the causality prohibitively difficult to understand. In reality, there are tons of examples to illustrate this phenomenon, which brought troubles for researchers to examine the relationships between global optimization in system and local optimization in subsystems. In the following paragraphs, we provide some examples.

Example 1 MiG-25, a supersonic interceptor designed by the Soviet Union's Mikoyan-Gurevich Bureau and built mainly using stainless steel, can reach an altitude of 35,000 meters, top speed of Mach 3.2, and an average speed of 2,319.12 km/h over a 1,000 km circuit (on 16 March 1965) (Gordon 2008). It is a highly maneuverable fighter. Although the airplane primarily used nickel-steel alloy (80%) and aluminum (11%) and only 9% of titanium, it attained super performance through advanced design and synergistic effects of its subsystem structures. This case became a classical example for illustrating how system theory (systems engineering) helped engineer to achieve a better performance in system design and operations.

Example 2 A common commercial airplane is primarily composed of 6 subsystems, i.e., wings, fuselage, tail wings and rudder, landing gears, engines, and control. The major function of the commercial airplane is to safely deliver passengers from departure location to destination, which must be achieved through the synergistic interaction of the 6 subsystems. During flying process, airflow on the top of the wing is faster than that of airflow underneath the wing, which generates lower air pressure on the top of the wing and higher air pressure underneath the wing. Therefore, the difference in air pressure produces the lift. Moreover, the spoilers, ailerons, and winglets on the wings offer the function of lift, drag, and roll actions. The wings also provide installation locations for turbine engines (2 or 4). The fuselage of an airplane is the backbone to install wing, tail, landing gears, and cockpit (control circuit and equipment) and carry passengers and payload as well. The tail wing is used as horizontal stabilizer and to change and control pitch. While the tail rudder is used as vertical stabilizer and to change yaw. Landing gears are used to support airplane on the ground and allow airplane to take off, land, and taxi without damage. Turbine engines generate thrust and also provide power supply for control equipment, air conditioning, and lighting for normal airplane operation. Given the above-mentioned descriptions, the features of subsystems have essential difference with the system's features of "safely deliver passengers from departure location to destination" and they do not have additivity towards the realization of the whole system's features. The global optimum of this kind of system can not be obtained by simply optimizing its subsystems.

Example 3 In a factory with three identical production lines, each production line is a subsystem of this factory. If daily output of the factory is the feature (goal) of this factory, the daily throughput (goal) of each production line apparently has additivity. The total daily throughput is the sum of three production lines' daily output. Under such circumstance, the global optimum of the system and local optimum of each subsystem can be simultaneously achieved.

Example 4 The prisoner's dilemma is a typical non-zero-sum game in game theory where the players can be win-win or lose-lose depending on how they play the game. In this game, the game is a system and the total years in prison of the two suspects is system's goal. Each member is a subsystem and the year this player serves is the feature of this subsystem. Suppose that both members want to optimize their features (betraying the other), it turns out that the feature of the whole system gets a total of 4 years instead of the global optimum of 2 years. Therefore, in this case, the global optimum of the system can not be guaranteed when each subsystem of the system reaches its optimum and vice versa.

From the above discussion and examples, we know that there exist certain relationships between the subsystem optimum and system optimum. What are those relationships? In this monograph, we will conduct in-depth research in this respect. Two major relationships are the major themes of our research: (1) relationship between the optimum of certain intrinsic feature GY_j of system S and the feature optimum of certain subsystem in this system; (2) relationship between the optimum of certain objective feature GY_j of system S and the feature optimum of certain subsystem in this system. One issue worth noting here is that the optimum of certain intrinsic feature GY_j of system S is different from the global optimum of the whole system. Global optimum of a system is attained when all intrinsic features having consistency with all corresponding objective features of the system reach optimum. The consistency between intrinsic features and objective features dictates the alignment of system objectives, which not only requires the consistency of objectives over time but also needs the alignment the subsystems' objectives with the system's objective as well as the dynamic coordination between subsystems' goals. The system's goal is divided into sub-goals and then assigned to different subsystems or elements. Before joining a system, subsystem, as an individual self-sustained entity, also has its own goal and particular interests. Nevertheless, once employed by a system, the subsystem must be subject to the goal of the whole system and should align its individual goal or interests with the system's goal. In other words, in the process of achieving global optimization of a system, the subsystem must provide the features required by the system even with the price of sacrificing individual interests. Or the subsystem can not negatively affect the whole's features when it exercises its own features or interests.

In social system, local interests should be subject to the whole organization's interests and lower hierarchy's tactical goals should be aligned with the organizational strategy. All resources are moving towards the realization for goals of the whole organization by which the optimization of the system can be achieved. Otherwise, if there is no alignment between local goals and global goal and each element acts on its own will, the system will become a chaotic mass. Similarly, in an engineering system, the characteristics and features of constituent parts of the system must be compatible and match with each other and they must conform to the requirements of the whole system.

The combination pattern of different elements in a system plays a critical role in determining what kind of characteristics and features a system might have. For instance, due to different structures that carbon atoms can build, multiple distinct materials (e.g., diamond, graphite, and graphene) can be formed, which even have absolutely distinct characteristics. Therefore, system structure determines system behavior and characteristics.

When examining the issues regarding optimization and relationship of subsystem and system, one must consider the cost of attaining both local goals and global optimum. In China's history, there was a very famous game theory example called "Tian Ji Horse Racing". In this story, the emperor of Qi Kingdom (Emperor Qiwei) wanted to conduct horse racing with Tian Ji (370 BC-313 BC) a general of Qi Kingdom. Both of them had three groups of horse categorized as fast, medium, and slow. In the first round, the stratagem of Tian Ji advised by Sun Bin (author of Sun Bin's Art of War) was to use slow horse to race with Emperor Qiwei's fast horse. Of course, there was no doubt that Emperor Qiwei won in this round with an overwhelming advantage. However, the cost of Emperor Qiwei was that he already used his fastest horse. Tian Ji won the second and third rounds since he used his fastest horse to race with Emperor Qiwei's medium speed horse in the second and used his medium speed horse to race with Emperor Qiwei's slow horse. Finally, Emperor Qiwei lost the whole game since he consumed too much resources in realizing local goal and negatively affected the realization of the goal of the whole system.

A well-functioned system demands coordination of its elements and subsystems. In a system with feature additivity, incentives or mechanisms must be designed to simultaneously reach local optimization and align individual's interests with the system goal to attain global optimization. In "Jingyezi Anecdote", a story illustrated an old Chinese proverb: "make the best possible use of a person according to his/her strengths just like selecting tools based on what they are capable of." A family had five sons which had different merits or defects with one rustic (unsophisticated), one smart, one blind, one hunchback, and one lame. According to their specific situations, the father helped them arrange their career: with rustic one working as a farmer, smart one being a businessman, blind one offering massage service, the one with hunchback stranding rope, and lame one hand-spinning cotton. In this family system, every member used their potentials and enabled the whole family to live a bountiful life.

While in a complicated system beyond the simple aggregation of elements/subsystems, the system design must handle the trade-off between sacrificing local optimization and attaining global optimization. More attentions should be paid to the interface between subsystems. For purpose of achieving global optimization of a system, dynamic interactions with other system constituent play more important role than attaining individual optimum. Examples can found in cases like “the Dilemmas of Prisoners” and “Tian Ji Horse Racing”.

A successful entrepreneur ever wrote this equation “100−1 = 0”. The meaning of this equation is that one-time bad service experience could offset the positive image created by 100 times excellent services. In 2000, a well-known real property management company in Shanghai lost the chance in managing a luxury community due to its poor service and ensuing boycotts from property owners, which rendered its built brand loyalty and image worthless. In many well-recognized companies, they deem quality as the life of the company and “either 100 or 0” is used to define the quality acceptance standard, which means 0 tolerance toward defect, failure, mistake, or error. One can imagine the operation of a nuclear power station. A minor traffic violation could cause catastrophic property damage and casualty. A 1% chance of maloperation in medical surgeries will exert 100% impact on the patients involved. Taking another example, in the process of inputting password for a bank account, you can not log in as long as you have one typo.

Based on the above analysis, in order to investigate system optimization, we must first build a series of concepts: (1) critical subsystems, major subsystems, and important subsystems; (2) critical structures, major structures, and important structures; (3) critical elements, major elements, important elements, and subsystem independence. Next, we discuss the theory and method for conducting system optimization. The steps of system optimization are listed as follows: (1) determine if a system has error; (2) error should be eliminated if the system has error. In some instances, for error occurred in a system, one can start addressing errors from the bottom layer of a system and then move up to higher hierarchies according to acting forces of different subsystems. The method for investigating system error is then confirmed and used to eliminate error in the whole system. (3) for a system without errors (or a system tolerating errors), a programming model is built in which: the expected overall intrinsic features are the objectives; each intrinsic feature contained in objective features is defined as an independent variable; and the system’s conditions are constraints. By solving the programming model, the values or the value ranges of each intrinsic feature are obtained. (4) feature-based system optimization is then conducted given the values or the value ranges of each intrinsic feature.

Except for the investigation on the relationship between system structure and system features, we also explore the strength, spatial dynamics, direction, and sequence of acting of mutual interacting forces of system structure and how they affect the attainment of system’s global optimum. For the sake of gaining better understanding on how interactions of system (or subsystem) structures affect system features, we propose the concepts of system structural acting force (“Shi” or “potential” or “quan”), chained structural acting force, and accumulated acting force.

Thereafter, transformations of system structural acting forces, relationship between system structural acting forces and system features, and relationship between system structural acting forces and optimization of error system are examined. The relevant issues, contents, and examples of system acting forces are provided accordingly.

Systems are categorized into two types when studying the relationship between subsystem optimization and system optimization.

1. Additivity of features
   (1) Complete additivity:

$$GY_j = \sum_{i=1}^{n} GY_{ji}$$

   (2) Partial additivity:

$$GY_j \neq \sum_{i=1}^{n} GY_{ji}$$

2. Non-additivity of features
   $S(GY_j) = S(S_1(GY_{j1}(a_1, b_1)),\ S_2(GY_{j2}(a_2, b_2)),\ \ldots,\ S_i(GY_{ji}(a_i, b_i)),\ \ldots, S_n(GY_{jn}(a_n, b_n)))$, where (a_i, b_i) denotes the range for the feature GY_{ji} of ith subsystem S_i (i = 1, 2,…, n).

In system design and operation, we should investigate the states of system and its subsystems based on the system structure when the system's global optimum is reached. Then, one should consider all critical subsystems and important subsystems. And then one should consider to choose the least-costly scenario of allocating resources among all the subsystems s_i when the system global optimum is attained if there are one more scenarios.

A typical error system S has 4 major factors, namely, domain, system, time, and judging rules. We can conduct transformation on each factor or their different combinations thereof. Then we have

(1) Domain transformation;
(2) System transformation;
(3) Temporal transformation;
(4) Rules transformation;
(5) Simultaneous transformation on domain and system;
(6) Simultaneous transformation on domain and time;
(7) Simultaneous transformation on domain and rules;
(8) Simultaneous transformation on system and time;
(9) Simultaneous transformation on system and rules;

(10) Simultaneous transformation on time and rules;
(11) Simultaneous transformation on system, domain, and time;
(12) Simultaneous transformation on system, domain, and rules;
(13) Simultaneous transformation on domain, time, and rules;
(14) Simultaneous transformation on system, time, and rules;
(15) Simultaneous transformation on system, domain, time, and rules.

Additionally, 6 basic transformations can be conducted on each factor.

1. Similarity or equivalence transformation $T_n \subseteq \{T_{xly}, T_{xsw}, T_{xlj}, T_{xtz}, T_{xlz}, T_{xcz}, T_{xhs}, T_{xsj}, T_{xgz}, T_{xzh}\}$ (similarity or equivalence), similarity or equivalence transformation includes similarity in domains, similarity in factors of conditions, similarity in structures of conditions, similarity in rules of conditions, similarity in factors of conclusions, similarity in structures of conclusions, similarity in rules of conclusions, similarity in factors of intrinsic features, similarity in structures of intrinsic features, similarity in rules of intrinsic features, similarity in factors of objective features, similarity in structures of objective features, similarity in rules of objective features, similarity in factors of structures, similarity in structures, and spatial similarity.
2. Displacement transformation $T_n \subseteq \{T_{zly}, T_{zsw}, T_{zlj}, T_{ztz}, T_{zlz}, T_{zcz}, T_{zhs}, T_{zsj}, T_{zgz}, T_{zzh}\}$ (displacement), displacement transformation includes displacement in domains, displacement in factors of conditions, displacement in structures of conditions, displacement in rules of conditions, displacement in factors of conclusions, displacement in structures of conclusions, displacement in rules of conclusions, displacement in factors of intrinsic features, displacement in structures of intrinsic features, displacement in rules of intrinsic features, displacement in factors of objective features, displacement in structures of objective features, displacement in rules of objective features, displacement in factors of structures, displacement in structures, and spatial displacement.
3. Addition transformation $T_n \subseteq \{T_{znly}, T_{znsw}, T_{znlj}, T_{zntz}, T_{znlz}, T_{zncz}, T_{zncz}, T_{znsj}, T_{zngz}, T_{znzh}\}$ (addition), addition transformation includes addition in domains, addition in factors of conditions, addition in structures of conditions, addition in rules of conditions, addition in factors of conclusions, addition in structures of conclusions, addition in rules of conclusions, addition in factors of intrinsic features, addition in structures of intrinsic features, addition in rules of intrinsic features, addition in factors of objective features, addition in structures of objective features, addition in rules of objective features, addition in factors of structures, addition in structures, and spatial addition.
4. Decomposition transformation $T_n \subseteq \{T_{fly}, T_{fsw}, T_{flj}, T_{ftz}, T_{flz}, T_{fcz}, T_{fhs}, T_{fsj}, T_{fgz}, T_{fzh}\}$ (decomposition), decomposition transformation includes decomposition in domains, decomposition in factors of conditions, decomposition in structures of conditions, decomposition in rules of conditions, decomposition in factors of conclusions, decomposition in structures of conclusions, decomposition in rules of conclusions, decomposition in factors of intrinsic features, decomposition in structures of intrinsic features,

decomposition in rules of intrinsic features, decomposition in factors of objective features, decomposition in structures of objective features, decomposition in rules of objective features, decomposition in factors of structures, decomposition in structures, and spatial decomposition.

5. Destruction transformation $T_n \subseteq \{T_{hly}, T_{hsw}, T_{hlj}, T_{htz}, T_{hlz}, T_{hcz}, T_{hhs}, T_{hsj}, T_{hgz}, T_{hzh}\}$ (destruction), destruction transformation includes destruction in domains, destruction in factors of conditions, destruction in structures of conditions, destruction in rules of conditions, destruction in factors of conclusions, destruction in structures of conclusions, destruction in rules of conclusions, destruction in factors of intrinsic features, destruction in structures of intrinsic features, destruction in rules of intrinsic features, destruction in factors of objective features, destruction in structures of objective features, destruction in rules of objective features, destruction in factors of structures, destruction in structures, and spatial destruction.
6. Unit transformation T_d (unit) and its corresponding inverse unit transformation T_d^{-1}.
7. Quantifier for error logic, there are another three combinations with respect to 6 basic transformation:

   (1) Conjunction of transformations;
   (2) Disjunction of transformations;
   (3) Inverse transformation.

In brevity, we employ 15 paths, 6 basic transformations, and 3 combinations to figure out solutions to prevent and eliminate errors. This is the core of our research, i.e., employing "15, 6, 3" methodology system to prevent and eliminate errors.

The book is arranged as follows. Chapter 1 proposes the basic concepts of error system. In Chap. 2, methods for identifying errors are discussed. In order to identify errors, the first thing is to define universe of discourse (research domain). And the next step is to define a group of rules G for judging errors. The conditions, fields, and time for qualifying G must be clearly defined in advance. The relationship among rules and relationship between rules and object of interest are then examined. Having done that, the interacting mechanism and laws are obtained. Step 3 is to find method for identifying error given that tools and processes are well mastered. Examples are provided in the end of this chapter. Five basic structures of system and their brief descriptions are presented in Chap. 3. They are: (a) series structure, (b) parallel structure, (c) feedback structure, (d) expanding and shrinking structure, (e) inclusion structure, and other types. Types (a), (b), and (d) can be represented by $m \times n$ form where m stands for the number of parallel series structures from starting point (observing from left to right) and n stands for the number of parallel series structures at the ending point (observing from left to right). Type (a) is $m = n = 1$; (b) is $m = n \leq 2$; (d) expanding is the case of $m = 1$ and $n \leq 2$ and shrinking is the case of $m \leq 2$ and $n = 1$. Therefore, the basic types of system are (1) $m \times n$ type, (2) feedback structure, (3) inclusion structure, and (4) other types. Chapter 4 provides the basic structures of error systems which are:

(a) series structure, (b) parallel structure, (c) feedback structure, (d) expanding and shrinking structure, (e) inclusion structure, and other types. Chapter 5 talks about the conditions and modes for conducting 6 basic transformations on 5 basic system structures. In Chap. 6, a new concept in system theory is proposed here, i.e., System Acting Force (abbreviated as **AF**, i.e., system's "shi" or potential). Structural AF of system, element AF of system, and the relationship between them are discussed at length. Chapter 7 mainly addresses the transformations on universe of discourse (domain) and rules of error systems. In Chap. 8, concepts and forms of error function[1] are presented. This chapter also explores the relationship between error function and judging rules. Chapter 9 provides the detailed application of error system. This chapter also presents practical methods and principles in avoiding and eliminating errors. Some examples are offered as well.

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[1]Function: it serves two purposes in this book with one denoting mathematical relationship between sets that maps each element in one set to exactly one element in another set and the other meaning is the action for which a person or thing is specially fitted or used or for which a thing exists: purpose (Merriam-Webster). Therefore, in order to avoid confusion, we prefer to use "feature" when second meaning is needed.

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