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Foundations and Applications of Information Systems Dynamics

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ABSTRACT

Although numerous advances have been made in information technology in the past decades, there is still a lack of progress in information systems dynamics (ISD), owing to the lack of a mathematical foundation needed to describe information and the lack of an analytical framework to evaluate information systems. The value of ISD lies in its ability to guide the design, development, application, and evaluation of large-scale information system-of-systems (SoSs), just as mechanical dynamics theories guide mechanical systems engineering. This paper reports on a breakthrough in these fundamental challenges by proposing a framework for information space, improving a mathematical theory for information measurement, and proposing a dynamic configuration model for information systems. In this way, it establishes a basic theoretical framework for ISD. The proposed theoretical methodologies have been successfully applied and verified in the Smart Court SoSs Engineering Project of China and have achieved significant improvements in the quality and efficiency of Chinese court informatization. The proposed ISD provides an innovative paradigm for the analysis, design, development, and evaluation of large-scale complex information systems, such as electronic government and smart cities.

1. Introduction

Gleick's *The Information: A History, a Theory, a Flood* [1] states that information is the blood, food, and vitality of our world. With the ever-growing scales and complexities of information systems, it is becoming increasingly difficult for people to understand and grasp information systems, particularly system-of-systems (SoSs). An SoSs is a collection of task-oriented systems that offer more functionality and a greater performance than simply the sum of the constituent systems. Owing to the influence of various internal and external uncertainties, the dynamic behavior of these complex SoSs may deviate from their original purpose, and unstable phenomena may appear. Moreover, in the construction and application of such large-scale SoSs, an emphasis on order alone, while ignoring vitality, will lead to system rigidity, whereas an emphasis on vitality alone, while ignoring order, will lead to system chaos [2]. Therefore, there is an urgent need for information systems dynamics (ISD)—similar to the mechanical dynamics guiding mechanical systems engineering—to guide the design, development, application, and evaluation of large-scale SoSs.

In fact, the study of information dynamics has existed for many years, albeit mostly at a qualitative level and with a lack of quantitative regularity [3–5]. For example, Yan [6] applied information entropy as the only metric used to measure the efficacy of information, making it difficult to analyze complex SoSs. The investigation into ISD has been ongoing for many years as well. Flory and Kouloumdjian [7] studied a database model in the name of ISD, which is far from the traditional aim of dynamics. Bounfour and Batra [8] investigated the effects of information technologies and information systems on business models, human resources, and social organizations, without applying mathematical metrics as a basis of the research.

Despite these efforts, it is clear that a reasonable research paradigm for ISD has yet begun, owing to the lack of solid theoretical foundations with universal significance [9]. Moreover, although the development and application of information technologies have progressed rapidly in recent years, a comprehensive, rigorous, and complete theoretical foundation for ISD has yet to be established. The main reasons can be summarized as follows.

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First, there is a lack of an effective and reasonable framework for information space. *Information space* is the objective reality of information movements and actions, in which *information systems* are the basic carrier for applying information to serve human beings. Generally, the input-processing-output model is applicable to any information system [10]. However, for an information space with complex information systems, this model is too simple to support the investigation and analysis of real systems. By contrast, if we pay too much attention to the complexity of an ever-changing information space, we will be bogged down by tedious details and lose the whole picture. Therefore, it is essential to apply an overall approach to construct the framework of the whole information space in order to support the theoretical system of ISD.

Second, there is a lack of the widely adopted mathematical expressions to describe the concept of information. Shannon's information theory reveals that the capacity of information in communication systems can be defined as entropy [11], which has led many people to mathematically regard information as negative entropy. However, the concept of information is far beyond that in communication systems. Thus, information entropy, as an information expression, cannot meet the general requirements of information science and technology, particularly for SoSs. In fact, scholars are far from reaching a consensus on the nature of information [12,13], which is considered as the key obstruction in developing a unified, convenient, and feasible mathematical information foundation.

Third, there is a lack of a clear and comprehensive of system for information metrics. To the best of our knowledge, Shannon's information entropy is the only widely adopted information metric [14–16]. However, because information systems have evolved into different functionalities with complex structures far beyond those of communications [17], metrics based on entropy cannot comprehensively measure the complex dynamics of various information systems [7,8]. Although other studies on the measurement of information exist [18–21], they lack for strict mathematical definitions and being systemic, making it difficult to establish an essential, basic reference framework for studying information mechanisms.

Fourth, there has been a lack of a thorough analysis of the efficacies of information systems. A *dynamic mechanism* describes how the target objects affect each other in a specific field. For example, in Newtonian mechanics, the efficiencies of speed, energy, and power were measured and analyzed to establish the theoretical system of mechanical dynamics [22]. This methodology has also been applied in other fields, such as chemical kinetics [23] and economic dynamics [24]. However, although information is pervasive in everyday life, there is a lack of a systematic approach to measuring and analyzing different efficacies of information systems. It is clear that only by establishing a complete analytical system of information efficacy can we accurately analyze the dynamic patterns in complex large-scale information systems.

To address these fundamental challenges, Xu et al. [25] proposed a mathematical theory named Objective Information Theory (OIT), which simplifies the concept of information from a general arbitrary idea to an objective concept in the real world, defining information as a mathematical mapping from objects in the real world to objects in information space. This approach was further used to explain the behavior of an air traffic control system, demonstrating the feasibility of applying OIT to investigate information systems [26].

In this study, we further modify and refine OIT by introducing the concept of restorable information. Because the restorability of information ensures mathematical isomorphism, which provides an important precondition to complete OIT, we can extend the number of metrics from nine to 11 in order to comprehensively measure information. Furthermore, to apply the 11 metrics to measure and analyze the dynamics of information systems, we propose an analytical model named dynamic configuration to conveniently analyze various efficacies of information systems. Taken together, the information space framework, OIT, the dynamic configuration model, and methodologies used to analyze various efficacies of information systems constitute a basic theoretical framework of ISD with universal significance. The proposed theory of ISD has been applied and verified in the Smart Court SoSs Engineering Project of China, which provides a reference for the analysis, design, development, and evaluation of large-scale complex SoSs.

2. Information space

The wide application of information technologies and systems, such as the Internet and mobile Internet (MI) [27,28], the Internet of Things (IoT) [29], big data (BD) [30], cloud computing (CC) [31,32], supercomputing [33,34], artificial intelligence (AI) [35], and blockchains [36], have profoundly changed human society. In particular, the emergence of the metaverse, which comprehensively integrates the achievements of information technologies, has a broad significance for our lives [37]. Therefore, it is crucial to establish an information space framework for comprehensive study of the principles of information movement and utilization from the overall perspective of the real world, society, and information systems.

2.1. Real-world information space

Wiener, the founder of cybernetics, pointed out that information is information, rather than matter or energy [38], implying that it is objective in nature. Inspired by Wiener's theory, we constrain information in the objective category and regard materials, energy, and information as the three major elements of the real world. In this context, information takes matter and energy as its medium and reflects objects and the states of their motion in the real world. Herein, we adopt the British philosopher Popper's three world ontology, which, while accommodating both the world of physical states and processes (World 1) and the mental world of psychological processes (World 2), represents knowledge in its objective sense as belonging to World 3—a third, objectively real, ontological category [39].

With sound and light providing information in nature, and language and images providing information to people, information space has existed in the real world since ancient times. Following Popper's theory, World 1 and World 3 constitute the information space in the real world, which are carriers of information. However, because the scope and effectiveness of such information are limited, people usually tend to ignore its existence.

2.2. Information space in the information age

In the information age, various information systems are continually emerging. Information in the real world is transformed into information within information systems through digitization, which in turn reflects the real world. In this scenario, the real world contains the information space based on information systems. For example, digital twins (DTs) are used to construct digital objects in information space in order to denotate the corresponding physical objects in the real world; thus, this technology uses the core of the information space to reflect the shell of the real world.

Furthermore, the interaction between the information space and the real world is conducive to a balance between conceptual, technological, and cultural levels. Conceivably, in the metaverse, human individuals will have their own avatars in the information space. Through their avatars, humans will thus be able to extend their social activities into the information space, as can already be done in some video game platforms such as massively multiplayer online role-playing games [37]. The avatars will be able to self-learn, self-adopt, self-interact, self-evolve, and even obtain more happiness. Moreover, such feelings and experiences can be brought back into the real world via the human–avatar connections, which is conducive to changing the real world in positive (or negative) ways. In this way, life may expand from physiological limitations to digital infinity in the information space.

In general, information space spans World 1 and World 3 in the real world, which obviously includes information systems. In particular, the information in information systems is in the form of data across the collection, transmission, processing, and action of information.

2.3. An information space framework

Construction of an information space framework is an important prerequisite for developing the theoretical system of ISD. An information space framework should fully integrate the real world and information systems, consider the achievements of information science and technology, cover all information processes, present the role of information movement, and support the research, analysis, and evaluation of information systems. These considerations can be summarized through the following four principles: ① The information space framework should be a comprehensive fusion of the real world and information systems; ② emphasis should be placed on the driving role of information flows; ③ there should be coverage of all important processes of information movement; and ④ as many important information technologies should be included as possible.

Following the above principles, we propose an information space framework, as shown in Fig. 1. In the figure, the orange area represents the subjective world, while all the blue areas represent carriers of the information space, covering both World 1 and World 3 within the real world. In particular, the blue rings in the circle represent the links of information collection/action, transmission, processing, as well as the data space from the center to the outside. The arrows moving through the various links represent information flows in the information space. Information flows through the links of collection, transmission, and processing from the outside to the inside of the circle, and finally converges and is deposited in the data space at the core of the circle. Subsequently, the information flows inversely from the inside to the outside through the three links of information processing, transmission, and action. Because the links of information collection and action come in direct contact with the physical world, we present them in the same ring and distinguish them only by different shades of blue and different directions of information flows. In theory, information systems are part of the real world; however, because of their special roles in information, information flows, and information space, which are the main subjects of ISD, we separate information systems from the rest of the real world in the information space framework and place them at the center of the framework structure. In general, information within the information space is a resource, information flows provide vitality, and information systems achieve efficacies.

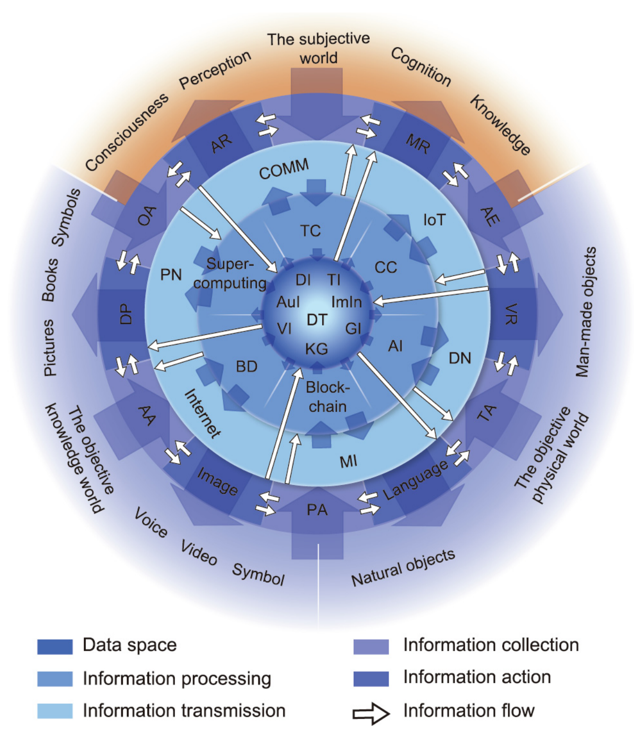

Fig. 1. Framework of information space. MR: mix reality; VR: virtual reality; AR: augmented reality; AE: electromagnetic acquisition; TA: temperature acquisition; PA: power acquisition; AA: audio acquisition; DP: data power; OA: optical acquisition; COMM: communication; DN: data networking; PN: private network; TC: traditional computing; DI: data information; TI: text information; AuI: audio information; ImIn: image information; VI: video information; GI: graphic information; KG: knowledge graph.

As shown in Fig. 1, the subjective world involves information systems for sending and receiving information and produces subjective content such as consciousness, cognition, and perception. The objective physical world consists of natural and artificial objects. The objective knowledge world includes knowledge products such as pictures, books, audio, and video. Both the objective physical world and objective knowledge world can produce, receive, and store information; therefore, they are important carriers of information space.

The *information collection link*, which consists of optical, audio, power, temperature, electromagnetic, and other types of acquisition systems, collects various forms of information from the real world and then sends it to other information systems via the transmission link. Conversely, the *information action link*, which consists of language, images, power, virtual reality (VR), augmented reality (AR), and so forth, receives information from other information systems, and then exerts actions on the real world, thereby generating effects. The *information transmission link*, which includes communication systems, private networks (PNs), the Internet, the MI, the Internet of Data, the IoT, and so forth, transmits various types of information between or within information systems. The *information processing link* includes traditional computing devices, supercomputing, CC, BD, AI, blockchains, and various algorithms with specific functions for processing different types of information in information systems in order to meet the requirements of various businesses and users.

The *data space* is the core of the information space. Through the collection, transmission, and processing links, information in the real world is converted into data of various types, such as numeric data, text, audio, images, videos, knowledge graphs (KGs), and so forth, to form a holographic mirror reflecting the real world. This holographic reflection of the real world through data has many advantages and conveniences in terms of transmission and processing, such that people can use the data almost at will, give back to the real world, and promote human civilization. Therefore, the essential of information systems is to construct a data space forming a holographic reflection of the real world.

3. A mathematical foundation for information measurement

A mathematical definition of information is the basis for inferring the properties and metrics of information. A solid and complete mathematical system is a key part of the ISD to guide the engineering practice of complex SoSs.

3.1. The information model

The OIT has its roots in the philosophical view that *information is the objective reflection of objects and their state of motion in the objective and subjective worlds*, as inspired by Wiener's triadic theory of matter, energy, and information [25]. In this study, the proposed information space framework also embodies this philosophical view of information, in which the real world is the essence and true nature of the information space, and provides the source of all information. In turn, the information space reflects the real world and feedbacks the real world by simulating and deducing objects and movements that are costly to conduct physically. Therefore, in the OIT, the objective information is mathematically modeled as follows:

$$I{:}f(o,T_{\mathrm{h}}) \rightarrow g(c,T_{\mathrm{m}}) \tag{1}$$

where I denotes objective information, o denotes noumena (i.e., objects that originate information in the real world), c denotes carriers (i.e., objects that transmit and maintain information in the real world), T_{h} denotes the occurrence time, and T_{m} denotes the reflection time. Noumena o belongs to either an objective world or subjective world, thus mathematically $o \in 2^{O \cup S}$. Carries c only belongs to an objective world, thus $c \in 2^{O}$. The occurrence time T_{h} and reflection time T_{m} are both in temporal domain, that is, $T_{\mathrm{h}} \in 2^{T}$ and $T_{\mathrm{m}} \in 2^{T}$. Here, O denotes an objective world set that includes the basic objects in World 1 and World 3; S denotes a subjective world set that includes the basic objects in World 2; and T denotes a time set that is the duration of information action. The elements in O, S, and T can be either continuous or discrete, subject to the requirement of the specific universe of discourse. Moreover, $f(o,T_{\mathrm{h}})$ represents a non-empty set of o over T_{h}, which is referred to as a state set; and $g(c,T_{\mathrm{m}})$ represents a non-empty set of c over T_{m}, which is referred to as a reflection set.

Eq.(1) can be rewritten as

$$I(f(o,T_{\mathrm{h}})) = g(c,T_{\mathrm{m}}) \tag{2}$$

Thus, information I is modeled mathematically as a full mapping from a state set $f(o,T_{\mathrm{h}})$ to a reflection set $g(c,T_{\mathrm{m}})$. To further clarify the interpretation of the model, an explanatory example is presented in Appendix A.

As information I can also be written as $I = \langle o, T_{\mathrm{h}}, f, c, T_{\mathrm{m}}, g \rangle$, this mathematical information definition is referred to as the *sextuple model* of information. In previous studies on the OIT, information can be both single-valued and multi-valued mappings to accommodate the widest range of possible situations [25]. However, multi-valued mappings are difficult to understand, and the corresponding practical applications are difficult to find. Therefore, in this study, we constrain information to single-valued mappings, which can bring about significant convenience to subsequent investigations without affecting most (or even all) applications.

With the sextuple model, we can realize the dual deconstruction of the subject, temporal domain, and form of the information, respectively. These deconstructions of information make it possible to conduct more profound and comprehensive investigations of information beyond Shannon's information theory, and provide a solid mathematical foundation for developing scientific and applicable ISD.

3.2. Information property

From the sextuple model, we can mathematically infer five primary properties of information: objectivity, restorability, transitivity, combinability, and relevance.

3.2.1. Objectivity

In the sextuple model, the separation of noumena o and carriers c is the binary deconstruction of the subjects of the information I. Based on the deconstruction, information I can be reflected through the reflection set $g(c,T_{\mathrm{m}})$, the state set of c over T_{m}. Herein, c belongs to the objective world; thus, information I can be perceived through the objective world, which is why the OIT is named after the objectivity of information.

Owing to the objectivity of information, people can collect, transmit, process, aggregate, and apply information using various technical means. In fact, the rapid development of emerging technologies, such as AI, brain-like systems, and brain–computer interfaces, is driven by advances that simulate the human mind and then transform humanity's subjective processes into objective information that can be processed by information systems. Therefore, we consider the OIT to plays a fundamental role in the analysis and research of information systems and technologies.

3.2.2. Restorability

Defined mathematically as a type of mapping, information I may have an inverse mapping I^{-1}. Here, if $g(c,T_{\mathrm{m}})$ on T_{m} of c can be restored to the state $f(o,T_{\mathrm{h}})$ of o on T_{h} by I^{-1}, we call information I restorable. This is the restorability of information. Here, $f(o,T_{\mathrm{h}})$ is also called the restored state of information I. The detailed mathematical inference is presented in Appendix A. Moreover, if there is a mapping J such that $J(g(c,T_{\mathrm{m}})) = \widetilde{f}\left(\widetilde{o},\widetilde{T_{\mathrm{h}}}\right)$, where $\widetilde{o}$ is referred to as reflection noumena ($\widetilde{o} \in 2^{O \cup S}$), $\widetilde{T_{\mathrm{h}}}$ is referred to as reflection occurrence time ($\widetilde{T_{\mathrm{h}}} \in 2^{T}$), and $\widetilde{f}\left(\widetilde{o},\widetilde{T_{\mathrm{h}}}\right)$ is a certain state set of $\widetilde{o}$ on $\widetilde{T_{\mathrm{h}}}$, then J is called a reflection of I, and $\widetilde{f}\left(\widetilde{o},\widetilde{T_{\mathrm{h}}}\right)$ is the reflection state of I based on J. When $J = I^{-1}$, $\widetilde{f}\left(\widetilde{o},\widetilde{T_{\mathrm{h}}}\right)$ is the restored state of I.

It should be noted that the isomorphism between the state set and the reflection set of restorable information is of great significance. Through isomorphism, the same mathematical method can be applied to two different sets of information—that is, noumenon states and carrier states—where the objects in these sets have the same attributes and operations. The proposition established for one set can be established for another. This facilitates the use of abundant mathematical theories to support extensive research in the field of information science.

3.2.3. Transitivity

Information I can be transmitted from o to c and from c to other carriers c', from T_{h} to T_{m} to and from T_{m} to another reflection time T'_{m}, and from $f(o,T_{\mathrm{h}})$ to $g(c,T_{\mathrm{m}})$ and from $g(c,T_{\mathrm{m}})$ to another reflection set $g'(c',T'_{\mathrm{m}})$ through the compound mapping $I'(I(f(o,T_{\mathrm{h}})))$; that is, via the transitivity of information. The detailed mathematical inference is presented in Appendix A. It is reasonable to state that it is due to the transmissibility of information such that information movement in the collection, transmission, processing, convergence, and action links can be realized. In particular, serial information transmission is a very common form of information movement in information systems, so it is greatly significant to analyze the mechanism of a serial information transmission chain for the construction of a theoretical system of ISD.

3.2.4. Compositionality

In Eq. (1), $f(o, T_h)$ and $g(c, T_m)$ are mathematical sets. Therefore, information I can naturally be decomposed or combined into different new sets; thus, information has compositionality. The detailed mathematical inference is presented in Appendix A. The compositionality of information determines that information can be flexibly split and arbitrarily combined, which creates sufficient conditions for people to determine the objects of information processing according to actual needs.

3.2.5. Relevance

The relevance of information manifests itself in at least three ways. First, for information $I = \langle o, T_h, f, c, T_m, g \rangle$, o and c, T_h and T_m, and $f(o, T_h)$ and $g(c, T_m)$ come in pairs, respectively. As a surjective map of $f(o, T_h)$ onto $g(c, T_m)$, information I establishes a particular connection between o and c. In particular, the information transmission is an important embodiment of information relevance, in which things are bridged together. Thus, people usually state that information is a bridge that connects things.

Second, there can be connections between different pieces of information or the containment of one piece of information in another. Because various mutual relationships can exist between different pieces of information, which is a form of information correlation, people can utilize various analytical approaches to mine the values of information.

Third, the most important form of information relevance is the internal relationships in a restored state. Here, restored information can completely retain the internal structure of the original information, which is an important prerequisite for accessing, processing, and analyzing the internal structure of information.

3.3. Information metrics

The philosophy of objective information and the related sextuple model of the OIT provide a powerful and flexible tool to derive various information metrics, which can be inspired by both theoretical research and practical experience. To guide and regulate the derivation of information metrics, we have come up with the following principles:

- **Traceability**: The metrics are mathematically defined and derived from the sextuple model.
- **Integrity**: The metrics are systematically defined and closely related to the value of the objective information.
- **Generality**: The metrics should be applicable to different information systems, such as information acquisition, transmission, processing, action, and their combinations, rather than being limited to a specific system.
- **Practicality**: The metrics should be able to guide the design, implementation, and analysis of practical information systems.
- **Openness**: Owing to the complex characteristics of information, the metrics should continually evolve to meet the needs of theoretical research and engineering applications.

Based on the above principles, we defined 11 metrics below. We emphasize that all metrics are based on restorable information. In addition, some metrics are modified from previous studies on the OIT [25].

3.3.1. Volume

Let $g(O \times T)$ be the set of state sets, which contains $g(c, T_m)$ on the objective world and temporal domain, and $\left(g(O \times T), 2^{g(O \times T)}, \sigma\right)$ be a measure space, where σ is a measure for the space. Then, the volume of information I relative to measure σ (viz volume$_\sigma(I)$) is the measure $\sigma(g(c, T_m))$ of $g(c, T_m)$, which is expressed as follows:

$$\text{volume}_\sigma(I) = \sigma(g(c, T_m)) \tag{3}$$

In information systems, the volume of information is usually measured in bits, which is the most understandable information metric. In practice, the measure σ of $\left(g(O \times T), 2^{g(O \times T)}, \sigma\right)$ for a specific task is determined by the universe of discourse. Therefore, the volume metric defined here is in a general form, but can be defined differently according to the practical needs. The metrics defined in the reminder of this study follow the same principle when applied in practice. This definition of volume is modified from that in a previous work [25]; the reasoning is presented in Appendix A.

3.3.2. Delay

Delay reflects the speed of the carrier response to the state of noumena. Therefore, the delay of information I (viz. delay(I)) is the difference between the supremum of its reflection time ($\sup T_m$) and the supremum of its occurrence time ($\sup T_h$), which is expressed as follows:

$$\text{delay}(I) = \sup T_m - \sup T_h \tag{4}$$

It is should be noted that this definition of delay allows for both positive and negative values. In particular, when $\sup T_m < \sup T_h$, delay$(I) < 0$. This represents the prediction of the future states by the carrier prior to the occurrence time T_h of the state for noumena. For example, the motion of targeted objects and the occurrence of events of interest can be predicted in information systems. This definition of delay is modified from that in a previous work [25]; the reasoning is presented in Appendix A.

3.3.3. Scope

Let $\left(O \cup S, 2^{O \cup S}, \sigma\right)$ be the measure space over $O \cup S$. Let σ be some measure on $(O \cup S)$. According to the definitions of O and S, noumena o are elements of O and S, that is, $o \in 2^{O \cup S}$. Then, the scope of information I relative to measure σ (viz scope$_\sigma(I)$) is the measure $\sigma(o)$ of o, which is defined as follows:

$$\text{scope}_\sigma(I) = \sigma(o) \tag{5}$$

3.3.4. Granularity

For a pair of information I and I', if I' is proper sub-information of I and there is no other proper sub-information I'' of I such that $I'' \subset I'$, then I' is called the atomic information of I.

Here, let $\left(O \cup S, 2^{O \cup S}, \sigma\right)$ be a measure space, and let σ be some measure on the set $(O \cup S)$. The set of all atomic information in information I is denoted as $A = \{I_\lambda = \langle o_\lambda, T_{h\lambda}, f_\lambda, c_\lambda, T_{m\lambda}, g_\lambda \rangle\}_{\lambda \in \Lambda}$, where Λ is an index set and λ is an index. In this case, let μ be the measure of the index set Λ and $\mu(\Lambda) \neq 0$. Then, the granularity of information I relative to measure σ (viz granularity$_\sigma(I)$) is the ratio of the integral of all noumenon measures of atomic information in A to the measure μ of index set Λ, which is expressed as follows:

$$\text{granularity}_\sigma(I) = \frac{\int_\Lambda \sigma(o_\lambda) \mathrm{d}\mu}{\mu(\Lambda)} \tag{6}$$

where it is most appropriate to take μ as the counting measure. This definition of granularity is modified from that in a previous work [25]; the reasoning is presented in Appendix A.

3.3.5. Variety

For information I, let R be an equivalence relation on the set of states $f(o,T_{\mathrm{h}})$, and the set of equivalence classes of the elements in $f(o,T_{\mathrm{h}})$ relative to R is $[f(o,T_{\mathrm{h}})]_R$. Then, the variety of information I relative to R (viz variety$_R(I)$) is the cardinality of set $[f(o,T_{\mathrm{h}})]_R$, which is expressed as follows:

$$\mathrm{variety}_R(I) = \overline{\overline{[f(o,T_{\mathrm{h}})]_R}} \tag{7}$$

Note that, for restorable information, the equivalence relation within state set can be transferred to reflection set. Therefore, the reflection set of the carrier can fully reflect the variety metric of information.

3.3.6. Duration

The duration of information I (viz duration(I)) is the difference between the supremum and infimum of T_{h}, which is expressed as follows:

$$\mathrm{duration}(I) = \sup T_{\mathrm{h}} - \inf T_{\mathrm{h}} \tag{8}$$

where $\inf T_{\mathrm{h}}$ is the infimum of the occurrence time T_{h}.

3.3.7. Sampling rate

For information I, if $\inf T_{\mathrm{h}} \neq \sup T_{\mathrm{h}}$, let $\{U_\lambda\}_{\lambda\in\Lambda}$ be a family of pairwise disjoint connected sets that satisfy the following: for any $\lambda\in\Lambda$, there are $U_\lambda \subseteq [\inf T_{\mathrm{h}}, \sup T_{\mathrm{h}}]$, and $T_{\mathrm{h}} \cap U_\lambda = \varnothing$. Then, the sampling rate of information I (viz sampling_rate(I)) is simply the ratio of the cardinality of Λ to the Lebesgue measure $|U|$ of $U = \bigcup_{\lambda\in\Lambda} U_\lambda$, which is expressed as follows:

$$\mathrm{sampling\_rate}(I) = \frac{\bar{\bar{\Lambda}}}{|U|} \tag{9}$$

Here, if $\inf T_{\mathrm{h}} = \sup T_{\mathrm{h}}$ or the Lebesgue measure of U is $|U| = 0$, then $\mathrm{sampling\_rate}(I) = \infty$ is defined, which indicates that the state set of information I is completely continuous in time.

3.3.8. Aggregation

For information I, if the cardinality of set $f(o,T_{\mathrm{h}})$ is $\overline{\overline{f(o,T_{\mathrm{h}})}} \neq 0$, let $\mathfrak{R}$ be the set of relations between all elements on the state set $f(o,T_{\mathrm{h}})$. Then, the aggregation of I (viz aggregation(I)) is the ratio of the cardinality of set $\mathfrak{R}$ to that of set $f(o,T_{\mathrm{h}})$, which is expressed as follows:

$$\mathrm{aggregation}(I) = \frac{\bar{\bar{\mathfrak{R}}}}{\overline{\overline{f(o,T_{\mathrm{h}})}}} \tag{10}$$

The aggregation metric characterizes the distance between the elements of the state set $f(o,T_{\mathrm{h}})$ in the information space. In general, the closer the distance is between the elements of the state set $f(o,T_{\mathrm{h}})$, the higher the degree of aggregation and the higher the value of the information.

3.3.9. Coverage

For information I and I', if there are inverse mappings I^{-1} and I'^{-1}, such that $I^{-1}(g(c,T_{\mathrm{m}})) = I'^{-1}(g'(c',T'_{\mathrm{m}})) = f(o,T_{\mathrm{h}})$, then information I and I' are called to be copies of each other. Here, let $\{I_\lambda = \langle o_\lambda, T_{\mathrm{h}\lambda}, f_\lambda, c_\lambda, T_{\mathrm{m}\lambda}, g_\lambda\rangle\}_{\lambda\in\Lambda}$ be a set containing information I and all of its copies. Then, the coverage of information I relative to some measure σ on a measurable set of c (viz coverage$_\sigma(I)$) is the integral of all measures c_λ, which is expressed as follows:

$$\mathrm{coverage}_\sigma(I) = \int_\Lambda \sigma(c_\lambda)\mathrm{d}\mu \tag{11}$$

3.3.10. Distortion

For information I and its reflection J, let the state set $f(o,T_{\mathrm{h}})$ and reflection state set $\widetilde{f}\left(\widetilde{o},\widetilde{T_{\mathrm{h}}}\right)$ be elements in a distance space $\langle\mathscr{F},d\rangle$, where $\mathscr{F}$ is the set of reflection sets and d is the distance on $\mathscr{F}$. Then, the distortion of reflection J of information I (viz. distortion$_J(I)$) is the distance between $\widetilde{f}\left(\widetilde{o},\widetilde{T_{\mathrm{h}}}\right)$ and $f(o,T_{\mathrm{h}})$ in the distance space $\langle\mathscr{F},d\rangle$, which is expressed as follows:

$$\mathrm{distortion}_J(I) = d\left(f,\widetilde{f}\right) \tag{12}$$

The distortion metric measures the degree of deviation between the reflection state and restored state. The reflection state of information I is its restored state if and only if the distortion$_J(I) = 0$.

3.3.11. Mismatch

Here, let information $I_0 = \langle o_0, T_{\mathrm{h}0}, f_0, c_0, T_{\mathrm{m}0}, g_0\rangle$ be the target of information $I = \langle o, T_{\mathrm{h}}, f, c, T_{\mathrm{m}}, g\rangle$, let o_0 and o, $T_{\mathrm{h}0}$ and T_{h}, f_0 and f, c_0 and c, $T_{\mathrm{m}0}$ and T_{m}, and g_0 and g be elements in the sets $\mathscr{P}_o, \mathscr{P}_{T_{\mathrm{h}}}, \mathscr{P}_f, \mathscr{P}_c, \mathscr{P}_{T_{\mathrm{m}}}$, and $\mathscr{P}_g$, respectively, and let I_0 and I be elements in the distance space $\left\langle\left(\mathscr{P}_o, \mathscr{P}_{T_{\mathrm{h}}}, \mathscr{P}_f, \mathscr{P}_c, \mathscr{P}_{T_{\mathrm{m}}}, \mathscr{P}_g\right), d\right\rangle$. Then, the mismatch of information I to target information I_0 (viz mismatch$_{I_0}(I)$) is the distance between I and I_0 in the distance space $\left\langle\left(\mathscr{P}_o, \mathscr{P}_{T_{\mathrm{h}}}, \mathscr{P}_f, \mathscr{P}_c, \mathscr{P}_{T_{\mathrm{m}}}, \mathscr{P}_g\right), d\right\rangle$, which can be expressed as follows:

$$\mathrm{mismatch}_{I_0}(I) = d(I, I_0) \tag{13}$$

Note that all of these metrics are defined and inferred using basic mathematical tools, such as set and measure, which allows them to accommodate various classical information theories or principles. For example, the Shannon information entropy is a special case of the volume metric to measure the capacity of a communication system that transmits messages. In fact, for each metric above, a corresponding example can be found in classical or common information science theories or principles (Table 1 [40–46]).

4. Efficacies and dynamic configurations of information systems

Dynamics are essentially the mathematical expression of the regularities and mechanics of motion and change in space and time, which are inseparable from measurements and their metrics in experimental science [6]. Therefore, mathematical expressions and measurement metrics are imperative conditions for investigating the dynamic mechanism in a specific field. In this study, the mathematical sextuple model and the comprehensive metrics of information provide a solid foundation for conducting profound and quantitative investigations for ISD.

4.1. Metric effects and efficacies of information systems

Any information system can be simplified as a basic process of information input, process, and output. The significance of information systems lies in their various efficacies—that is, the abilities of information systems to act on the input information and the effects expressed through the output information. In a large scale SoSs, different efficacies are usually intertwined owing to complex information movements. Without a comprehensive analysis, reasonable deconstruction, and quantitative expression of these efficacies, it is difficult to deeply understand the inherent rules of the operation mechanism of information systems. Consequently, it is impossible to develop theoretical ISD to guide the construction and development of large-scale SoSs. Therefore, accurately and comprehensively measuring various efficacies of information systems is of decisive significance for an in-depth study on ISD.

Efficacy cannot be expressed quantitatively without certain metrics; thus, there must be an effective metric for a specific efficacy. The aforementioned 11 metrics can be used to measure various aspects of the effect on the input and output of information

Table 1
Classical theories of information science corresponding to different metrics.

Metric	Classical/common theory	Basic inference
Volume	Shannon information entropy	The minimum volume of restorable random event information is its information entropy
Delay	Whole and partial delay principle	The overall delay of serial information transmission is equal to the sum of the delays of each link
Scope	Radar equation [40]	The extent of radar detection information is directly proportional to the square root of transmitting power, antenna aperture, and antenna gain, and inversely proportional to the square root of detection sensitivity
Granularity	Rayleigh criterion for optical imaging [41]	The granularity of optical imaging information is proportional to the wavelength of light and inversely proportional to the width of the sampling pore
Variety	Invariance principle of restorable information type	Restorable information can keep the type of information unchanged
Duration	Average duration of continuous information monitoring [42]	The average time of information collection of the continuous monitoring system is equal to the mean time between failures of the system
Sampling rate	Nyquist's sampling theorem [43]	The lowest sampling rate of the restorable periodic function information is equal to half of its frequency
Aggregation	Invariance principle of aggregation degree of restorable information	Restorable information can keep the aggregation degree of the information unchanged
Coverage	Metcalfe's law [44]	The value of a network system is equal to the product of the maximum scope and the maximum coverage of all contained information
Distortion	Kalman's filtering principle [45]	A minimum distortion estimation method for linear systems with known metric variances
Mismatch	Average search length principle [46]	The shortest search path for minimum mismatch information in a finite set of information

systems, which we refer to as the *metric effect*. It is therefore natural to apply these metrics to comprehensively and quantitatively describe and analyze the main efficacies of information systems. Specifically, there are 11 information system efficacies that can be established through 11 types of metric effects—namely, the volume, delay, scope, granularity, class, duration, sampling rate, aggregation, coverage, distortion, and mismatch efficacies. A detailed elaboration of information system efficacies is presented in Appendix A.

Fig. 2 illustrates the information efficiency distribution across the information space. In the figure, the star symbol indicates the existence of the corresponding efficiencies, represented by the sectors, of some link. The collection and action of information are positioned in the same ring at the periphery, and are distinguished by two different shades of blue: The dark blue represents the information collection link, and the light blue represents the information action link. Therefore, the functionality and performance of an SoSs can be deconstructed through the efficacy distribution, which provides a sufficient and quantitative basis for the design, analysis, testing, and integration of an SoSs.

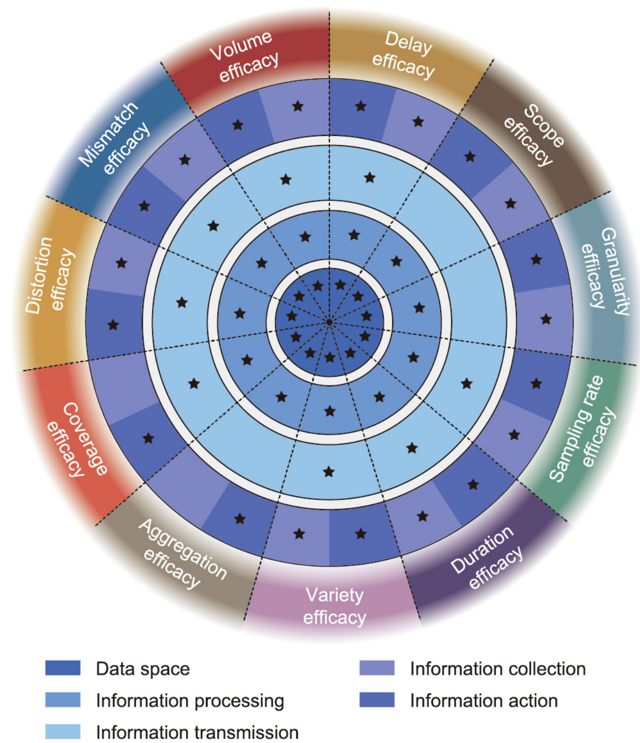

Fig. 2. Efficacy distribution for each link in information space.

4.2. Dynamic configurations of information systems

In Fig. 3, the operating mechanism and efficacy distribution of various information links—that is, information collection, transmission, processing, storage, and action are presented, along with the possible information flows between the links; these are referred to as the integral *dynamic configuration* of an SoSs. Information flow is the form and carrier of information movement in an SoSs. In general, as long as information flow maintains its continuity, we can use the local metric effects at various links to analyze the global functionalities and performance of an entire SoSs, which is the starting point to investigate ISD and the original intent of applying ISD to guide the planning, design, research and development, and integration of information systems.

In Fig. 3, each link in an SoSs can affect the functionality and performance of an entire system. In general, the effects of the same class at each link can have mutual superposition or mutual restraint. For example, the delay effect at each link can be superimposed to form the delay effect of the entire SoSs. In addition, the volume metric of the previous link forms the volume requirement for the subsequent link. If the requirement is not satisfied at the subsequent link, the volume efficiency of the entire SoSs is affected.

It should be noted that there are mutual effects among the different metrics. For example, the volume effect impacts the distortion effect of the system. With insufficient volume, the elements in the reflection set will be abandoned, which will result in an increase in the distortion metric. The degree of mismatch reflects the degree to which the information output of the system deviates from the needs of specific users. The volume, delay, scope, granularity, duration, class, sampling rate, and aggregation metrics are closely related to the needs of specific users, meaning that any of these metrics can affect the mismatch metric of the entire SoSs. For example, to control the range of information acquisition, the coverage metric must be adjusted according to the desires of the users. Therefore, the coverage metric is not related to the mismatch metric in a single direction. In addition, the distortion metric is not positively correlated with the mismatch metric. For

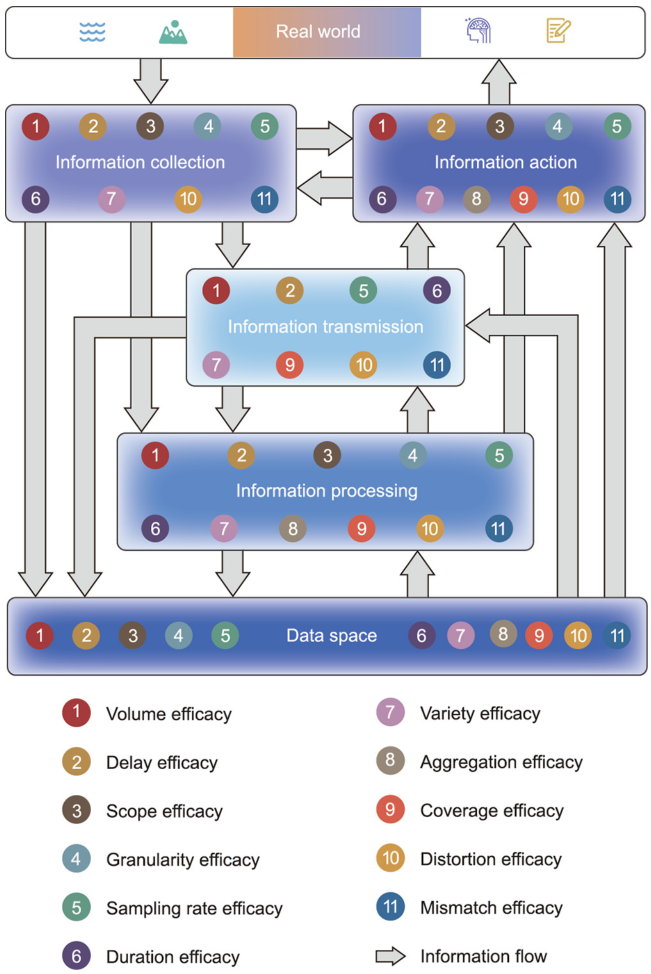

Fig. 3. Complete dynamic configuration of information systems.

example, in an encrypted information system, higher distortion results in lower mismatch for a specific user.

In engineering practices, users do not always need to apply the integral dynamic configuration of information systems. In many cases, some links of the SoSs may not determine or affect the key efficacies of the entire SoSs. In such cases, it is possible to limit the consideration of system designers to relatively minor links and form the simplified dynamic configurations for the information systems. Studying the mechanism of the efficacies with various configurations to reveal the inherent operating regularities of information systems provides a powerful means of guiding the planning and development of the large-scale SoSs in engineering practices.

4.3. The Smart Court SoSs Engineering Project of China

Since 2013, Chinese courts have employed the theories and methodologies of ISD to promote the construction of Smart Courts at a nationwide scale, gaining remarkable achievements and bringing China to a world-leading position in judicial informatization [47].

4.3.1. Overview of the Smart Court SoSs Engineering Project of China

The construction of Smart Courts in China involves more than 3000 regular courts, 10 000 dispatched courts, and 4000 collaborative departments nationwide. The number of information systems, such as infrastructure systems, intelligent applications, data management, network security, and operation and maintenance support, has exceeded 13 000. These systems operate relatively independently and simultaneously every day at a large scale and with a wide spatial distribution and varying durations. It is an extremely complicated SoSs engineering project, featuring heterogeneous systems, various functions and tasks, numerous collaborative departments, and close sharing and linkage [48].

In the Smart Court SoSs of China, there are five types of information systems that directly interact with a vast number of users and undertake information collection and action tasks—that is, the intelligent service, intelligent trial, intelligent execution, intelligent management, and judicial information disclosure systems, as listed in Table 2. The Internet, private court networks, private mobile networks, and external private networks connect users inside and outside of the courts of law and undertake the task of information transmission. The automatic cataloging of electronic files, automatic backfilling of case information, legal knowledge service, intelligent recommendation of similar cases, intelligent inspection of court audio and video, intelligent analysis of judgment deviation, and one-click filing of file materials are the information systems responsible for information processing tasks. The Judicial Big Data Management and Service Platform (JBDMSP) gathers the trial and execution data, judicial personnel data, judicial administration data, external data, judicial research data, and information operation data from the courts nationwide, and is the core data space reflecting the trial execution and operation management status of the courts of law nationwide.

4.3.2. Key Efficacies of the Smart Court SoSs of China

The overall effect of the construction and application of the Smart Court SoSs of China depends on the various efficacies produced by the integration of all the involved information systems as a whole. Although almost all systems and types of information movement will have an impact on the user experiences and business effects, the critical performance metrics of key systems will have a more important impact on the efficacies of the entire system. In practice, we have developed a system of 75 performance

Table 2
Main component systems in China's Smart Court SoSs.

System type	Independent system
Intelligent service	• China Mobile Micro-Court • People's court mediation platform • Litigation service network • 12368 litigation service hotline • Electronic service • Online preservation • Online identification • Etc.
Intelligent trial	• Trial process management • Electronic file transfer application • Intelligent trial assistance • Etc.
Intelligent execution	• Execution command of civil cases • Information management of civil case execution process • Investigation and control of civil case execution • Punishment of discrediting • Online judicial auction • "One account per case" management for civil case execution • Mobile execution for civil case • Etc.
Intelligent management	• Online office • Trial supervision • Electronic archives
Judicial openness	• China trial process information disclosure • China Court Trial Online • China Judgements Online • China execution information disclosure

Table 3
Performance indicators of information systems corresponding to the key efficacies of the Smart Court SoSs of China.

Metric effect	Information collection	Information action	Information transmission	Information processing	Data space
Volume	Total input data of application system	Total output data of application system	• Internet access bandwidth • Private court network bandwidth • Private mobile network bandwidth	• Total amount of on-cloud storage resources • Cloud storage resource utilization	• JBDMSP aggregates the total amount of judicial data resources • JBDMSP aggregates the total amount of case data
Delay	• Data submission delay of case-handling systems • Case file information upload delay	Application system operation response delay	• Video information transmission delay • File information transmission delay	• Judicial BD, judicial AI, and other computing processing delay • Total CC resources • Central processing unit (CPU) resource utilization on the cloud	Judicial BD daily full data aggregation delay
Scope	• Number of courts nationwide covered by the case-handling systems • Number of tribunals nationwide covered by the case-handling systems • Distribution and number of users covered by the intelligent service systems	Total amount of service data that the legal knowledge service system can provide		Total amount of laws, regulations, and case information processed by the Legal Knowledge Service System	Number of courts covered of judicial BD
Granularity	• Judicial statistical information integrity rate • Integrity ratio of case information items • Video information resolution	Video information display resolution		Legal knowledge decomposition and refinement granularity	• Case coverage integrity nation-wide on JBDMSP
Variety	Types and modes of data, text, file, video, audio, and other information input by the application system	Types and modes of data, text, file, video, audio，and other information output by the application system	• Internet, private court network, private mobile network, private external network transmission data, texts, files, videos • Number of types of information such as audio	Number of types of information such as data, text, files, video, and audio processed by judicial BD, CC, AI, blockchains, and other systems	• Number of data, text, files, video, and audio contained on JBDMSP • Number of judicial statistical information items on JBDMSP
Duration	Application mean time between failures (MTBF)	Application MTBF	Network MTBF	• Computing storage facility MTBF • Mean time between failures of the information-processing systems	Mean time between failures of JBDMSP
Sampling rate	Input data sampling rate of application system	Data output rate of application system per unit time	Network load utilization rate	• Throughput ratio of computing storage facility • Processing-period of information-processing systems	Data access period of JBDMSP
Aggregation		Aggregation degree of application system output data		• Number of case association types • Number of person-case association types • Number of related types of a case • Number of associated types of case payment	Data aggregation degree of JBDMSP
Coverage		User distribution of application systems Number of users of the application system	• Private court network coverage area • Private mobile network coverage area • Number of departments covered by the private external network	• Effectiveness of information encryption • Accuracy of user permission control • Reliability of security isolation between networks	Storage space and regional distribution of JBDMSP
Distortion	Input information accuracy of application systems	Output information accuracy of application systems	Transmission information distortion of communication systems	Information-processing accuracy of processing systems	• Full data confidence of JBDMSP • Shared data confidence of JBDMSP
Mismatch	Adoptability of input data format, type, content, and quantity of application system	• Adoptability of output data format, type, content, and quantity of application systems • User satisfaction rate of information systems	Adoptability of transmission information format and type of communication systems	Accuracy of data-user association computation	Accuracy of data model of JBDMSP

indicators for the Smart Court SoSs of China, as listed in Table 3. These indicators correspond to the 11 metric effects and are used to measure the 11 corresponding efficacies of the Smart Court SoSs of China.

4.3.3. Analyses of the performance of the Smart Court SoSs of China

The changing curves of the key performance indicators of the Smart Court SoSs of China in recent years are illustrated in Fig. 4.

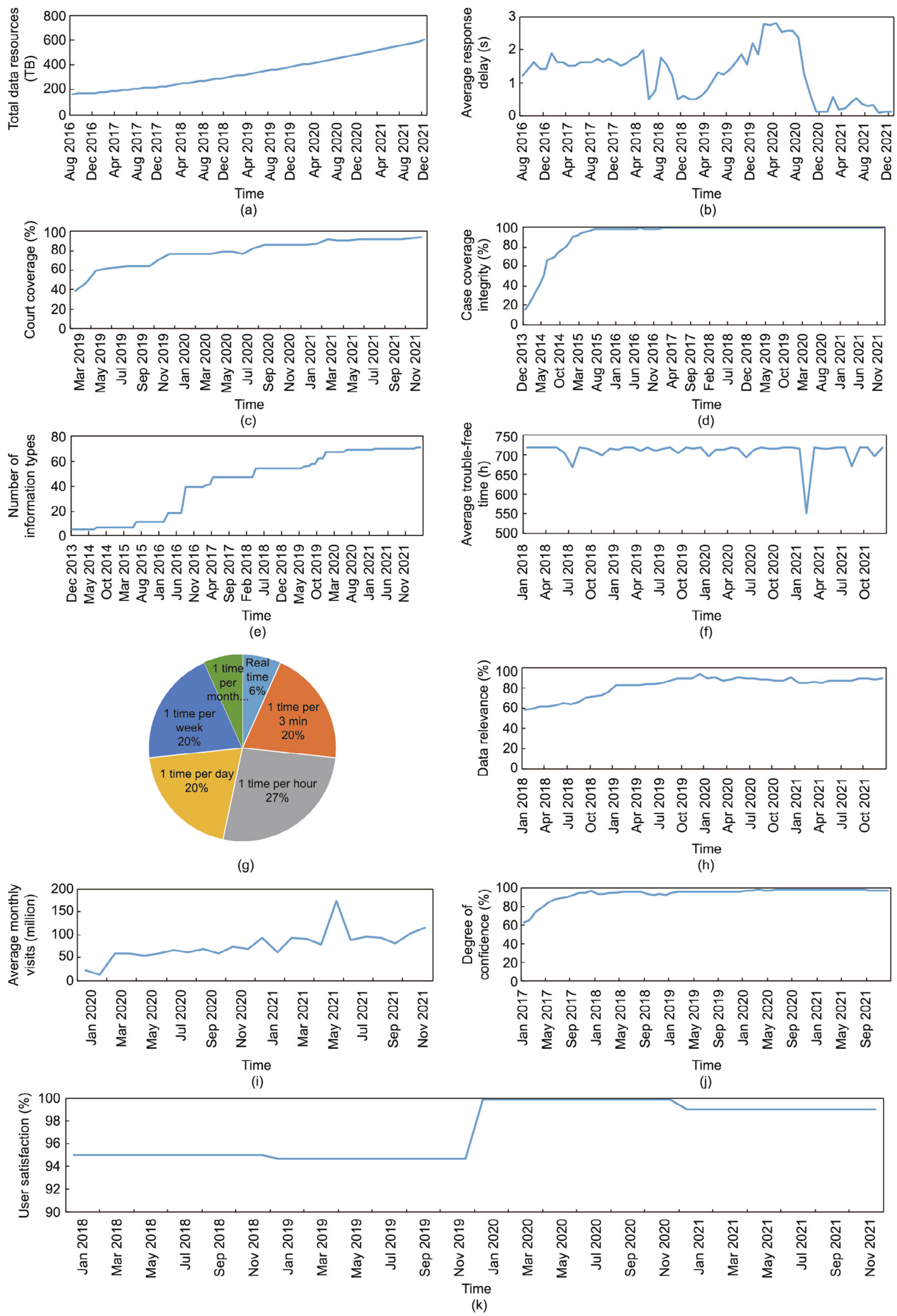

Fig. 4. Key performance indicators of information systems in China Smart Court SoSs.

As shown in Fig. 4(a), the total number of data resources on JBDMSP, reflecting the volume efficacy of the Supreme Court in gathering JBDMSP from the courts nationwide. The steady rise of volume efficacy shows that the accumulation of judicial BD resources continues to increase. As shown in Fig. 4(b), since November 2020, the average response latency indicator of the Court Office Platform has decreased to less than 0.8 s, which is related to the delay efficacy and directly affects the experience of almost all users, earning unanimous praise. As Fig. 4(c) shows, since November 2021, the Court Video Network has covered more than 93% of the Science and Technology courts (i.e., the courts that are equipped with the advanced technology and systems) across China, reflecting the increase in scope efficacy (i.e., the courtroom video information nationwide).

As shown in Fig. 4(d), since August 2015, the case coverage rate has been maintained at 100% nationwide, which is related to the granularity efficacy of judicial information management and indicates that such management has reached a fine (i.e., single-case) level nationwide. As Fig. 4(e) indicates, since December 2013 (the time when the judicial data platform was officially launched), the number of information types has steadily increased, basically realizing the convergence, management, and application of all information types. This indicator is related to the variety efficacy of JBDMSP and reflects the integrity of information management. As shown in Fig. 4(f), since March 2018, the average time between failures of the court information systems has remained stable at over 700 h, which is related to the duration efficacy of the court information systems.

As Fig. 4(g) illustrates, the sampling rate of 53% of the information monitoring is higher than once per hour and that of 73% of the information monitoring is higher than once per day on the LawEye Platform. The LawEye Platform monitors and manages the operating quality of court information systems nationwide, and its sampling rate is related to the sampling rate efficacy of the court information systems. As shown in Fig. 4(h), since January 2019, the degree of information aggregation of JBDMSP has been higher than 80%, which is related to the aggregation efficacy and indicates that the utilization of judicial BD is at a high level. As Fig. 4(i) indicates, since February 2020, the number of monthly visits to the China Mobile Micro-Court, a unified service platform for the public, has steadily increased, and has exceeded 100 million as of December 2021. The number of information system visits is related to the coverage efficacy of the information systems and demonstrates the remarkable effectiveness in facilitating the public.

As shown in Fig. 4(j), since January 2018, the confidence level of judicial BD has been higher than 97% and has remained stable at above 99%. The data confidence level is negatively related to the distortion efficacy, which lays a credible foundation for various BD analyses and services. As Fig. 4(k) shows, since January 2020, the user satisfaction of the court information systems has been higher than 98%, which is a negative indicator of the mismatch efficacy of the court information systems and demonstrates the remarkable achievements of the Smart Court SoSs Engineering Project of China.

The excellent performance of the Smart Court SoSs of China, as demonstrated by the indicators shown in Fig. 4, was achieved through the application of the aforementioned ISD methodologies. More specifically, all of the 75 indicators in Table 3 are monitored 24 h per day annually by the LawEye Platform, reflecting the operation statuses of the critical information systems including the aforementioned intelligent service, intelligent trial, intelligent execution, intelligent management, and judicial openness information systems. Any unusual changes in these indicators are analyzed and adjustments are conducted according to the dynamic configuration of the information systems (as illustrated in Fig. 3). For example, a decrease in the amount of data resources means that the volume efficacy of JBDMSP is reduced. According to the dynamic configuration of the Smart Court SoSs of China, the volume efficacy involves all the links of information collection, transmission, processing, action, and data space. Therefore, corresponding approaches such as enlarging the data space storage, increasing the bandwidth of private court networks, and data compression processing are conducted accordingly. In fact, it is the systematic application of the proposed ISD methodologies that helps us to continually improve the operation quality and efficiency of China Smart Court SoSs.

5. Conclusions

Although information technology has been progressing rapidly in the past decades, there is still a lack of ISD that can guide the design, development, application, and evaluation of large-scale SoSs, owing to the lack of a mathematical foundation to describe information and an analytical framework to evaluate information systems. This paper achieves a breakthrough in these fundamental challenges by proposing an information space framework, a solid mathematical theory to define and measure information, and a diagram model of dynamic configuration. In this way, it establishes a basic theoretical system for ISD. The mathematical foundations of the proposed approach are set theory, measure theory, relational algebra, and topology. Despite being abstract, they have a direct and clear correspondence to widely used statistical and computational methods. Moreover, the proposed ISD can be supplemented and enriched in terms of the conformity of the information metrics of different classical theorems and principles of information science and technology, the interactions among the efficacies behind the metric effects, and the fine-grained decomposition of the dynamic configuration model.

Any theory can only manifest its value and be continuously improved through practice. The completeness and practicality of the proposed ISD should also be tested and revised using extensive subsequent applications. The methodologies of the proposed ISD have already been applied and verified in the Smart Court SoSs Engineering Project of China. Empirical analyses of the key performance indicators demonstrate that the systematic application of the proposed ISD methodologies is what helps us to continually improve the operating quality and efficiency of China Smart Court SoSs. The proposed ISD is also applicable to the analysis, design, development, and evaluation of other large-scale information SoSs, such as electronic government and smart cities, which are currently attracting considerable attention.

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Compliance with ethics guidelines

Jianfeng Xu, Zhenyu Liu, Shuliang Wang, Tao Zheng, Yashi Wang, Yingfei Wang, and Yingxu Dang declare that they have no conflict of interest or financial conflicts to disclose.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2022.04.018.

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