https://doi.org/10.26599/IJCS.2022.9100026 International Journal of Crowd Science

# Research Roadmap of Service Ecosystems: A Crowd Intelligence Perspective

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**ABSTRACT**

With the mutual interaction and dependence of several intelligent services, a crowd intelligence service network has been formed, and a service ecosystem has gradually emerged. Such a development produces an ever-increasing effect on our lives and the functioning of the whole society. These facts call for research on these phenomena with a new theory or perspective, including what a smart society looks like, how it functions and evolves, and where its boundaries and challenges are. However, the research on service ecosystems is distributed in many disciplines and fields, including computer science, artificial intelligence, complex theory, social network, biological ecosystem, and network economics, and there is still no unified research framework. The researchers always have a restricted view of the research process. Under this context, this paper summarizes the research status and future developments of service ecosystems, including their conceptual origin, evolutionary logic, research topic and scale, challenges, and opportunities. We hope to provide a roadmap for the research in this field and promote sound development.

**KEYWORDS**

service ecosystem; crowd intelligence; smart service; service-oriented architecture (SOA) like operation logic; DOSPR research framework; hierarchical research scale

At present, intelligent technology is rapidly developing, and related technologies include the Internet, Internet of Things, big data, cloud computing, virtual reality, blockchain and artificial intelligence (AI), and other information and communication technologies (ICTs). Moreover, new technologies or products are constantly emerging. With the help of software definition technology[1–3], these intelligent technology communities are constantly undergoing various combinations and fusions to meet complex application scenarios. The "big data + computing power + AI algorithm = smart service" is forming a new social infrastructure. In this technical architecture, the service gradually provides a unified logic to everything in society, including applications, platforms, data, algorithms, resources, and everything else[4,5].

Furthermore, the service technology gives full play to the role of "connecting everything" and acts as a connector and lubricant across boundaries of different fields, industries, and organizations, making the synergy and fusion among different elements truly possible[6–8]. In terms of data, persons, computers, and things can be interconnected through the mass data fusion of the Internet of Things and the Internet. In terms of computing power, it gradually evolves into a new computing architecture through the collaboration of cloud computing, edge computing, and mobile computing. In terms of AI algorithms, various intelligent applications are no longer isolated but a series of interdependent and mutually beneficial networked structures. The entire social picture is redefined under the service logic and gradually becomes an ecosystem that can be jointly created and operated by all members of the society (crowd intelligence). Accordingly, it can constantly evolve iteratively, grow by itself, and show energy and vitality beyond imagination.

Intelligent services constantly produce chemical reactions with our social ecosystem, pushing individuals, organizations, industries, and the world to continuously complete particulate deconstruction and intelligent reorganization[9,10]. According to their characteristics, these services can be divided into four categories: life services, productive services, public services, and infrastructure services. Life services have changed our daily acts and living habits to some extent, such as healthcare services, online education, digital entertainment, and living services. Productive services have changed the marketing, design and production, and project implementation and operating management of enterprises, such as e-commerce, service-oriented manufacturing, and intelligent logistics. Public services focus on the modernization of social governance, such as smart cities, public health, and emergency management. Infrastructure services provide the infrastructure for various new services, such as communication, IT, and video services. With the mutual interaction and dependence of several intelligent services, a crowd intelligence service network is formed.

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The phenomenon of crowd intelligence has long existed in nature and human society, and the division of labor and cooperation has been an important expression of crowd intelligence. With the continuous development of information technology, the new generation of intelligent services has broken the original barriers of time and space in the collaboration process. As the depth and breadth of the interconnection between intelligent services continue to expand, more and more traditional applications are gradually evolving toward crowd intelligence networks, such as medical and health networks, smart government networks, and e-commerce networks. All these services constitute an organic ecosystem and show the characteristics of a crowd intelligence system.

A service ecosystem is involved in many fields, has many influencing factors, and is in rapid iterative evolution. On one hand, the emergence of a service ecosystem is a bottom-up, self-organizing, and self-growing process, and its overall state depends on the spontaneous interaction among services. On the other hand, a service ecosystem is a product of top-down planning. The law we get using big data can change the initial planning and evolution path of a service ecosystem. However, we still have a restricted view of the governance complexity of a service ecosystem[11, 12]. Currently, it is hard to clearly determine the evolution of a service ecosystem with only vague thoughts.

Scientists who study the service ecosystem are mostly computer scientists, AI scientists, and software engineers who design intelligent systems at the beginning. They are less exposed to the methodology of complex systems and pay little attention to the complexity challenges caused by the service ecosystem. Thus far, these researchers have been focusing on establishing, realizing, and optimizing various service systems and implementing them in different application fields[13–16]. The researchers of social ecosystems have long paid attention to the influence of service ecosystems and regarded them as among the typical representatives of contemporary technological governance[17–19]. However, due to the complexity and opacity of smart services, coupled with the lack of necessary expertise, their research process is often in the state of "black box research". In addition, the depth and breadth of the influence of service ecosystems are still expanding and have obvious characteristics of cross-field, cross-business, and cross-level, which may easily make the research conclusion fall into the dilemma of "understanding an elephant solely by touch".

Under this context, we need to make a painstaking investigation of the complicated phenomenon and find a new perspective to observe and understand service ecosystems so as to strike a balance between implementing the planning and conforming to the law. First, we describe the conceptual origin and interdisciplinary characteristics of service ecosystems. Afterward, we present the components and run the logic of the service ecosystem and the complexity problems we face. Then, we provide a conceptual framework for the research on service ecosystems. Finally, we discuss a series of challenges that the research on service ecosystems needs to face in technology, law, economy, institution, and other aspects.

## 1 Concept of Service Ecosystems

Service ecosystems play an important role in social functioning and are synchronously evolving with the changes in smart societies with crowd intelligence. This section will sort out the conceptual origin and interdisciplinary characteristics of service ecosystems to help us understand the origin and development of this concept.

### 1.1 Conceptual origin of service ecosystems

The conceptual origin of service ecosystems has two main lines. One main line is the business ecosystem[20] and the service-oriented logic[21, 22] from the business domain, and the other main line is the software ecosystem[23] and service-oriented computing (SOC)[4, 5] from the information domain. As shown in Fig. 1, the two main lines interweave and interact to jointly give birth to the concept of service ecosystems.

**(1) Main line of business**

Everything in nature has its place and function and is interwoven into a web. In 1935, British ecologist Arthur George Tansley first proposed the concept of ecosystem to describe the phenomena. In a natural ecosystem, the biological population and inorganic environment are a unified whole. Different species and environments constantly exchange substances and energy, and

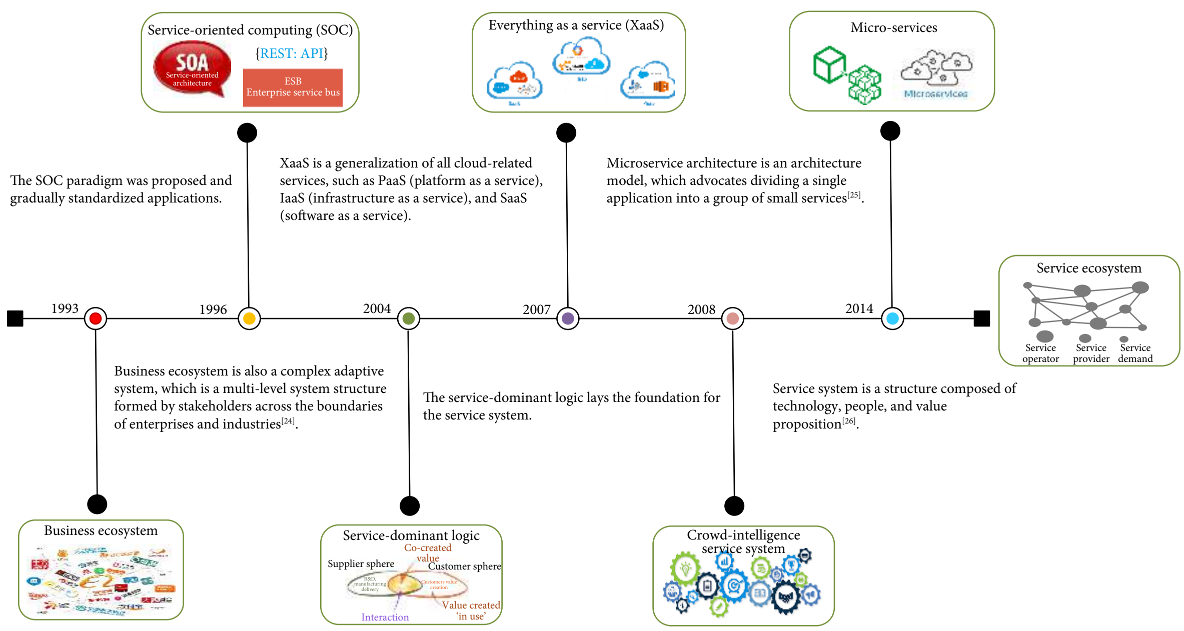


**Fig. 1 Conceptual origin of a service ecosystem.**

different species transfer energy through the food chain, thus maintaining a dynamic equilibrium[27]. The invisible hand of natural selection is constantly pushing the competitive evolution of the natural ecosystem, with existing species becoming extinct and new ones being born. Eventually, the ecosystem reaches a complex and stable equilibrium structure, and the disruption of an ecosystem may lead to the permanent loss of some species.

Hannan and Freeman[28] applied the idea of ecosystem to organizational research and believed that all organizations with common forms within a specific boundary constitute a population and that the environment influences the activity mode and structure of organizations. It makes the idea of ecosystem go beyond the field of biology and thus lays the foundation of the organizational ecosystem. Furthermore, Moore[20] applied the idea of ecosystem to the business domain and put forward the concept of the business ecosystem, in which enterprises are regarded as members of the ecosystem. In the business ecosystem, resources are transferred among the core enterprises, customers, suppliers, and market intermediaries through the value net, which can enhance competitiveness and achieve innovation through symbiotic evolution. Peltoniemi and Vuori[24] believed that the business ecosystem is a complex adaptive system, and the multi-level system structure formed by stakeholders crossing the boundaries of enterprises and industries is featured by emergence, coevolution, adaptability, and self-organization.

With the rise of the service economy, Vargo and Lusch[21,22] put forward the idea of service-dominant logic to replace the traditional commodity-dominant logic and emphasized that all economies are service economies, and enterprises and customers create value through interactions. Vargo and Lusch first defined the service ecosystem in the business domain. A service ecosystem is defined as a "relatively self-contained, self-adjusting system of resource-integrating actors connected by shared institutional arrangements and mutual value creation through service exchange"[29]. This view draws attention to multiple levels of interaction and "institutions"—social norms, collective meanings, and other coordinating heuristics—as drivers of value creation[30]. Complexity, emergence, and self-organization are critical components of service ecosystems[31].

In the Internet era, the crowd intelligence service platform has become the most important industrial organization form of the service economy. Most of the newly emerging and rapidly growing Internet enterprises are platform enterprises. The crowd intelligence service platform is a bilateral or multilateral market mechanism, the operation strategy of which is to promote the value cooperation between service consumers and service providers and to eliminate conflicts of interest so that both can obtain benefits and maximize the platform value, customer value, and service value[32,33]. Once the platform is established, it will become a bridge to create and gather value, emerging the multilateral effect and agglomeration effect. However, the utility of a service platform is related to the number of users of suppliers and demanders. In the case of the structure disequilibrium between a supplier and demander, the platform crisis may be triggered.

**(2) Main line of technology**

In the mid-1990s, with the progress of information technology and the development of the modern service industry, Gartner[34] first proposed the concept of service computing, providing technical support for achieving cross-platform, cross-system, and cross-language interactive software reuse. With the standardization of web service protocols by the World Wide Web Consortium and the support of many software and IT enterprises for web service specification, web service technology has increasingly become the practice standard for the concept of software-defined everything. Furthermore, service-oriented architecture (SOA) has become a means for capturing the principles of SOC and developing service-oriented applications[4,5]. SOA requires three fundamental operations: publish, find, and bind. Service providers publish services to a service broker. Service requesters find required services using a service broker and bind to them. By implementing the SOA triangle, one could gain flexible solutions with respect to the manageability and adaptivity of software systems[35,36].

From the perspective of software design and development, SOC is a method to carry out application system development with service as the basic element. From the perspective of discipline, SOC is a basic discipline that crosses computer and information technology, business management, and consulting services. It aims to eliminate the gap between business requirements and information technologies using service science and service technology[4]. With the development and application of SOC technology, software, data, market, technical factors, and business factors are combined with SOC to form software as a service, data as a service, and even everything as a service[4–8]. Therefore, SOC can be used as an adhesive to realize the connection among different elements through service encapsulation, service matching, service combination, and other technologies.

Based on this, Messerschmitt and Szyperski[23] proposed a software ecosystem in 2003. After over ten years of research and practice, people's understanding of the software ecosystem has increasingly unified. In 2016, Manikas[37] redefined a software ecosystem as "a complex system formed by the interaction of software products and services as well as relevant stakeholders on the basis of public technological infrastructure", emphasizing that stakeholders contribute to the software ecosystem by means of data sharing, knowledge sharing, and service delivery.

Under the dual effect of the continuous evolution of the software ecosystem and the rapid development of the modern service industry, software ecosystems have gradually evolved into service ecosystems. In 2016, Wu and Deng first used crossover service to describe the cross-border integration service model in the modern service industry, which is featured by crossover, convergence, and complexity[38,39]. Xu et al.[40,41] proposed the concept of "big service", coping with the challenges brought about by big data through the integration and collaboration of a large number of services in multiple fields. Chen et al.[42] proposed the concept of "semantic service network" and used semantic web and social network technologies to describe the organization and integration of web services, including semantic information, business context, and interaction relationship.

### 1.2 Application cases of service ecosystem

In recent years, the service ecosystem theory has also attracted the attention of the industry. As shown in Fig. 2, traditional industries and emerging industries are devoted to constructing service ecosystems to maintain their competitive advantages. The typical cases are shown below:

**(1) Manufacturing service ecosystem**

With the development of cloud computing, the Internet of Things, and other new-generation information technologies, the manufacturing industry is transforming and upgrading toward networking, servitization, and socialization[43,44]. The emerging trends focus on providing personalized products and individualized services for various prosumers. To adapt to the manufacturing trends in the future, more enterprises encapsulate

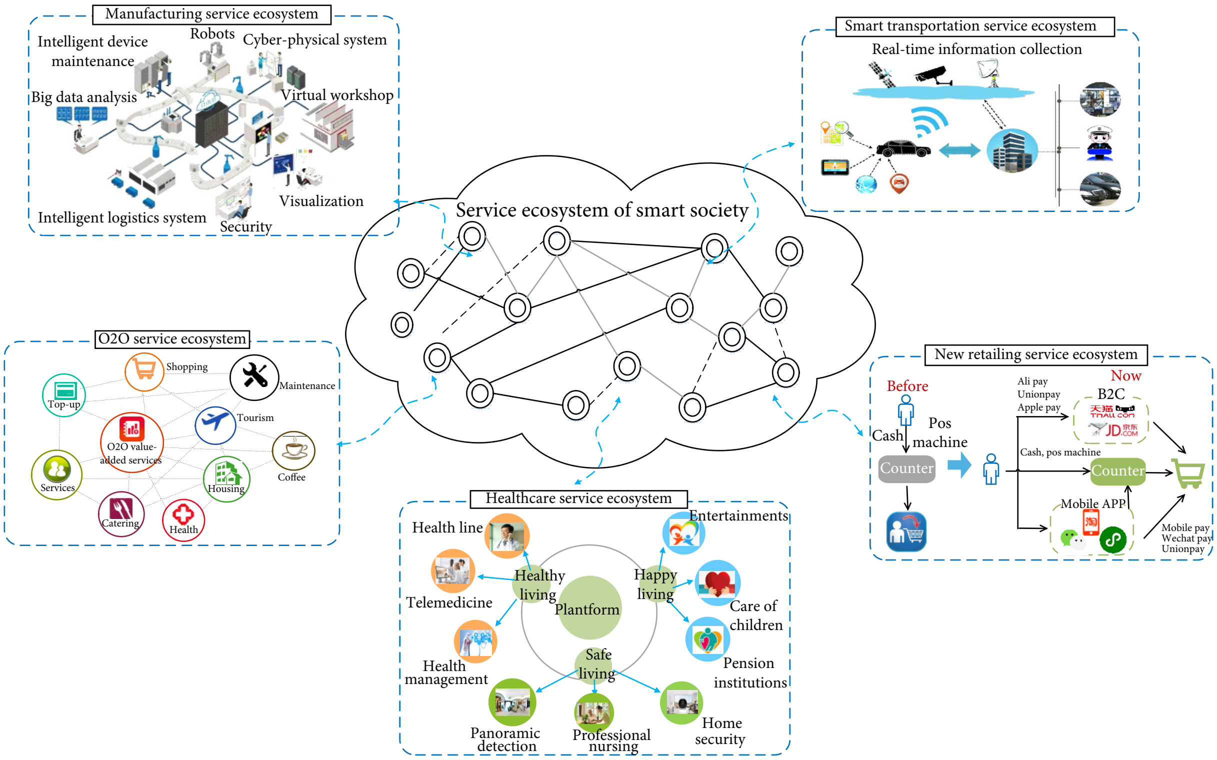


**Fig. 2 Application cases of service ecosystem.**

their respective distributed resources (e.g., production capability, design resources, and management resources) into web services to form service-oriented enterprises[45]. Based on the cloud manufacturing service platform, more manufacturing services can integrate and share diverse and distributed manufacturing resources to cover the whole product development life cycle. With the expansion of the industrial chain, the manufacturing service ecosystem emerges at the right moment.

The manufacturing service ecosystem mainly consists of social space and information space. The social space mainly includes users who make a request (e.g., process, quality, and price) for the services and enterprises that provide the service (e.g., research and development, management, manufacturing, logistics, and sales). The information space represents a complex network composed of the correlation among manufacturing services, which can provide users with various customized services on-demand. Service consumers are allowed to retrieve, purchase, and use the manufacturing service according to the demand on the platform. Meanwhile, service providers can accommodate the consumer behavior and business model through dynamic configuration and production optimization. It can bring many strengths for manufacturing enterprises to coordinate the cross-border and distributed task[44].

The research on manufacturing service ecosystems is mainly divided into the following categories: (1) infrastructure research, including the design and building of a cloud manufacturing service system, construction of a cloud manufacturing service platform, construction of a network system, and virtualization of manufacturing resources and services[46]; (2) dynamic service supply and demand matching, which is mainly carried out from two perspectives: the overall perspective of the service ecosystem and the individual perspective of manufacturing resources[47]; (3) operation management of the ecosystem, including service quality management, security management, and service composition management[48]; and (4) evolution analysis of the ecosystem, including the business model and design method of the system, correlation mining of the service network, and computational and experimental evaluation of external intervention strategies[49].

**(2) E-commerce service ecosystem**

In recent years, e-business has been developing at full speed far beyond people's imagination. Up to now, electronic commerce development in China has entered the New Retail stage[50]. As for the reconstruction and upgrading of "user, commodity, and market", the New Retail trend gradually emerges, which takes the community retail as the front end, Internet-based logistics as the middle end, and big data and financial innovation as the back end. At this stage, competition among enterprises is gradually surpassing the boundaries of individual enterprises and has evolved into competition among service ecosystems.

Most companies aim to build their service ecosystem to control the entire value chain, thereby raising the barriers to enter into the industry. Alibaba is the most typical representative of Chinese Internet companies, and its service ecosystem has become increasingly mature[51]. In Alibaba's entire service ecosystem, e-commerce and financial services are its core businesses; portals act as the role of user traffic guidance, such as UC.cn, aMap.com, and Weibo.com; local life services are its current focus, including CaiNiao logistics, healthcare, and other offline businesses; and some attempts are made in emerging areas, including gaming, video, music, and other entertainment services. The core of this service ecosystem is data and traffic sharing, and Alipay is the leader in effective service integration.

The evolution of Alibaba's service ecosystem is closely related to the value explosion caused by Internet technology. During the initial stage of the Internet, Alibaba focused on its core businesses, i.e., its online store (Taobao) and credit payment mechanism (Alipay), and successively established and acquired Alimama, Koubei.com, and Alibaba software, among others. Currently relying on core e-commerce services, Alibaba made several attempts in several areas, such as logistics services, financial services, and local life services. In its ecosystem, the overall synergy is constantly increasing: the core business provides cash flow for other businesses, while other fields provide support for the core business through differentiated service provision.

**(3) Smart healthcare service ecosystem**

With the improvement of people's living standards, to ensure that people have a healthy life, there is a need for a sound healthcare service system for the elderly, such as life services, medical services, cultural and entertainment services, and education services. Healthcare is one of the most typical examples of service ecosystem applications. Roles in healthcare can be classified into three distinct but closely related categories: service consumers (i.e., patients), service providers (i.e., hospitals, pharmacies, nursing homes, and communities), and service operators (healthcare service platforms)[52]. Each service provider has different values of reputation, capacity, and influence. The service operator needs to adopt an efficient manner to motivate service providers with high evaluation values to retrieve the information of patients, through which patients can acquire good services even at a distance.

The healthcare service ecosystem has a four-layer structure from bottom to top: terminal layer, data layer, healthcare service layer, and user layer. At the terminal layer, sensors can be distributed on the body or even in the home or clinic/hospital to detect changing health conditions, potential diseases, or health problems. The data layer includes various types of data acquired from the terminal layer and data cleaning and processing analysis. The healthcare service layer is the core of the healthcare service ecosystem, in which the service provider matches and trades with users on a third-party platform to provide users with services in living, cultural and entertainment, medical treatment, and other aspects. The user layer mainly includes people who enjoy healthcare services and their social networks.

A service ecosystem is the basic paradigm of the evolution of the healthcare service industry, where smart service navigation systems can be viewed as novel techniques to implement personalized intelligent computing. Today, most patients may be bothered about how to choose a proper doctor due to the lack of relevant experience or professional knowledge. Reference [53] proposed a doctor recommendation algorithm that can help patients select appropriate doctors according to doctor performances and patient preferences. Reference [54] further proposed an integrated doctor recommender framework that extends patients' demand characteristics to the preference and illness symptoms. The proposed framework can determine similarities between patient consultations and doctor profiles, and an analytic hierarchy process is integrated for providing doctor recommendations and promoting user experience using an accurate and efficient recommendation list.

**(4) Online-to-offline local life service ecosystem**

With the development of the mobile Internet and sharing economy, the traditional e-commerce model could no longer meet the growing living needs of consumers. The online-to-offline (O2O) life service ecosystem is a new kind of commercial element integration mode, which can realize the integration and interaction among an online platform, offline stores, online payment, logistics, consumers, and other factors[55]. Consumers can use Meituan, Tuniu, Uber, and other apps to select services (e.g., catering service, beauty service, and taxi service), make online payments, and enjoy and experience services in offline stores. With the continuous expansion of consumers, platforms, and service scales, the O2O life service ecosystem has been gradually formed.

The O2O life service ecosystem mainly has five roles: offline layer, intermediate layer, third-party layer, online layer, and user layer. The offline layer mainly refers to offline physical stores, related personnel, and goods involved in offline stores. The intermediate layer is the bridge among the online layer, offline layer, and third-party layer and supports their interaction through data processing, computing and operation, and maintenance capabilities. The third-party layer mainly includes various infrastructure services, such as payment, logistics, and location-based services. The online layer mainly provides users with life, travel, entertainment, and other services through various apps. The user layer mainly includes users and their social relations, where users enjoy online and offline services and put forward their demands.

The O2O life service ecosystem hopes to cover all aspects of people's daily lives, including food, clothing, housing, and entertainment. After these daily life service resources are redesigned and reorganized to form a closed loop of user consumption, the O2O life service ecosystem can maintain a long-term competitive advantage[56]. Service providers can publish various service information on the Internet at any time, whereas service consumers can locate and enjoy services through direct and real-time inquiries. Personalized service recommendations can make full use of originally idle service resources, effectively improving the operating efficiency of the traditional service industry[57]. In addition, because O2O services involve much personal data, special attention shall be paid to the privacy of users.

## 1.3 Interdisciplinary research on service ecosystems

The research on service ecosystems explores the knowledge maze of different disciplines to find the law of interaction between the service technology and the social ecosystem. To clearly describe the current situation and service ecosystem trend, Fig. 3 integrates knowledge and insights of different disciplines to form a blueprint for its analysis and understanding. The service ecosystem is at the intersection of technology, business, and service. The technology field involves various technologies for constructing smart services, including big data, the Internet of Things, AI, and blockchains. The business area covers various application areas of smart services, including intelligent transportation, intelligent manufacturing, and smart healthcare. The service field supports the technology of SOC, including service composition, service

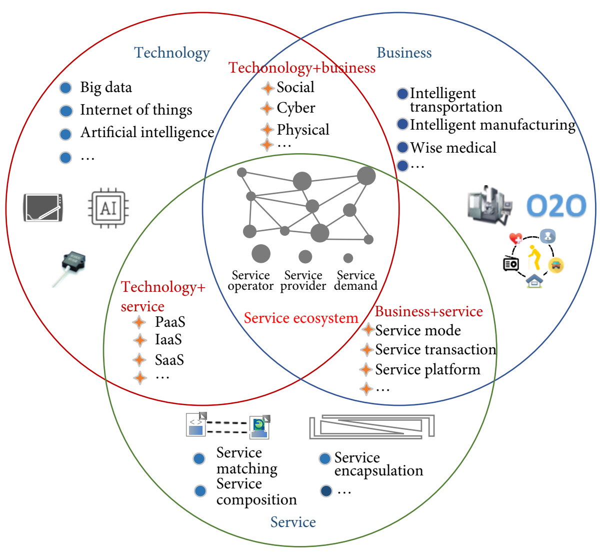


**Fig. 3 Service ecosystem relation graph.**

matching, and service encapsulation. The following section highlights the intersections of the different fields, which are also the key to forming a service ecosystem.

**(1) Technology + service**

The combination of service and technology forms technology as a service, among which platform as a service (PaaS)[58], infrastructure as a service (IaaS)[59], and software as a service (SaaS)[60] are more representative. In the combination process of services and technologies, various technology or function modules can be encapsulated into different types of services. Each service can be viewed as a node. The cooperation, call, competition, and other interactive relationships among services represent the correlation among nodes. Different services are interrelated and interact with each other, constituting an ecological structure.

Taking SaaS as an example, some web APIs' sharing forms service-sharing communities, and Xu solved the service matching problem by constructing a service correlation graph[61,62].

With the diversification of service contents, all kinds of offline resources are constantly subjected to service encapsulation and made available to the public. For example, the services of intelligent manufacturing cover the full life cycle of manufacturing, including design as a service, fabrication as a service, management as a service, experiment as a service (EaaS), and integration as a service. Under the guidance of business modularization and service orientation thinking, various business units are transformed into business components that provide various services, and "service-oriented enterprise" or "service-oriented organizations"[42,43] are realized through business collaborations of different service units within and among organizations in service delivery and service consumption.

As the cross-border service integration trend is increasingly highlighted, the depth (from pure business fusion to pattern fusion, quality fusion, and value fusion) and breadth (from the collaboration among enterprises to the collaboration crossing the value chain and ecosystem) of collaboration among services have been greatly developed. In this context, a simple service combination can no longer meet the demand, and the dynamic adaptation and depth integration among services have become the focus of academia and industrial circles. Because data are the representation of all underlying resources, data fusion is the basis for service convergence. Knowledge fusion is further realized on the basis of data integration, including data understanding and mining, knowledge evolution and reasoning, description and generation of intelligent elements, and self-maintenance and reinforcement learning.

**(2) Business + service**

With the diversification and complexity of business requirements, service technology gives full play to the role of "connecting everything", which can act as a connector and lubricant across fields, industries, and organizations, making the collaboration and fusion among different elements truly possible[6–8]. The whole social picture is redefined under the service logic, and various intelligent applications are no longer isolated individuals but a series of interdependent and mutually beneficial ecosystems. At the individual life level, the appearance of an intelligent lifestyle, such as an intelligent home and intelligent travel, has changed our daily acts and living habits to some extent. At the organizational structure level, intelligent services begin to change organization forms in various fields, including education, community, security, health, business, social intercourses, and other industries are being redefined.

New business logic needs to be supported by new service patterns, which can describe how the participants of service ecosystems support the collaborative co-creation of business values through the exchange of information and resources. The traditional research on service patterns focuses on process structures and ignores data and resource exchange among collaborators. Yin et al.[38] conducted abstraction on the business process from the perspective of the integration of workflow, data, and resources and formally described the service pattern of the modern service industry. He also proposed a service pattern description language to support the analysis, design, and reconstruction of the business process of data and resource exchange[38]. Furthermore, Ref. [63] attempted to establish the correlation matrix between the demand pattern and service pattern under specific circumstances by increasing the matching granularity and improving the matching efficiency.

As the carrier of the service pattern, the service platform realizes the value transfer between a supplier and demander through a service transaction. The service transaction mainly includes service launch, service pricing, service matching, and value distribution. To meet the large-scale complex requirements, the service launch needs to dynamically discover several existing enterprise services according to certain rules and assemble them into a value-added and coarse-grained service or function module. The cost of a service launch determines the price of a service, whereas the efficiency of a service launch determines whether the service is competitive or not. At present, service matching is the focus in academia. The proposed methods include a method based on template/ontology and keywords, a process-driven method, a method based on AI and planning, a graph theory based method, and a mediator-based method[64–66]. After service matching, close attention shall also be paid to how to make a reasonable value distribution among service providers and between them and the service platform.

**(3) Technology + business**

The development of a society cannot be separated from the support of information technology. With the development of information technology, society is constantly undergoing reform, innovation, and upgrading. The combination of technology and society makes human beings, technology, and society constitute a unified whole, encompassing the cyber-physical-social system[11,12]. In this theory framework, "cyber" represents the information system, such as various state information collected through various physical devices, "physical" represents the traditional physical system, and "social" represents the human social system, namely, various economic and social activities of the human society. All elements interact with one another for value co-creation and constitute an organic combination through mutual coordination. Information and value communicate and interact with each other through their connection and maintain a relatively stable dynamic equilibrium state within a certain period.

**Physical layer**: The physical layer covers widely distributed devices and infrastructures, and these facilities can be interconnected by the IoT. They are involved in various fields, including home, electricity, traffic, hospital, industry, and agriculture. Several sensors and actuators arranged in the physical layer could realize the intelligent monitoring of the surroundings.

**Cyber layer**: A correspondence relationship exists between each computation module in the cyber layer and each physical object in the physical layer. The cyber layer can be regarded as a bridge that connects the physical layer and social layer. The central controllers and widespread distributed controllers in the cyber layer usually have the functions of data archive and data processing. With the help of these controllers, the cyber layer supports data collection, information collation and processing, decision making, and assignment. Meanwhile, the cyber layer provides some related services or tasks to users in the social layer and distributes the authorities with the collected information about the physical layer.

**Social layer**: For a service ecosystem, users in the social roles can be treated as an experiencer, a maintainer, or layer could have different social roles, such as doctors, customers, servers, workers, and nurses. Based on these social roles, users can be treated as experiencers, maintainers, or even decision makers. They can be viewed as service consumers that submit their experience information to the cyber layer to assist the maintenance and operation of the system, and they can also be viewed as service providers and authorized to participate in decision making to further promote system development.

## 2 Operation Logic of the Service Ecosystem

To examine a service ecosystem, we must first know its components and run logic and understand the complex challenges it faces. Figure 4 shows the operation login of the service ecosystem. This section presents the basis for understanding the next section (research themes).

### 2.1 Basic elements of a service ecosystem

In the natural environment, all things have their own niches and functions, and they are interwoven into a single network. Driven by the continuous input of energy and materials from external environments, the energy loop between species is formed through the food chain[67]. Finally, the natural ecosystem achieves a complex and dynamic equilibrium, in which existing species may compete and die while new species may appear and merge. Similar to a natural ecosystem, a service ecosystem also has three elements: species, environment, and cycle. Table 1 lists the similarities and differences of a natural ecosystem, business ecosystem, software ecosystem, and service ecosystem according to the three elements.

### 2.2 Unified logic of a service ecosystem

The research framework of a service ecosystem borrows ideas from SOA[35,36]. Social networks, service networks, and value networks extend from the concepts of service demanders, service providers, and service agents in SOA, respectively. The details are shown as follows: (1) Social network (external environments): Social environments are an important factor influencing the implementation of the service ecosystem, including population, law, culture, customs, and industries, especially the coordination of interests among the government, enterprises, and citizens. (2) Service network (technical species): Services are no longer limited to software services. Various types of "service species" co-exist in the cyber space, including human intelligence services, machine intelligence services, and human-machine coordination services. (3) Value network (circulation mechanism): The value network realizes the value circulation of services through service commercialization and then drives the evolution of various participants (service demanders, providers, and operators) in the service ecosystem.

The running of a service ecosystem consists of three steps:

**(1) Everything as a service (EaaS):** All kinds of online or offline resources (applications, platforms, data, algorithms, and facilities) from a social network are virtualized and published in the form of services[4,5]. Through their interconnection and cooperation, these services can realize the customization of a single resource and the on-demand aggregation of multiple resources[6–8]. Hence, it is possible to create various "virtual organizations" (e.g., teams, enterprises, and governments) and to redefine various public affairs (e.g., environment, traffic, education, and health)[75,76].

**(2) Service as a commodity:** The service matching between provision and demands can be finished in a "service marketplace", just like a commodity transaction, to achieve value creation, realization, and distribution. Enterprises will act as service providers and give birth to smart services to satisfy ubiquitous demands. The public having diversified appeals may reach a consensus in a way and bring about the emergence of demands. The governments have the responsibility to guard social equality and public interests by virtue of policies, laws, and regulations.

**(3) Value as a coordinator:** Such a value circulation can promote the adjustment and evolution of a social network, including the changes in individual recognition and decision making behaviors, cross-domain intersection and integration of

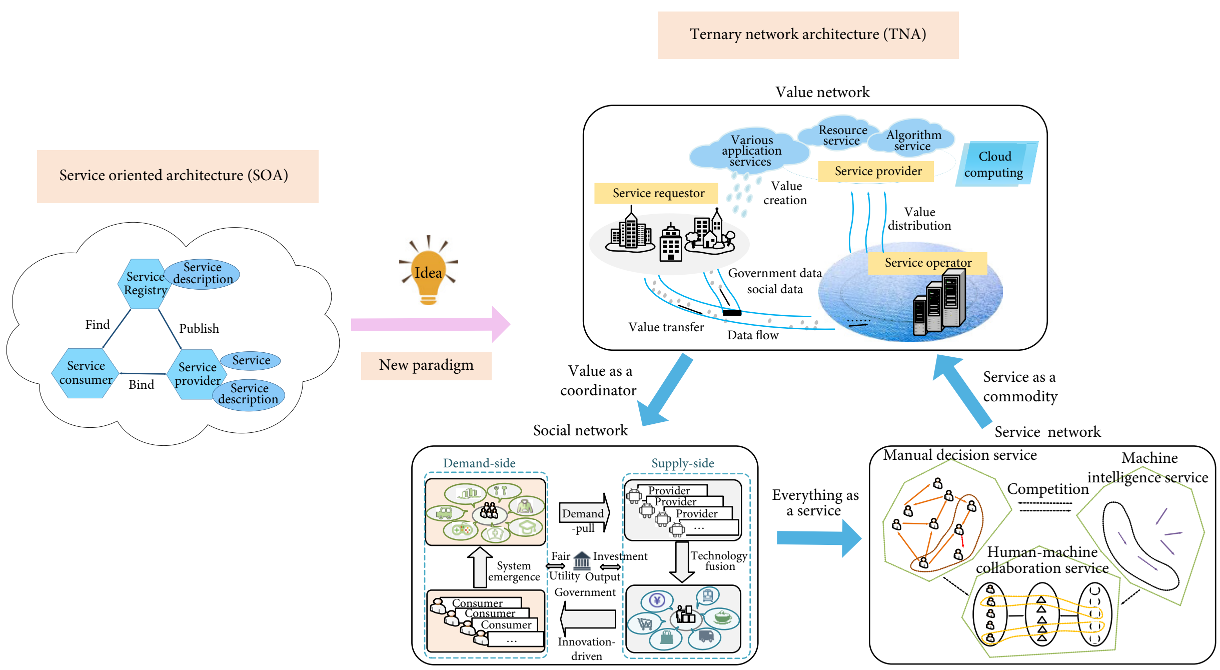


**Fig. 4 Operation diagram of a service ecosystem.**

Table 1 Successful applications and potential threats in a smart society.

| Application scenario | Composition (static) | Cycle (dynamic) |
| --- | --- | --- |
| Natural ecosystem | **External environment:** Climate, sunlight, air, mountains, rivers, and other non-biological factors<br><br>**Ecological species:** Various creatures, including plants and animals, that have a certain hierarchical structure: individuals (a single creature), populations (the same creature), communities (the aggregation of multiple populations), and ecosystem (a combination of biocenoses and abiotic environments).<br><br>**Typical examples:** Mountains, swamps, forests, and grasslands | **Energy cycle:** There is a constant exchange of substance and energy between species and the environment, and energy transfer between different species is carried out through the food chain to maintain a dynamic equilibrium. There is positive and negative feedback in the ecosystem, and the negative feedback helps maintain the stability of the system[68].<br><br>**Species evolution:** In the natural ecological evolution process, the superior species are selected, and the inferior species are eliminated (i.e., the fittest survives). It is a self-organizing and self-growing process from the low level to the high level and from simple to complex. |
| Business ecosystem | **External environments:** Social and market factors, such as economy, policy, law, culture, and industry; stakeholders, including customers, manufacturers, intermediaries, suppliers, investors, governments, and standard-setting agencies<br><br>**Ecological species:** With core enterprises as the main ones, the stakeholders depend on one another to constitute a dynamic system. The correlation among enterprises includes horizontal coordination among similar enterprises and vertical coordination among upstream and downstream enterprises.<br><br>**Typical example:** Business activities within enterprises and economic association among enterprises | **Value cycle:** Core enterprises, consumers, suppliers, and market intermediaries constitute a value network; the resource-dependent value network is transferred among members; competitiveness is enhanced; and innovation is realized through a symbiotic evolution.<br><br>**Species evolution:** It can be divided into four stages: (1) development—enterprises need to create new values and form key products and services; (2) expansion—enterprises expand the boundary of the system through competition and cooperation; (3) domination—enterprises need to dominate the coordinated development and compete with other organizations; and (4) the ecological environment has undergone great changes, and enterprises are facing the market competition of the survival of the fittest[20]. |
| Software ecosystem (technology level) | **External environment:** The main stakeholders include application developers, operators, final users, infrastructure providers, and advertisers. The constraint conditions include relevant policies, laws, technical standards, and relevant cultures.<br><br>**Ecological species:** There are complex components and interface call relationships among various software, services, and systems, which form a software artifact-dependent network. For example, many enterprise systems depend on the development framework or software libraries of open-source projects, and downstream projects depend on the infrastructure or functional components provided by upstream projects. The application software can be called each other, such as skipping from Taobao to Alipay and skipping from Jinri Toutiao's ads to Taobao.<br><br>**Typical examples:** GitHub open-source community, software ecosystem within enterprises, and software ecosystem of the App store | **Value cycle:** The competitive and cooperative relationship among stakeholders is established with software artifacts and software services as the link, forming a collaborative network of stakeholders. In the interaction process, explicit or implicit interest exchange exists among stakeholders, forming a value network among stakeholders [69].<br><br>**Species evolution:** Due to dependence, the updates or defects in upstream software artifacts will transfer their effects to downstream software artifacts. With the increasing dependence on software artifacts and the increasing size and complexity of software ecosystems, the symbiotic evolution relationship among software artifacts will be strengthened[70, 71]. |
| Service ecosystem (business level) | **External environment:** The driving factors of the external environment include technological innovation and the emergence of demand. Stakeholders include service consumers, service providers, and service operators.<br><br>**Ecological species:** The elements in the society are no longer pure human intelligence species (artificial customer service and delivery service), but they include more machine intelligence species (recommendation service, logistics dispatch service, intelligent customer service, and advertising service) and elements integrating the two (decision making service). Service nodes depend on one another and evolve independently to some extent. When service nodes collaborate with one another and a new service pattern is provided, service aggregation will occur. Different services converge to constitute a service community. When the number of service communities increases, a service ecosystem is formed.<br><br>**Typical examples:** E-commerce service ecosystem (Amazon and Taobao), O2O life service ecosystem (Uber, Meituan, and Hema Xiansheng), and smart city service ecosystems (Alphabet's "Sidewalk Toronto"[72] and Alibaba's "City Brain"[73]) | **Value cycle:** Driven by the external environment and with requirement satisfaction as the goal, the information flow, capital flow, and logistics flow act as a link of the transmission and feedback. The service ecosystem realizes value creation and circulation among service demanders, service providers, and service operators and establishes the connection among them through value driving, forming a value cycle with equilibrium in the supply and demand relationship[74].<br><br>**Species evolution:** Different services collaborate and compete in the service ecosystem, and the fittest survives. On one hand, all kinds of service nodes keep iterative optimization to improve their value realization ability, hoping to gain advantages in a series of process operations, such as on-demand selection, combination, and scheduling of services. On the other hand, machine intelligence services continuously explore new value creation opportunities through intersection and cooperation with traditional fields. |

organizations, and refinement of the social governance mode. In the end, value circulation will further promote the evolution of a service network into a hierarchical structure similar to a natural ecosystem, including individuals, populations, and communities.

### 2.3 Complex challenges of a service ecosystem

To adapt to the change in the external environment and the adjustment of its own structural behavior, a service ecosystem has various interactions within the system and between the system and external environment, which is always in the continuous evolution of the system function and structure. It makes the service ecosystem present self-organization, self-adaptation, self-aggregation, self-strengthening, self-coordination, and other characteristics. To grasp the running law of the service ecosystem and coordinate the interests among residents, enterprises, and governments, the following complexity challenges need to be addressed:

**(1) Correlation**

The development of an ecosystem is not isolated, fragmented, or disconnected, but it is a unified whole that is interconnected, interacted, and mutually restricted. Because of the network characteristics, the assumption of individual independence in the system is no longer valid, which directly leads to various complex phenomena, such as nonlinearity, chaos, and emergence. Because the common characteristic of such a system is a long-range correlation, it tends to lead to 1+1>2 or 1+1<2, i.e., nonlinear phenomena. As the dimensions of such an interaction increase in the system, it will produce a new phenomenon, that is, chaos. Chaos means that the dynamic properties of a system no longer belong to the closed orbit but to the open or unpredictable trajectory. A classic example of amplification through chaos is the "butterfly effect"[77].

As a result, the trends of the service ecosystem become uncertain and unpredictable. In the service ecosystem, the local optimization of a single smart service does not necessarily lead to the global optimization of the overall system. For example, smart transportation services may alleviate traffic congestion in a certain local area, but due to the big data traps caused by limited resources and user games, they may have a limited effect on alleviating global traffic conditions[78,79].

**(2) Cycle feedback**

In all complex systems, there are two mechanisms—positive feedback and negative feedback. The negative feedback leads to a fixed-point equilibrium, whereas the positive feedback leads to instability, such as avalanches and stock market crashes. The feedback has the concept of a loop, in which the information is transmitted from one unit to another unit through interaction, and in turn, the information can be transmitted back to another unit. According to Stephen Jones' classification of the complex system emergence mechanisms, the emergence with only a one-way feedback mechanism is called the first-order emergence, and the emergence with the feedforward and feedback mechanisms between the system performance and individual behavior is called the second-order emergence[80].

Under the self-organization of a service ecosystem, new individual behaviors will be generated due to the feedback from the system. These new individual behaviors will be aggregated and affect the system, thus forming a bidirectional feedback closed loop of the service ecosystem. In terms of service consumers, users might suffer from information cocoons[81,82] and algorithm discrimination[83,84], among others. As far as service providers are concerned, the algorithm drift might lead to inaccurate prediction in the case of emergencies, and the platform economy might contribute to the rise of monopolies in industries, eventually stifling innovation and consumer choice[18].

**(3) Critical phase transition**

A phase transition is a process in which the whole system goes from one phase to another through external variables[80]. The state at which the phase transition occurs is critical and the most special moment. Taking the phase transition from water to ice as an example, the external variable that we can control is temperature. At a certain temperature, disorder (water) alternates with order (ice), which is called critical. The emergence and phase transition points are also inextricably linked. For the explosion phenomenon in the service ecosystem, the essence of the reason for their formation lies in the dynamics in the micro-evolution rather than the scene. In other words, different initial structures and connection generation mechanisms in the ecosystem will affect the changes in each local area and the method of connection growth.

In the service ecosystem, the initial advantages tend to form a natural tendency to monopolize, and the possible adverse effects and potential pitfalls can be fully magnified. With the emergence of a devastating technology or innovative business model, the service ecosystem may experience a state transition from one phase to another. The failures to predict the financial crisis and stock market volatility are classic cases where the reason lies in the continuous occurrence of various black swan events. An evolutionary game exists between the macroscopic regulation of a service ecosystem and the autonomous behavior of individuals. It is difficult to obtain effective governance measures once and forever, such as the changes in urban planning[85] and conflicts in social ethics[86].

## 3 Research Theme

Despite fundamental differences between the natural ecosystem and service ecosystem, the study on the service ecosystem can benefit from a similar analogy. A service ecosystem also has driving forces that promote evolution, undergoes an operation that integrates the social space into the cyber space by means of a value network, reaches a certain state under the combined effect of various factors, and embodies adaptive responses by continuously adjusting the relationship between smart services and social ecosystem. Inspired by the Driver-Pressure-State-Impact-Response Framework in natural ecosystems[87], we reconstructed the model to emphasize the research themes of service ecosystems, summarizing them into five themes: driving forces, operation, status, traceability, and response (DOSTR). The goal of these distinctions is not division but integration. A complete understanding of service ecosystems will require integrating the five links. We discuss the five topics in the following section and present Fig. 5 as a summary.

### 3.1 Driving force

The natural ecosystem maintains its own energy cycle by absorbing negative entropy[88]. For a service ecosystem, service innovation is negative entropy, reshaping the value cycle rules of the service ecosystem and making the service ecosystem meet user demands efficiently[89–91]. Figure 6 shows the driving force of service ecosystem.

**(1) Technology driving force**

After completing the digital transformation of an urban infrastructure system, everything can be interconnected, real-time online, sensible, and controllable. The influence of the service ecosystem has already been evidenced in all levels and domains of

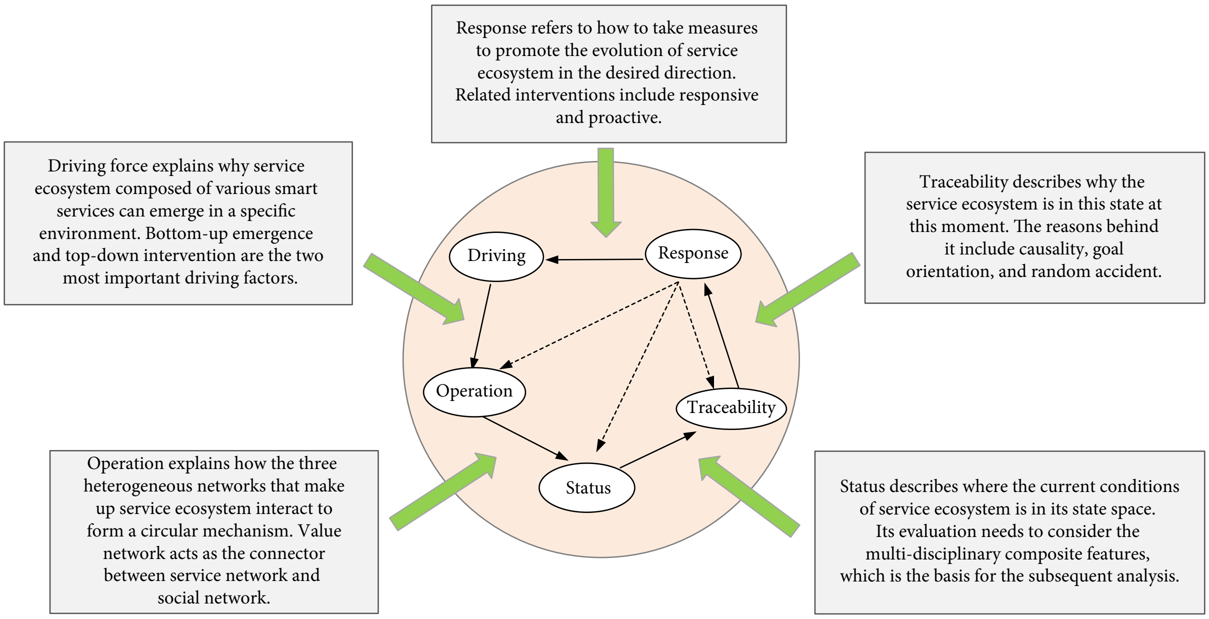


**Fig. 5 Research themes of service ecosystem.**

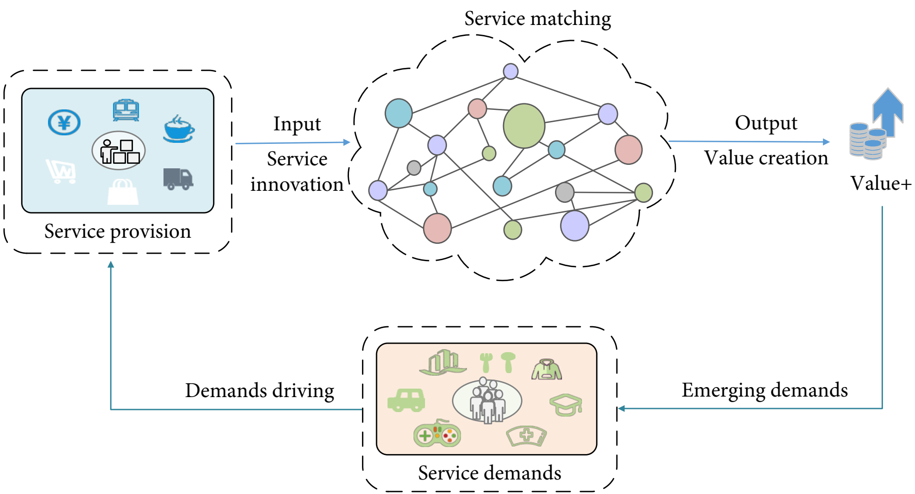


**Fig. 6 Driving force of the service ecosystem.**

our society, such as urban infrastructure, social management, people's livelihood service, ecological protection, and economic development. Service innovation is a prerequisite for driving the evolution of the service ecosystem. However, a new service species may be isolated ecological niche nodes in the initial stage, and it is difficult to predict what kind of service mode change will be triggered and what impact will be made on the existing service ecosystem, such as the current 5G, blockchain, and autonomous driving. The evolution of the service ecosystem caused by the technology driving force is mainly divided into three stages.

In the first stage (1998–2012), smart services were mainly applied to the cyber space. To solve the information overload problem in the Internet era, recommendation services are constructed to bridge information resources and end users[92–94]. Amazon and Taobao are killer applications in the e-commerce field. Google, Netflix, Toutiao, and the equivalences are representatives in the information flow field.

In the second stage (2011–present), smart services began to spread in the physical space. Traffic congestion, public service shortage (e.g., finance, education, and medical treatment), and environmental pollution all reflect the contradiction between the limited service capacity and rapidly increasing demands. The goal of smart services is to either provide users with new alternatives or connect them with new service resources, platforms, and values. Uber, Meituan, and Airbnb are typical representatives of O2O life services; Alipay and PayPal are representatives of financial services; and Alphabet's "Sidewalk Toronto" project[72] and Alibaba's "City Brain"[73] are representatives of smart cities.

In the third stage (2015–present), the continuous coupling of smart services and social space will eventually form a service ecosystem. This stage has the following characteristics: (a) Enhanced integration: All human, things, and environmental factors are all incorporated into a service ecosystem and are fully perceived, understood, and calculated. (b) Comprehensive intelligence: Smart services would be widely distributed in society and seamlessly integrated with human intelligence. (c) Autonomous planning: In the presence of unknown risks, smart services can actively provide public services according to the situation, such as the autonomous driving systems of Apple and Google. If the above three goals can be achieved, some scholars declare that it is possible to accurately predict the market and ultimately achieve a planned economy[19].

**(2) Demand-pull**

The nature of a service ecosystem can be expressed as "a complex functional network platform that achieves the improvement of production efficiency and residents' happiness under the condition of limited resources such as space, environment, and energy through the centralized supply of infrastructure and public services". Almost all the problems we solve can be attributed to a common pain point: resolving the contradiction between limited infrastructure, serviceability, and rapidly growing demand. Taking a smart city as an example, traffic jams, emergency management, and environmental pollution reflect the lack of dynamic serviceability and efficiency of infrastructure, and the problems in public utilities, such as housing, education, and healthcare, reflect the insufficient supply of public services and low service level.

Therefore, the demand-pull becomes the necessary condition to promote service innovation. However, due to the randomness and freedom of individual demands, our perception and the control ability of such systems were very poor in the past, many of which are closely attributed to random phenomena. In addition, individual demands will be transmitted and diffused through the network to form the demand trend with common behavioral characteristics, which may be in a gradual and continuous manner or discontinuous and abrupt manner. Therefore, the collection and analysis of demands are faced with the following challenges: (a) The generated demands may be spontaneous, disordered, indirect, and obscure. (b) The generation time of demands also becomes unpredictable and uncontrollable, and the spatial distribution of demands will become very non-uniform with the movement of the population. (c) The available demand is only a sample of the complete dataset, and such a sample may deviate from the complete dataset.

Based on the above reasons, the modeling of a demand space is no longer just a process of perception but includes a computational step in which effective knowledge can be obtained from complex, obscure, missing, and non-uniformly distributed data[75]. With the development of various sensing technologies and the maturity of big data technology, several demand behaviors can be perceived and observed, including basic information (e.g., demand scale, category, quality range, price range, and delivery location), dynamic information (e.g., frequency of demand, change of price and quality, and service feedback and evaluation), and social information (e.g., association and similarity among demand subjects).

The digitalization of social operations provides a good insight into the whole society, with one aspect of dynamic demand information represented by a stream of people, traffic stream, environmental pollution, and negative events, and another aspect of the operation status of roads and infrastructure provided. On this basis, the data platform and algorithm can realize dynamic prediction and matching between the supply and demand. For systems with different intervention degrees, some can realize fully automatic real-time intelligent intervention, some can perform long-term policy regulation, and some conduct artificial enforcement disposal. The service ecosystem realizes that timely responses to abnormal events and the exploration of time-spatial rules of citizens' behavior can improve public infrastructure services.

**(3) Feedback loop**

The continuous evolution of service ecosystems depends on the interaction between service innovation and social demand. Accordingly, a feedback loop is formed between the two: (a) Individual demands converge to generate the demand trend at the system level through the self-growing and self-organizing process and then influence service innovations on the supply side. (b) To meet the complex demand scene, the single-point technology on the supply side will constantly perform various combinations and redefine original business processes in an interactive, sharing, elastic, and fine mode to form the fusion of service innovation communities. (c) Although service innovation solves old demands, it will give birth to new demands through the influence and change of individual behaviors, forming a closed loop of the system.

In most service ecosystems, a demand uncertainty analysis is more important than a supply uncertainty analysis. However, with the growth of service socialization, the importance of supply uncertainty research becomes increasingly obvious. How to realize the feedback loop between demand emergence and service innovation in a dynamic and uncertain environment is one of the challenges[95–97]. As shown in Table 1, the correlation relationship between demand emergence and service innovation in the service ecosystem is mainly divided into the following categories: starting from the matching type, that is, including uncertainty of the initial state and dynamic nature of the running process; starting from the types of matching objects, including innovation of a single service and innovation of multiple services; and starting from the subject of the realizing match, including innovations at the individual level and innovations at the system level. The details are shown in Table 2.

When the initial state of demands is determined and has no change in a certain period, the correlation problem between demands and services can be simplified as the problem of service selection. When two different objects, i.e., service or demand, are considered, the existing supply-demand correlation can be roughly divided into the selection of services and static scheduling of tasks, and service innovation is not so important. Relevant research works do not pay attention to the correlation among services, businesses, and demands, and the supply and demand matching is mainly based on the comparison and analysis of quality of service (QoS) characteristics[95–97]. However, when the number of services and demands rapidly increases, these methods will become slow and inefficient, being unable to meet dynamic

**Table 2 Classification of the correlation relationship between demand emergence and service innovation.**

| Perspective | Category | Description |
|---|---|---|
| Types of matching objects | Innovation of a single service | Solve the selection and scheduling that a single supply or single demand faces |
| | Innovation of multiple services | Solve matching and scheduling between multiple supplies and multiple demands |
| Subject of realizing matching | Individual supply and demand matching | Supply and demand matching of a single entity from the perspective of decentralized decision making |
| | System supply and demand matching | Supply and demand matching that the market/system faces from the perspective of centralized decision making |
| Matching type | Uncertain initial sate | The initial state of services and demands may be defined or dynamically changed |
| | Uncertain matching process | The process of supply and demand matching has a certain continuity. The initial state and matching process of the supply and demand dynamically change |

and real-time requirements.

When the initial state of the demand and supply is uncertain, the dynamic nature of demand is manifested as the submission and withdrawal of individual demands, the growth and decline of demands, and the dynamic nature of supply are manifested as the entry and exit and improvement and innovation of services. The existing research on supply and demand matching still cannot fully describe and solve the correlation problem between the two in the system. Demand dynamic modeling is mainly used to estimate and quantify the uncertainties of demands through hierarchy and delimitation, whereas supply dynamic modeling is used to balance the competition among service providers or to select and plan dynamic service resources.

Because some demands need to be continuously executed, the process of supply and demand matching also has a certain continuity. Within a certain period, the state of service, quality of service, and correlation among services are dynamically changing, and the function demand, process demand, and relationship among sub-tasks are also dynamically changing. O2O service recommendation and intelligent navigation belong to this type[98]. In existing research, efforts are made to explore the service patterns that are frequently used in the field, are used in the service formation process, and have certain business functions. Service innovation needs to consider the limited resource allocation model (i.e., changes in resource allocation can only occur at the beginning of a new service execution) and a fully flexible resource allocation model (i.e., changes in resource allocation can occur throughout the service execution cycle).

## 3.2 Operation

In essence, a service ecosystem is a sociotechnical complex system under the influence of the external environment and can be described by multilayer heterogeneous networks, as shown in Fig. 7, including social networks, service networks, and value networks. The social network represents the external environment of the service ecosystem, the service network represents the technical species in the service ecosystem, and the value network represents the cycle mechanism of the service ecosystem.

**(1) Social networks**

Social networks are a key part of service ecosystems. They are mainly comprised of social realities, such as service consumers, service providers, and service operators, and can integrate these social realities into the service network. Based on these social roles, they can be viewed as service consumers as a method to submit their experience information to the service network to assist in the maintenance and operation of the system. At the same time, they can be viewed as service providers and authorized to participate in service innovation to further promote system development. They can also be viewed as service operators to improve the matching efficiency of the service supply and service demand. In the social network, social realities can be considered interconnected nodes with some specific types of interdependency, such as friendship, beliefs, financial exchanges, and common interests.

With the increasing popularity of service ecosystems, the total number of users joining social networks has continued to rise in recent years. Due to this status quo, the social network is greatly difficult to be analyzed and improved with a large number of entities. Moreover, social entities have dynamic characteristics, which further increase the difficulty of analysis and processing. In this context, social computing emerges and focuses on the promotion of social studies and social dynamics by handling the large-scale social context with information techniques.

In addition, we need to focus on how to improve the information propagation in the social networks so that the data can be propagated in a few hubs, thus improving communication efficiency. The authors in Ref. [99] investigated a method to enhance the information propagation for social networks. By adding new linkages to social networks and decreasing the total number of communication hubs, the communication effectiveness can be improved, which contributes to the development of practical social network communications and cyber-physical-social interaction and computing.

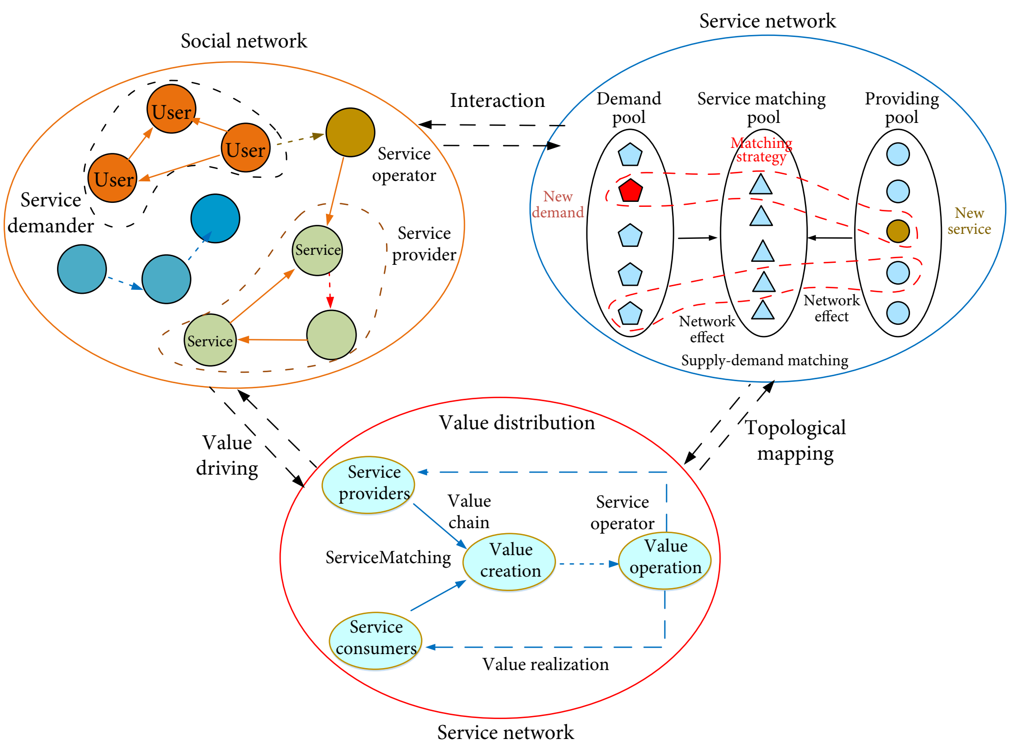


Fig. 7 Operation model of a service ecosystem.

In most of the discussions before this subsection, humans are always viewed as individuals with different levels of credibility, influence, or professional quality. The incorporation of social networks regards the human society as a whole that can be arbitrarily divided. Under different divisions, relationships exist among people in terms of friendship, beliefs, financial exchanges, and common interests. That is, social networks emphasize human dependency. When we utilize collective wisdom to serve the system instead of individual wisdom, it will produce even more outstanding results. The service community and service aggregation in the service network are all based on collective wisdom.

**(2) Service network**

In service ecosystem, heterogeneous services interconnect to form a complex service network, the core of which is the services with rich physical and social information and the interactive relationship among services. Scholars have identified several types of service convergence, including data convergence (the combination of knowledge bases of industry-specific services), capability convergence (the combination of previously distinct services into a new service), and domain convergence (the collision of business models and the redefinition of market boundaries)[100].

**Data convergence:** In order to solve the problem that the service granularity is too small and too dispersed, and a single service cannot support the complex demand of customers, it is necessary to aggregate these distributed services into multiple clusters so as to form a service community. Data convergence is the combination of knowledge bases and the erosion of boundaries that define and isolate industry-specific service. It is sometimes also referred to as a process where distinct disciplines begin to collaborate with each other. The openness of the models and their technology-independence provide the grounds for the emergence of service community. The data convergence is the basis for the further propagation and evolution of service network.

**Capability convergence:** In order to meet the users' complex function demands, various fine-grained services within the field or organization need to be combined to form a service chain. Capability convergence is closely linked to data convergence and is defined as the combination of previously distinct services into a common product. It leads to new value-creating opportunities and product and service offerings. Capability convergence is generally motivated by an industry actor's identification of new opportunities lying at the boundaries of the industry and awareness of the potential of combining own knowledge with external one, thereby leading to novel and potentially innovative activities.

**Domain convergence:** Many complex service applications require "cross-chain" service aggregation and comprehensive application. When capability convergence and applications from distinct domains are combined, they infringe on existing value-creating territories of underlying sectors and industries. This leads to collision of business models and gradual blurring, or redefinition, of market boundaries. This phenomenon is called domain convergence. Prior research has shown that domain convergence often leads to a new cross-industry segment that widens markets, lowers barriers to entry, and increases competition. Moreover, domain convergence can lead to reconfiguration of the value chain through the addition or elimination of activities, consolidation through mergers and acquisitions, as well as a complete shakeout of players from the ecosystem.

The construction of smart city clearly reflects the three development stages of service network. The first-generation urban data platform expands data aggregation to all areas of urban governance, including environmental protection, traffic, urban management, emergency, industry, culture, and population. Data convergence focuses on the comprehensive perception of complex urban events, including environment, weather, noise, human and vehicle behavior, pollutant discharge and transmission, and illegal construction. The second-generation urban data platform focuses on the fusion of operational capabilities across departments. For example, Alibaba's urban (traffic) brain alleviates traffic congestion by getting through to cameras, traffic lights, and signal timing. The core lies in extracting and modeling the huge multidimensional data according to matters rather than departments, and re-presenting the causality and correlation of various social issues and events using events and matters as clues. In this way, it can help decision-makers quickly identify and deal with key links, thus greatly improving the efficiency and utility of social governance[75,76].

**(3) Value network**

The value network represents the increase and circulation of values among service nodes and is similar to the energy cycle process in a natural ecosystem[74]. In the matching process of the service supply and demand, the utility value of the service can be realized by satisfying customer needs. Consumers transfer value to providers to enjoy services, and the value distribution is achieved among related service providers. Different service operation strategies will lead to large differences in the output or cost of the value network, which will affect the operational efficiency of the service ecosystem. The details are as follows:

(a) Value creation

Value creation is the mechanism of value generation in the ecosystem. The supply and demand matching can be met by multiple value chains. To achieve the best matching between the supply side and demand side, it is necessary to determine which value chain can maximize the value creation. Here, the operation mechanism of the value network is given as follows:

$$S_I \times S_C \times K_P \to \Delta \tag{1}$$

Among them, $S_I$ represents the state space of service resources and subsystems of the supply side; $S_C$ represents the state space of the demand side; $K_P$ is the final selected service operation strategy, including the organizational model of network collaboration, task assignment rules, and revenue distribution rules; and $\Delta$ is the final service matching and value generation result.

This mechanism is often a concern for platform owners. It needs to balance the control of the coordinator (closed tendency) with the autonomy of participants (open tendency). Such governance mechanisms include autonomy priority, knowledge sharing, control right allocation, and decision sharing. The authors in Refs. [22, 26] constructed a value co-creation model in the service system and argued that the resource dependence between actors resulted in service exchange, resource integration, and value creation. The authors in Ref. [101] proposed a method of network value analysis, explaining the position of a value in the network and how to create a value.

(b) Value realization

Value realization explains the mechanisms used by participants to maintain the ecosystem. The value realization of the service ecosystem mainly measures to what extent can the supply side meet the requirements of the demand side. According to the concept of value engineering[102], the *Value* function of a service operation is defined as follows:

$$Value = \frac{Outcome}{Cost} \tag{2}$$

Here, *Outcome* indicates the overall benefits of the service ecosystem in the supply-demand matching process, including the profits earned on the supply side and user satisfaction on the demand side. *Cost* represents the total cost of delivering services throughout its life cycle. *Value* represents the ratio of *Outcome* to *Cost*.

The authors in Ref. [103] proposed a partnership model to define the roles and responsibilities of participants and mechanisms to improve communication and collaboration within the system. In Ref. [104], the value realization process among stakeholders was demonstrated, including the direct value exchange (i.e., direct payment for services provided and used) or indirect value exchange (i.e., revenue generated through advertising). The authors in Ref. [105] explained the value proposition of stakeholders from a business perspective and presented a description paradigm of a value proposition. The authors in Ref. [106] used analysis of covariance to evaluate the value of software service platforms, considering the impact of different roles on the realization of system value, including QoS, service developers, service platforms, users, and service prices.

(c) Value distribution

In the service ecosystem, the source of service provision is social. This sociality exacerbates the diversity, uncertainty, and dynamics of service provision. To promote the stability of the service ecosystem, the service operation strategy needs to continuously adjust the value allocation to attract and retain participants through value distribution. The design of value allocation needs to consider many factors, including profit distribution models, incentive mechanisms, and investment and cost sharing.

The authors in Ref. [107] pointed out that the profit sharing ratio between different value links is very important to the development of coopetition relations, which has been proven in many economic studies. The authors in Ref. [108] proposed a goal-oriented value analysis framework using supply chain dependency analysis and cash flow analysis to evaluate the operation of the ecosystem. The authors in Ref. [109] proposed a dynamic pricing model based on the perceived value of users, which maximized the value of cloud service providers by capturing the supply-demand relationship in the cloud service market. In Ref. [110], value-driven service system design methods were developed to improve customer satisfaction based on the premise of meeting the profit of service providers.

### 3.3 Status

In the service ecosystem, services with similar functions will be aggregated into a service community structure in the long-term collaboration process. In the end, the service ecosystem will have a structure similar to the "individual-population-community". In the service ecosystem, service providers provide services to meet users' specific needs and achieve added value. Because users take satisfaction with their business needs as the fundamental goal, the service ecosystem is an economic system. In addition, services in the service ecosystem are not independent but form a complex correlation in the process of long-term competition and collaboration. As shown in Fig. 8, a complex social network is formed among service providers and users, and the service ecosystem has the characteristics of a typical complex network.

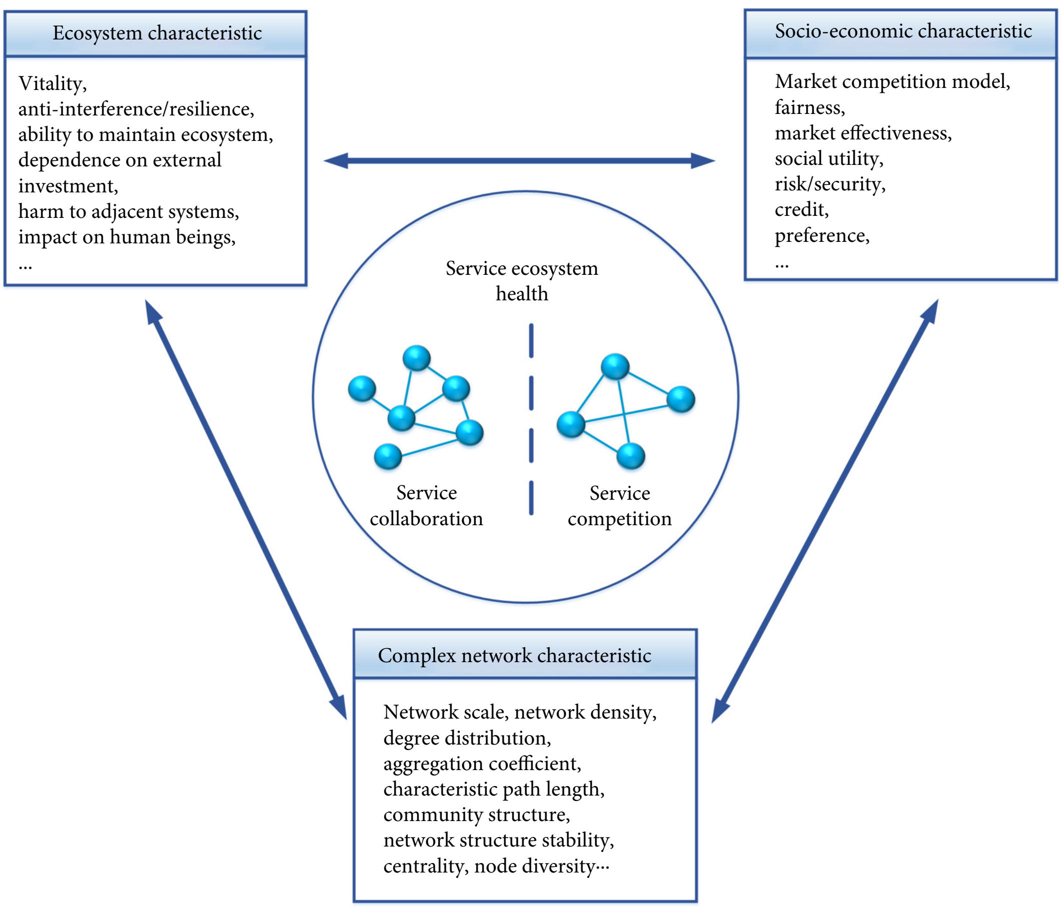


**Fig. 8 Status model of the service ecosystem.**

Thus, the service ecosystem combines the self-organizing characteristics of the complex system, coevolution characteristics of the ecological system, and value-driven characteristics of the economic system. To promote the healthy development of a service ecosystem, the measurement and evaluation of the service ecosystem shall be performed from three dimensions: ecosystem, socioeconomic system, and complex network.

**(1) Complex network characteristic**

The index of the complex network characteristic of the service ecosystem is mainly used for a comparative analysis of the basic structure and interaction of different ecosystems[111, 112]. The researchers hope to construct a knowledge map of the service ecosystem to provide the basis for the sustainable development of the service ecosystem. The research mainly includes three perspectives: (a) relational approach, which focuses on the connection relationship among nodes and adopts indexes, such as density, scale, centrality, and symmetry, to explain specific behaviors and processes; (b) positional approach, which focuses on the social structure reflected by the relationship among multiple nodes, adopts indexes, such as communities, hotspots, structural holes, and path length[113–115], and emphasizes the use of structural equivalence to understand social behavior; and (c) performance approach, which focuses on the performance of the entire network system and adopts indexes, such as functionality, responsiveness, reliability, and availability.

(a) Relational approach

The service ecosystem in a smart society with crowd intelligence is very complex, and the interactions among services are often unexpected without top-level design. In a service ecosystem, every service node has its specific function and location. Service nodes in different fields will establish connections with one another through a self-growing and self-organizing process to achieve strong functions. With the development of service technology, the real world and information space can cross various boundaries, such as regional boundaries, industrial boundaries, organizational boundaries, online and offline boundaries, and value chain boundaries, to infiltrate and fuse with one another. With intelligent transportation as an example, its ecosystem covers several services in traffic control, municipal administration, medical treatment and health, weather, mobile communication, public security, emergency disposal, social network, and other fields. For traffic control, traffic accidents, transport services, specific customer demands, and other routines and unexpected traffic events, these services will be linked together through the service chain, dynamically constituting a comprehensive, personalized, and context-aware complex traffic service network.

(b) Positional approach

The topological structure of a service ecosystem may be centralized or fragmented. The service-based feature vector is used to calculate the functional similarity of services, and a knowledge map of the service system is constructed in combination with hot spot information and category information of the services, thus presenting services in the service system in an intuitive form. On one hand, we can know the time characteristics and importance of different topics. On the other hand, we can know the directional dependence among different service topics to know the trend of service community changes in the service ecosystem and improve the long-term availability of service aggregation. The continuous evolution of a service ecosystem may lead to "structural holes" among service communities; that is, some businesses and their value expectations cannot be supported by existing service networks[113, 114]. To make up for the structural holes, the bridge connection is performed on different subnetworks through a few nodes, and such nodes are vividly called "bridge points". In a service ecosystem, the cross-border fusion among services acts as such bridge nodes, thus forming a value flow among nodes.

(c) Performance approach

In long-term cooperation and competition, not only the status of the service nodes themselves will change (the services will change), but also the connection relationship (growth or degradation and migration) among nodes will change. The small but continuous changes among these local network nodes will lead to a significant or insignificant evolution of the entire service network and even "explosive diffusion"[116, 117]. In particular, the crossover services as the bridge points have 3C characteristics, namely, crossover, convergence, and complexity. This process needs to realize not only the integration of data, processes, services, and other technical levels but also the deep fusion of different service patterns. Many barriers resolve the conflict among patterns. For different business fields in cross-services, there may be explicit or implicit interest conflicts among service nodes, so it is difficult to satisfy the interest maximization demands of all nodes at the same time. For example, as the service provider in the same group, Taobao wants users to spend more money on online shopping, whereas Alipay wants users to save money and deposit more money in it. How to solve these contradictions and weigh various value elements to create a greater value is the challenge that performance analysis faces[39].

**(2) Ecosystem characteristics**

The ecological characteristic index of the service ecosystem is mainly used for its macro evaluation, which is conducted from three dimensions: external environment, ecological species, and cycle mechanism. The environmental dimension mainly studies if the system acquires negative entropy from the environment in order to maintain the order and output of the system and adopts indexes, such as openness and sustainability[118]. The species dimension mainly examines the ecological niche formed by the interaction among species in the system and adopts indexes, such as diversity and hierarchy. The cycle dimension mainly examines the characteristics and changes in the system at different stages and focuses on the periodicity and anti-interference of the ecosystem, hoping to provide a basis for future predictions[49].

(a) Species dimension

In the service ecosystem, the service node is the most basic species, is capable of metabolism and self-renewal, and presents growth, development, decline, and death. The concept of service population arises when service nodes in the same field can connect with one another and provide a new integrated service pattern. The population is the basic unit of evolution, and all services in the same population share one feature library. The aggregation of all service populations living in a certain environment is called a service community. The population is not randomly pieced together but regularly combined. Only with complex interspecific relationships can a stable community be formed. The service ecosystem is the combination of service communities and the external environment in the same space. From the perspective of the biological ecosystem, variation or diversity is quite important. We usually measure the health degree of a business ecosystem with two indexes. One is the increase in service diversity, that is, the number of new services created in a given time. The other is the increase in the diversity of combinational relationships among services. As the ecological diversity constantly increases, the ecosystem becomes richer and more inclusive to enable new members to easily find similar services and establish connections with them and grow increasingly faster.

(b) Environment dimension

The natural ecosystem maintains its order by aborting negative entropy. Therefore, it must be an open system because the closed system will become more disorderly and ultimately cannot be maintained[88]. For the service ecosystem, service innovation is its negative entropy[119]. Through the recombination of production factors and production conditions, the running rules of a service ecosystem are reshaped to make the service ecosystem run efficiently. Mobile Internet, e-commerce, and AI are all in this case. These technological innovations will reshape the growth equation of the service ecosystem and restart its growth process. The environmental dimension primarily evaluates various factors influencing technological innovations, mainly including (1) whether to solve specific problems for service consumers; (2) whether to produce a scale economy; (3) intensity of competition among services, difficulty of entry barriers, and other factors; (4) innovation system and research and development (R&D) investment within the enterprises, including technological innovation-related soft and hard resources, system, structure, location, culture, and other factors.

(c) Cycle dimension

Through the value chain (the proportion of the number of species of different ecological niches is maintained relatively stable), survival of the fittest (competition promotes the differentiation of ecological characteristics of species, such as an increase in new services and extinction of old services), and mutualism (interdependent relationship among species), service communities will show their complex and stable structure, that is, ecological equilibrium. The destruction of the equilibrium may result in the permanent loss of a service resource. The cycle dimension is used to measure the ability of an ecosystem to cope with environmental disturbances and impacts. When a healthy ecosystem is disturbed and impacted by the environment, it can survive for a long time and ensure the stability and adaptability of the service ecosystem at the overall level. Its indexes mainly include survival rate, sustainability, and predictability. Because the development of technology is cyclical, the evolution of the service ecosystem also presents cyclical characteristics[49]. The key concerns here include how can the service ecosystem achieve equilibrium when new services are introduced into the value chain and how can the entire value network achieve equilibrium when the external market environment changes.

**(3) Socioeconomic characteristics**

Humans in the service ecosystem could be not only service consumers but also service providers. An efficient social evaluation mechanism is conducive to putting humans in the loop mechanism of the service ecosystem. However, the current status of the service ecosystem is still lacking in the research field of social evaluation. Here, the authors will present some possible evaluation directions that can be used in the service ecosystem. The socioeconomic characteristics of the service ecosystem determine its sustainable development, mainly including the competition mode, fairness, effectiveness, QoS, social utility, externality, risk/safety, credit, and preference. Here, we mainly analyze from the perspectives of service providers, service consumers, and service operators.

(a) Perspective of service providers

From the perspective of service providers, the social evaluation mechanism of the service ecosystem covers more possibilities, such as influence evaluation, capability evaluation, and reputation evaluation. The influence evaluation measures the social influence of a service ecosystem. For example, it could be used to determine the influence of a service ecosystem in the industry, thus taking full advantage of the collaborative power of service providers at the right time. In addition, the capability and reputation need to be evaluated, which can reflect whether there is a healthy competition mechanism within the service ecosystem. Capability means that the completion quality of a service ecosystem can fulfill the fluctuated demand sequence. Reputation signifies whether a service ecosystem honestly completes the fluctuated demand sequence within the task's time to live.

(b) Perspective of service consumers

From the perspective of service consumers, the social evaluation mechanism of a service ecosystem could be the satisfaction evaluation, which is used to estimate the satisfaction degree of users after acquiring the required services. This kind of evaluation is very common on most existing systems or networks, and it can be used as an index to guide the direction of the service ecosystem evolution. The satisfaction degree can also be predicted before business supplying, thus promoting service quality[120]. Specifically, in the service ecosystem, the satisfaction evaluation mechanism can be performed for smart recommendation systems in real target environments because recommendation lists should be not only accurate and helpful but also a pleasure for users. In particular, the fairness of the recommendation algorithm is as important as the utility for service consumers.

(c) Perspective of service operators

The role of service operators needs to coordinate the interests of governments, enterprises, and citizens. A reasonable mechanism can adequately inspect the interests of all parties, thus making good use of service resources and serving people better. The social evaluation mechanism pays attention to the strategy adopted by service operators to balance social benefits and social risks caused by the service ecosystem[32,33]. It is related to several typical effects of social governance, including the following: (1) Monopoly of the platform economy: The development of the service ecosystem has a strong scale economy effect and scope economy effect. Once advantages or disadvantages appear and reach a certain degree, it will result in constant intensification and self-reinforcement, bringing the monopoly of "the strong is stronger, the weak is weaker"[18,19]. (2) Progressive increase in return to scale: The operating costs of a service ecosystem significantly decrease as the number of service providers increases. In the network economy, the growth of service providers presents a strong nonlinear growth mode, and the risk of environmental change is also nonlinear. (3) Progressive decrease in marginal returns: The growth process of the service ecosystem is a metabolism process, and it also faces technological, policy, and resource constraints. When these constraints come into effect, its input and output will face the boundary of accumulation and growth rather than unrestricted expansion[121,122].

### 3.4 Traceability

The influencing factors in the evolution of the service ecosystem are complex and difficult to be confirmed. In addition, evolution may be influenced by people's free will and subjective initiative, and sometimes the evolution path may be changed due to accidental events. To clarify the reason for having an effective or ineffective service ecosystem, we need to conduct research from three aspects—causality determinacy, purposive tendency, and random contingency—and reveal the laws behind these problems. Figure 9 shows the traceability model of the service ecosystem.

**(1) Casual determinacy**

A problem model in the real world can be described by a

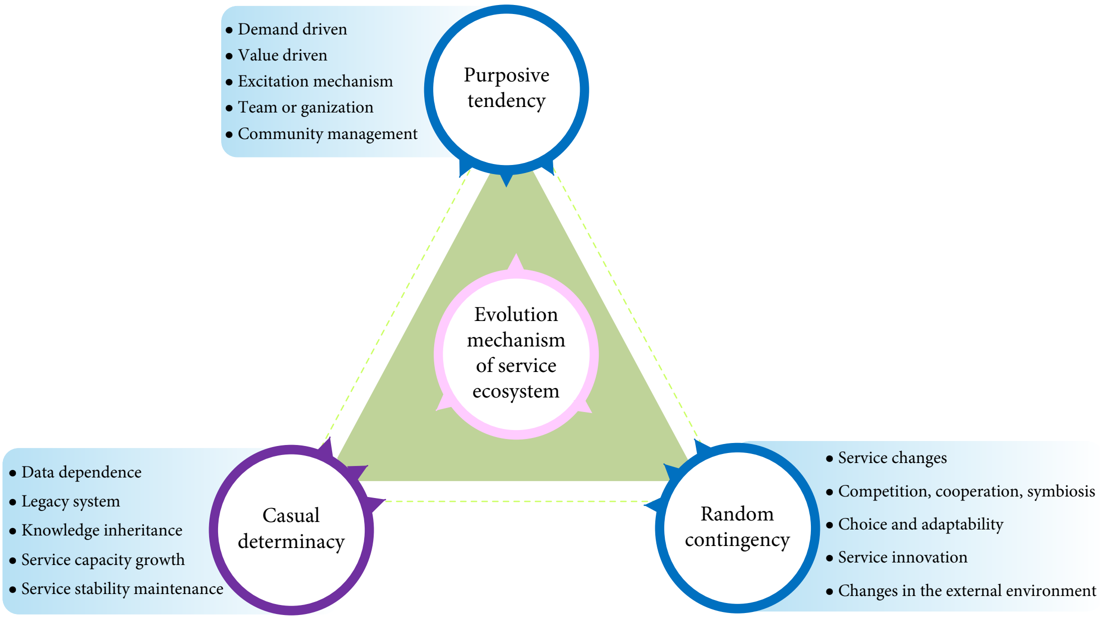


**Fig. 9 Traceability model of the service ecosystem.**

number of variables that have a relationship with one another, i.e., the equation $Y=F(X_1, X_2, \ldots, X_n)$. This equation is used to describe the causal relationship among a number of variables. Once we have the equation, we can have the ability to predict. In other words, the derivation of dependent variables is jointly determined by several independent variables, and each independent variable has its own influence weight (coefficient), which is determined by a causal relationship. The operation of the service ecosystem heavily relies on machine decision making, such as service matching and service recommendation. The recommendation algorithm has typical characteristics of data dependence and will acquire wrong behaviors in the self-learning and self-adaptation interaction process. Furthermore, it will be solidified or amplified through the networked characteristics of the service ecosystem, finally forming a "self-fulfilling wrong feedback loop"[123].

For service consumers, the special preference or special goal of service decisions may not be with their interest and utility standard. For example, information cocoons[81,82] and algorithm discrimination[83,84] are cases that have happened in real life. Some discrimination may be insignificant, but in major activities, such as credit assessment, crime risk assessment, and employment assessment, discrimination is no longer insignificant. Hence, it is essential for service decision making to weaken or avoid algorithm discrimination and ensure fairness and justice. Therefore, we need to focus on the causal relationship between data dependence and fairness in service decision making.

At present, the causality research on the performance of these services is still at a very preliminary stage. In 2003, Brady[124] divided many causal relationship test methods in natural science and social science into five types: (1) New Hume theory, the so-called causal relationship, is essentially the inductive reasoning of "correlation", but the causal relationship cannot be guaranteed by the correlation[125]. (2) Counterfactual causal relationship theory, that is, the thought experiment assuming that events do not occur[126]. (3) Manipulation experiment theory, that is, how to analyze the causal relationship with an experiment. The random and double-blind experiment is the most commonly used causal relationship test method in the medical field and is often used in drug effect testing[127]. (4) Mechanism theory, that is, the causal relationship can be truly judged only after finding the influencing mechanism from the cause to the result based on the internal mechanism among factors[128]. (5) The compressed sensing method is used to research the causal relationship. After compressed or sparse sampling, noise and non-essential information are filtered, and the causal relationship in the data can be easily found[129].

With the scale expansion of the service ecosystem, the influencing factors have become increasingly complex and difficult to be identified, and it has become very difficult to find the causal relationship as in the past. In many cases, we have to substitute it with a strong correlation. According to Chebyshev's inequality, as long as enough representative samples (data) are found, a model or a combination of models can be found to fit the truth very well, and the influence of randomness and noise can be ignored. This method is called the data-driven method. However, it has high requirements for data integrity. Most often, we cannot have direct access to information, so we need to use indirect data to gain the information we want. For example, establishing a correlation between disease transmission and changes in searching keywords in the region can be used to predict influenza[130]. According to the similarity among different roads, the known traffic flow of some roads can be used to estimate the unknown traffic flow of other roads[131,132].

**(2) Purposive tendency**

The service ecosystem is complex because services are purposeful and adaptive rather than passive subjects, which reflects people's free will and limited rationality. The purposive tendency of services is embodied in various forms, such as demand-driven, value-driven, and incentive-driven (e.g., crowdsourcing, rewards, reputation, and ranking). In such a system, adaptive services can continuously "learn" or "accumulate experience" in the interaction with the environment and change their own behavior and structure according to the changes in the environment to survive and develop. As the goal constantly changes, the services will also evolve in the life cycle. On one hand, all kinds of service nodes will keep iterative optimization to improve their ability to realize the value, expecting to gain advantages in operations, such as selection, combination, and scheduling of services. On the other hand, the relationship of the crossover and cooperation among service nodes is constantly adjusted to mine new value creation opportunities, the typical characteristics of which are cross-domain and aggregation.

The core idea of the service adjustment strategy is similar to that of reinforcement learning[133,134]. That is, when an individual takes action, he or she will get a reward from the environment. To maximize long-term rewards, an individual needs to adjust his or her behavior strategy, evaluate the potential benefits of all behaviors, select the one with the highest value as the action option, and give other options a small probability of execution. The utility function of the purposive tendency is defined as follows:

$$G^*(s) = \max_{policy} E_{\tau \sim policy}[R(\tau)|s_t = s] \quad (3)$$

where $G^*(s)$ represents the reward obtained by the service after adopting a certain strategy, *policy* represents the behavior strategy adopted by the service, $R(\tau)$ represents the cumulative reward value, and $s_t = s$ represents the service state at time $t$ as $s$.

Compared with the evolution that is a passive and random search strategy, reinforcement learning is more similar to the active and targeted adjustment, which greatly accelerates the efficiency of the strategy update. The process of service nodes improving their own capabilities will give birth to new species and ecosystems, which will lead to impact the growth of new species brought by old species, such as all kinds of third-party services in the Taobao ecosystem.

However, this purposive behavior may lead to unfair competition among services, such as the bidding rank of search engines and scalping of e-commerce[135]. Furthermore, such a purposive behavior may destroy the healthy development of the service ecosystem and make the ecosystem constantly adjust its evolution direction, strategy, and structure. To prevent such a tendency, we need to analyze the impact diffusion and reaction mechanisms of the evolution of service nodes. The impact analysis method of the service evolution diffusion is mainly based on the specific evolution performance of a single service to predict other services that may be affected. The research on the reaction mechanism of the service evolution shows that the evolution of one service will lead to the evolution of other services, and the evolution of these services will, in turn, produce an effect on the original service.

"Impact analysis" and "reaction" are two opposite processes, reflecting the game among multiple services. In the framework of the evolutionary game, strategies and returns can be used to describe the behavior and fitness of individuals, and strategy updating represents the process of the individual survival of the fittest in natural selection, in which different evolutionary dynamic processes correspond to different strategy update rules. From the perspective of game theory, rational individuals tend to pursue the maximization of their own benefits. However, when all individuals pursue their own maximum benefits, it will lead to a decline in the overall benefits of the system, thus causing the so-called social dilemma, i.e., the contradiction between the individual optimal and global optimal[136]. One of the research purposes of evolutionary games is to examine the dynamic phenomena in the cooperation evolution process and the methods to promote cooperation under such a contradiction.

**(3) Random contingency**

Random contingency is the result of the accumulation of quantitative changes, which will promote the evolution of the ecosystem from low to high, such as selection and adaptation brought about by technological innovation and environmental mutation. In the service ecosystem, the sources of service provision and service consumers are social. This sociality exacerbates the diversity, uncertainty, and dynamics of service provision and service demands. Many intelligence problems are fundamentally about eliminating uncertainties. When the data are complete, that is, the datasets of the training model and test set using the model are of the same set or are highly repetitive, their cross entropy is close to zero. In this case, a disaster that does not cover several small-probability events will not occur. In this way, the data-driven method will become universal rather than effective or ineffective from time to time.

However, relative to the complexity of the problem, if we only master a small amount of information, the data-driven method will be inadequate because of the data sparsity. There are not enough data, and even when they are used, they are still not enough to eliminate uncertainties. In the past, any model based on probability statistics may not cover many small-probability events, which is regarded as the weakness of the data-driven method. Therefore, the classical statistical method cannot explain phenomena caused by interrelated and complicated causes (related parameters). Thus, to determine the best match among all possibilities, scientists depended more or less on intuition to make up for the loss and gap of data. Bayes' formula helps them achieve that in a rigorous mathematical form.

In the 1980s, Judea Pearl demonstrated that the use of Bayesian networks should reveal the causes behind complex phenomena[137,138], which works in the following manner: If we do not know the cause of a phenomenon, we first build a model based on what we think is the most likely cause, each possible cause is then connected as a node in the network, and a probability value is assigned to each connection based on existing knowledge, our predictions, or expert opinion. Next, we only need to substitute the observation data in this model and recalculate the probability value through the Bayes' formula among the network nodes. Such a calculation is repeated for each new datum and connection until a network diagram is formed and an exact probability value for the connection between any two causes is obtained. Even if the experimental data are blank or full of noise, the Bayesian network, which unremittingly pursues the causes of various phenomena, can still build models of various complex phenomena.

The value of the Bayes' formula is that when observational data are insufficient, the Bayes' formula can combine expert opinions with original data to make up for the deficiency in the measurement. The greater our cognitive deficits are, the greater the value of the Bayes' formula is. As more and more data are observed, the posterior probability becomes closer and closer to the truth. Through continuous observation, the prior probability is constantly transformed into the posterior probability to constantly approach the real probability. A good example of using Bayes' formula comes from searching for aircraft falling into the sea, such as in the Malaysia Airlines incident[139].

### 3.5 Intervention

There may be different trends in the evolution of the service ecosystem, including the evolution from the low level to the high level and from simple to complex. It is also possible to degenerate from the high level to the low level and from complex to simple. To promote the healthy development of the ecosystem, it is necessary to perform limited and reasonable interventions in its evolution. With the expansion of the scale of the service socialization supply, the optimization of a simplified mathematical model can no longer meet the actual demand. The evolutionary game theory provides a feasible framework for solving the intervention problem. As shown in Fig. 10, service matching is the result of the combined action of top-down intervention and bottom-up emergence. The strategy and benefits can be used to describe the service matching degree, whereas the strategy update represents the process of the service survival of the fittest.

**(1) Design of the intervention strategy**

As shown in Fig. 10, the design of the intervention strategy basically evolves in the following pattern: (a) Description: clarify what is happening. The first level of interpretation of supply and demand matching data is description. In the context of big data, reducing noise interference and finding problems through data description have become the top priorities. (b) Diagnosis: why does it happen? The core work is to establish the connection among data, understand the causal relationship among data, and ultimately find the driving factors or triggers for a particular problem. The diagnosis results can help us sort out our experience for future decisions. (c) Prediction: What will happen? As the data, algorithms, and computing power are rich enough, the diagnosis results can be gradually expanded and applied to the future to complete the prediction function. (d) Design: What should be done? The final design of the intervention strategy can be realized only when the system can use data, algorithms, and computing power to fuse with human judgment.

Moore[140] thought that the most important network governance relationship is the community (group) governance system and semi-democratic governance. Moore's concept of ecosystem governance includes market and hierarchy. He believed that ecosystems internalize enterprise systems and markets and connect them through the guidance of community leaders. Korhonen et al.[141] mentioned different research perspectives of network governance: First, the market system, which is based on the transaction cost theory, takes the definition of price as the main governance mechanism and emphasizes the realization of configuration through free competition and free exchange. Second, hierarchy takes command as the main governance mechanism and emphasizes benefit sharing and mutual trust. Third, the network is an intermediate form between the market and hierarchy. In such an explanation, the partnership is a more complete form than the market but less than the hierarchy.

In the real world, individual activities are increasingly complex, diverse, and differentiated, but intervention methods often adopt simple, uniform, and centralized control. In light of the dynamic nature and uncertainties of the external environment, the intervention strategy is bound to lead to adaptive changes in some services based on the surrounding environment, thus leading to the failure of traditional optimization methods. In view of this, centralized control and optimization methods will no longer be applicable to the optimization of service ecosystems, and the inductive strategy will be an effective governance mechanism. As the services in the service ecosystem are composed of stock and incremental services, the inductive mechanism can be designed from two perspectives. According to the induction mechanism of incremental services based on the ecological niche recognition model (recommendation strategy), new services are constantly introduced into the service ecosystem to participate in the dynamic competition and collaboration among services[112]. According to the replacement mechanism of stock services based on social utility evaluation (evaluation strategy), services improve their service capability autonomously to promote the extinction of negative effect services and push the optimization of the service ecosystem[142].

During the implementation of the intervention strategy, special attention should be paid to the selection of intervention objects. The objects here are generally divided into three categories: network core type, dominant type, and market niche type. The network core type is the core species in the ecosystem, and many connections among other members have to be made through the core. These species can bring benefits to the ecosystem and its members, and the disappearance of core species can bring disasters to the ecosystem. The dominant type is also the core of the ecosystem, and it directly controls or owns most nodes in the network through vertical or horizontal integration. Such an ecosystem is fragile and cannot easily withstand external shocks. The market niche type refers to an individual that will not produce a great impact on other species in the ecosystem but constitutes a large part of the ecosystem and has an extended impact on the entire ecosystem. For this kind of role, the most important thing is value creation, creating a continuous value in

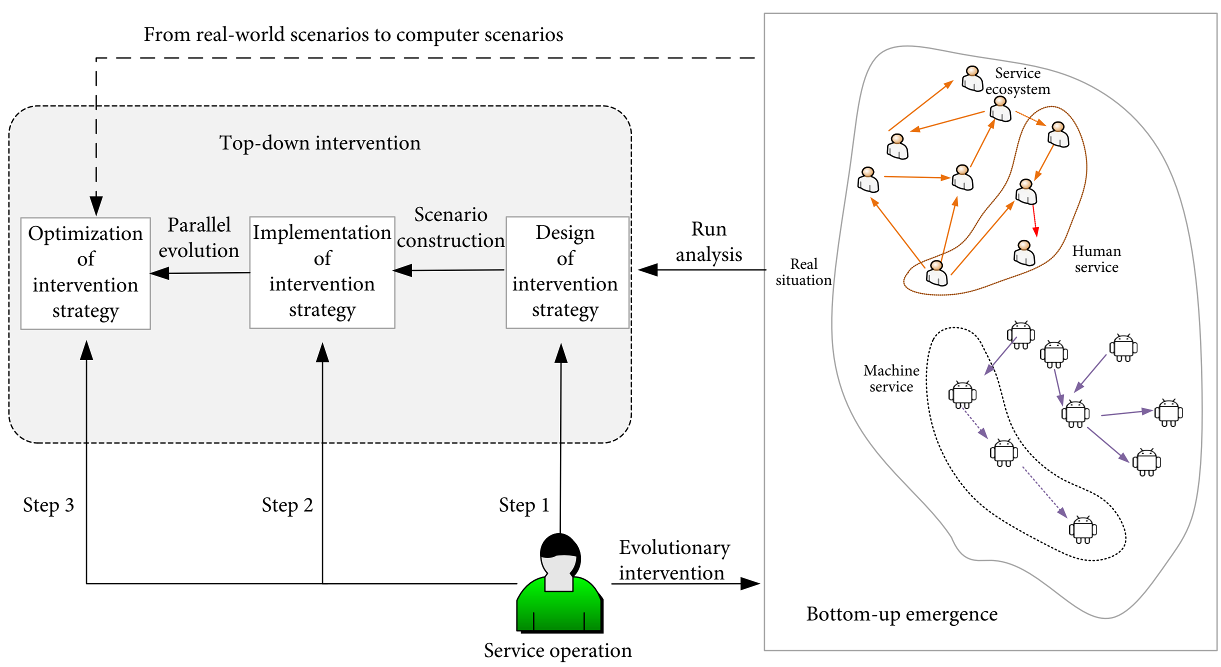


**Fig. 10 Intervention model of the service ecosystem.**

its special division of labor based on specialization.

**(2) Implementation of the intervention strategy**

The construction of a service ecosystem involves infrastructure, social management, people's livelihood services, ecological protection, economic development, and many other fields. The intelligent urban hardware, such as bicycle sharing, driverless buses, intelligent garbage cans, and intelligent street lamps, starting from local product innovation, gradually changed the operation mode of the entire infrastructure and public service system. On this basis, the service ecosystem has gradually entered the era of the coexistence of machine intelligence service and manual service. In other words, the machine assists the person in making decisions, and gradually, the machine directly provides the decision. For example, in takeout and travel scenarios, the machine intelligence service automatically completes the decision making and issues tasks to riders and drivers. The relatively common scenarios in the consumer-oriented Internet will gradually appear in the industrial Internet and enterprise transaction scenarios.

The machine intelligence service is the formal representation, reasoning, and calculation of objective facts with symbol/behavior/connectionism, and it rarely involves the judgment and decision making on the causal relationships of value and responsibility. The implementation of the intervention strategy is just a "double-helix" structure, in which the objective factual data and information/knowledge can be called a fact chain, whereas the parameter part involving the subjective value can be called the value chain. Many problem domains are challenging and often require the fusion of facts, values, and responsibilities, and planning needs to be adaptable to the constraints of potential changes. Data intelligence is good at the calculation process of objective facts. It can extract, explore, and acquire knowledge from a large amount of data to provide support for people in making decisions, but it cannot cope with emergencies. Social intelligence is good at a balanced mastery of subjective values. In the case of not knowing global facts (incomplete information) or being uncertain about certain facts (uncertainty), it can weigh the factors related to a particular decision and the risks and benefits it may cause in the near future or future. The intervention strategy can achieve effective judgment and accurate decision making function only by realizing the matching between the "double-helix" structures.

Oftentimes, the intervention strategy of the service ecosystem can be jointly completed by human intelligence and machine intelligence services to balance the influence of various factors on decision making. The combination of the two has provided a huge opportunity for combining the advantages of humans and machines, thus achieving the capability that cannot be obtained in the short term[143]. Manual services can help machine intelligence services become highly effective, and machine intelligence services, in turn, can enhance the capability of human services. The combined system has three main characteristics: (a) Micro-tasking: Crowdsourcing generally divides a large complex task into many micro-tasks, known as micro-tasking, where each service can participate in completing a part of the work[144]. (b) Workflow: A complex workflow is assigned to a number of participants. The major task of roles in different steps is to use and add more information based on the previous participant. (c) Problem-solving ecosystem: In creating a problem-solving ecosystem, combining manual services with machine intelligence services and building a complex credible model have become the basis for solving the most challenging problems in the world.

In this society of human–machine symbiosis, the service ecosystem will be highly efficient with the rational arrangement of the position of robots in the social network and elaborate setting of their behavior rules[145]. In a social network, certain nodes can be placed in multiple redundant links by installing certain public opinion robots to prevent the spread of false news[86]. Amazon Mechanical Turk is a crowdsourcing platform that employs a large number of volunteers and allows them to participate in an online color-coordination game experiment[146]. Wikipedia deploys a series of web robots to help administrators maintain the website and prevent the formation of the so-called "Wikiality" when people write entries. Humans perform what they are good at, while machines are responsible for comparing results, testing effectiveness, controlling cheating, and other details[147].

**(3) Optimization of the intervention strategy**

The service ecosystem is an open and complex system in which complex connections and interactions occur among elements, and a slight move in one part may affect the situation as a whole. In addition, the self-organization and emergence of the complex system make the whole far greater than the sum of individuals. Thus, how to achieve equilibrium between the bottom-up intervention and down-top emergence is a difficult problem. The intervention strategy has various implementation paths and possibilities. The implementation time, implementation length, implementation object, and implementation range may lead to a totally different final cost and effect. Therefore, the strategy adjustment often requires constant trial-and-error, iteration, and improvement to reach a consensus.

To fully understand the interventions before they are implemented, we need to deduce the future caused by different options and their consequences, as if we unfold the future of different options in a parallel universe and reduce the bad options to increase the probability that we make the right decisions. However, the experiment cannot be performed in a real social system, the reasons for which can be attributed to the following aspects: (a) Economic aspect: Due to the scale of the social system and cost factors, the test is too costly to carry out in the real world. (b) Legal aspect: Many social issues involve legal issues, and systematic testing cannot be carried out. (c) Moral aspect: Social systems often involve a large number of people, and tests on these systems may impact people's normal life and even endanger their life and property, so such tests cannot be accepted morally.

Through a simulation calculation, the computational experiment method is used to examine the internal problems of the service ecosystem and their evolution law, intervene in the current development path and operation status of the ecosystem in the view of the future, find possible negative effects, conflicts, and potential risks brought by the system, and provide "references", "forecasts", and "guidance" for coping with possible situations[148]. In the continuous integration of more data, the manipulation, training, and simulation of the computational experiment will become real and accurate and has the ability of self-growth and self-optimization through interaction and feedback with the real world. The trial-and-error method is costly, but the new methodology can reduce the cost of the trial-and-error method to the minimum, constantly approaching zero cost. Nonetheless, we can create extreme scenarios that are difficult to reproduce in the current real world. Combined with the optimization theory of operational research on uncertain and multi-objective conditions, we can deduce the effects of different intervention strategies to obtain the expected optimization effect[149, 150].

However, computational experiment, as a new methodology and technological means, has not been widely accepted by mainstream researchers. The main reason is that the agent model has large design freedom and lacks clear standards to verify whether the designed model accurately represents the original system. Therefore, if the computational experiment is to become the mainstream research tool for complex systems, the problem of model verification shall be fully solved. Moreover, the intervention strategy involves many variables, each variable has multiple level values, and there are interactions among variables. Hence, it is difficult to measure the impact of each variable on the system response. To determine the importance of each variable and the interactions among variables and then optimize the intervention strategy, it is necessary to design the computational experiment properly, arrange the experiment reasonably, and analyze the experimental data efficiently. The commonly used experimental design methods include a randomized block design, Latin square design, and factorial design. Through the response surface method, the output response under the action of multiple intervention variables is analyzed to gradually determine the optimal intervention strategy. The guidance effect of the experimental design in the implementation of the computational experiment can improve the optimization speed and reliability of the intervention strategy.

## 4 Research Scales: Individual, Organization, and Society

Characterizing a service ecosystem requires understanding the complexity of its evolution at multiple scales. To achieve this goal, the service ecosystem supports the research from three dimensions: “micro individual”, “meso structure”, and “macro governance”. Figure 11 shows a competency matrix for assessing the service ecosystem, including operational perception, measurement (traceability), and intervention (control). Among them, the check mark indicates the field in which the service ecosystem can really make great achievements, and the question mark indicates the field in which limited achievements can be made while considering calm understanding.

### 4.1 Micro level

Over the past decade, wearable sensors, smartphones, and social media have rapidly developed, allowing people to observe and collect masses of personal data. With the development of multimodal sensing technology, people’s physiological parameters (e.g., heart rate or blood sugar level) and lifestyle (e.g., daily activities or online social circle services) will be obtained continuously and unobtrusively[151,152]. In a service ecosystem, an individual’s behavior trace includes the time that an individual spends on each service and the traces of movements among different services. An electronic archive of the digital self can be created by synergies among different services. Through data analysis and mining, personalized information about each individual can be obtained, such as consumer preference, lifestyle, aesthetics, and value orientation. On this basis, services can be customized for each individual, and a service circle with the goal of individuation can be gradually formed, thus affecting individuals’ cognitive boundaries, living habits, and behavior decisions.

A conflict occurs between the convenience of smart life and the limitation of personal cognition. Hence, how to balance the two and determine the boundaries of the affected individuals will be the focus of future research. Collaboration, competition, and evolution in the service ecosystem are factors that have potential impacts on individuals, but very few people can model them well. According to the social learning theory proposed by Bandura, human intellectual development relies on individuals’ innate foundation, acquired learning environment, and sociocultural influence[153]. In a word, the degree of impact of an individual is the joint result affected by individual learning, organizational learning, and cultural influence. Such a view provides an idea for us to analyze the impact of a service ecosystem on individuals.

Figure 12 shows a hierarchical framework of the analysis from the aspect of social learning evolution (SLE)[154]. The left column indicates the level of the modeling framework, and the right column shows the related services adopted by the level. The SLE framework contains three evolutionary layers. The bottom layer is the individual evolution space, which describes the phenomenon that the individual is evolving due to influence, corresponding to various recommendation services, navigation services, and personal intelligent assistant services. The intermediary layer is the organizational evolution space where individuals change their cognition through imitation and observational learning, corresponding to services, such as the circle of friends and other social circle services. The top layer is the cultural space that imitates the accelerated evolution of individual cognition promoted by culture, corresponding to various hot spot lists and top searches. By drawing individual information from the bottom layer, culture is established to guide the evolution of individuals in the bottom layer. The implementation logic of SLE is shown in Table 3.

| Scales of inquiry \ Impact of service ecosystem | Operation/status | Analysis/traceability | Intervention/adjustment |
|---|---|---|---|
| Micro-level (individual behavior) | ✓ | ✓ | ✓ |
| Medium-level (organizational competitiveness) | ✓ | ✓ | ? |
| Macro-level (social governance ability) | ✓ | ? | ? |

**Fig. 11 Research scales of the service ecosystem.**

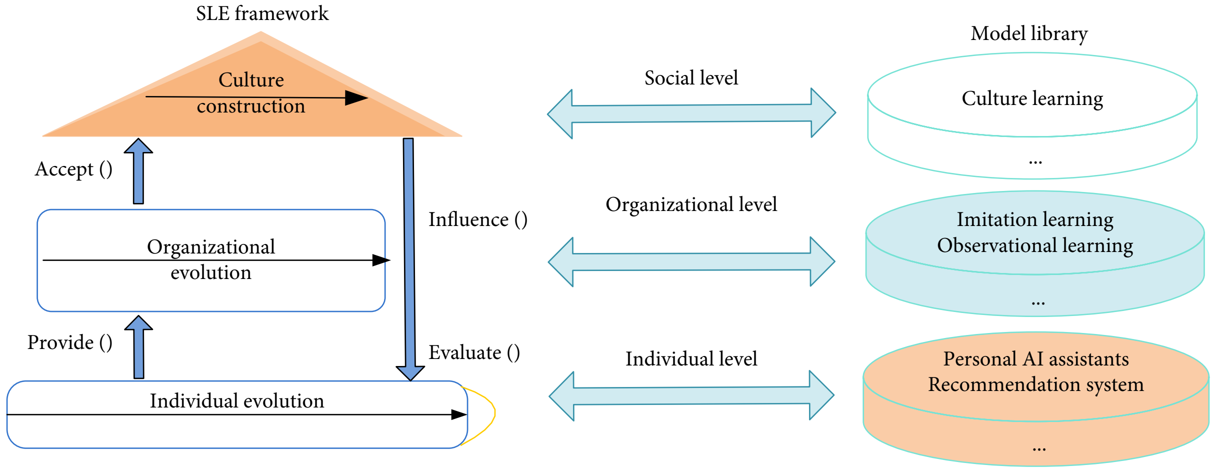


**Fig. 12 SLE modeling framework.**

**Table 3 Implementation logic of SLE.**

| Evolutionary stage | Evolutionary content |
|---|---|
| Step 1: Individual evolution stage | The bottom layer is the micro-space, where individual evolution takes place. At the individual level, the recommendation algorithm irreversibly changes the information ecosystem. Before the recommendation system appeared, the export of information must be an aggregation of multiple types of information, such as those from newspapers, radio, television, and web portals. Different types of information vary in the number of audiences, but they do not vary in content. However, the recommendation system successfully combines different types of information for comparison through indicators, such as users' residence time, thus affecting people's cognitive level. Furthermore, personal AI assistants will become increasingly common and affect our decisions by observing our online behaviors, including shopping, cooking, management of investments, management of health, and scheduling of trips. |
| Step 2: Organizational evolution stage | The middle layer is the organizational space, where individuals enhance their capability through imitation learning and observational learning. When a social platform is associated with family members, colleagues, leaders, friends, and partners, it will naturally generate cross-influencing of information, which will become a disguised parallel world. On one hand, what you see is what others want you to see, and on the other hand, what you show is your best or what you want a specified person to see. The spread of your opinion is only in certain circles. The circle will confine your thinking to the circle and make it difficult for you to empathize with the cognition of other circles. When this topic spreads in the circle, it will naturally form an illusion that the topic is spreading around the world, and people will be deceived by the circle. This phenomenon is called the echo chamber effect. |
| Step 3: Social evolution stage | Culture is used to guide the evolution of individual cognition in the macro-space. This simulates the phenomenon in which culture can accelerate the evolution speed of individual cognition. In addition to individual factors, there is something more special in the process of human cognition formation, that is, social structure and social mechanism. Social tools have now become important knowledge carriers, such as microblogs and official accounts. These tools allow one person's cognition of the world to quickly spread to others in the world. At the social level, all personal information is gathered to form various hot spot cultures, such as top songs, top sellers, public opinion rankings, and top searches. |
| Step 4: Cyclic feedback stage | The co-competition among services is the key driving force behind the evolution of the service ecosystem. All services continuously learn the experiences of elites to improve their competency. Because of different initial conditions and evolution capabilities, some elites may lag behind, and some new services with stronger capabilities will become the new examples. As a result, new services will emerge at the individual level, and their impact on individuals is likely to be deeper than those of the other services. Finally, the evolution of the whole ecosystem enters the next cycle. |

## 4.2 Middle level

At present, service ecosystems are rapidly rising in different industrial fields, such as intelligent health, intelligent retail, intelligent security, and intelligent transportation[13–16]. Furthermore, these intelligent services realize the convergence of business-oriented fields, such as epidemic prevention and control, environmental protection, and social governance[6–8]. Finally, smart services cover smart homes, smart communities, and smart cities, all of which are sub-ecosystems that are interconnected, interdependent, and relatively independent[75,76]. As shown in Fig. 13, driven by value, some new smart services keep expanding, competing, and growing, and several traditional services also keep shrinking and merging and even die out in the competition. With the evolution of the competition and cooperation relationship among services, the relationship among them can be established or broken, strengthened or weakened. With service ecosystems, we can make detailed analyses of the impact of smart services on a certain industry or field.

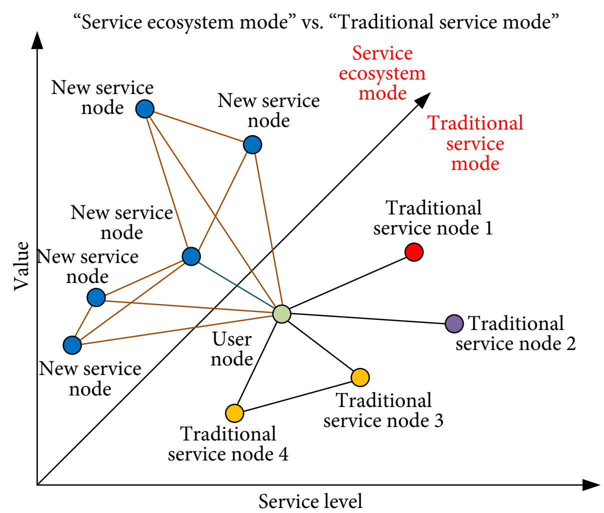


**Fig. 13 Dimensionality reduction strikes of the service ecosystem.**

Now, whether the service ecosystem can disrupt an industry or to what extent it can change an industry has always been a hot topic of debate. In the seller-oriented market, the basic problem is the contradiction between scarce resources and unlimited demands. The key to solving this problem lies in the efficiency of organizing and configuring resources. In the customer-oriented market, the problem is whether the gap between supply and demand can be removed. If a service ecosystem only acts as a tool or accelerator of the traditional mode, it cannot solve the shortage problem of high-quality service resources (e.g., good medical services). On the contrary, if the service ecosystem could improve the supply and demand matching ability to resolve their gap, it will outrun the traditional mode[56].

The researchers basically analyzed the ecosystem from four dimensions: points, lines, planes, and spheres. The points include service users and service providers. The lines connect the users to services and can be generated during users' usage of the services and sometimes include platform service providers. On the basis of points and lines, planes are thus formed, and the concept of planes comes into being when service points can be connected with one another, and a new integrated service pattern is provided. The service points in the plane are connected to one another through lines to form a service set. The user points are associated with service points in the set in the process of constantly using the service set. Finally, as there are more user points on the whole plane, the strength of the lines is increased. In this process, the scope of the plane is constantly expanded, and the strength of the line determines the stability of the plane. One specific point, whether representing a user or service, may belong to multiple planes. As the number of planes increases, these intricate planes eventually constitute the domain ecosystem.

The fundamental change of the domain ecosystem is the change in point, so the sphere is not accurately described as a static system but is constantly changing. If the business develops in a healthy direction, there will be more and more users, followed by services for users and service points. As the number of service points increases, the integration foundation and mutual support capability among different services will be stronger, thus resulting in more planes, and the whole system will cause a continuous expansion toward high dimensions. Generally, the capability of the business center is the interaction degree of various planes in the system. The high interaction degree among planes represents the strong interrelation of various service points in the system. Therefore, the capability of the business center to provide services is strong.

The construction of a multidimensional collaborative domain ecosystem is conducive to gaining a competitive advantage in a certain business domain, which has been verified by emerging Internet giants such as Uber, Airbnb, and Meituan[155, 156]. Taking e-business as an example, the advantage mainly lies in three aspects: (1) Enhancing the network effect by increasing the network connection points: increase international buyer connection points through a layout of export e-commerce, increase national seller connection points through a layout of import e-commerce, and increase domestic connection points by opening up sinking markets. (2) Enhancing the network effect by increasing the frequency and intensity of network connection: increase the network intensity using the new product strategy to arouse the retention motive of users and merchants and increase the frequency of network connection by creating hot spots. (3) Enriching the ecosystem by remedying the defects of the network effect. The social tool property of the network effect is improved through instant messaging tools, and the content property of the network effect is improved through different methods, such as live broadcasts.

### 4.3 Macro level

The research and practice of smart societies with crowd intelligence have been mainly dependent on the copy of administrative management, such as the well-known smart health, intelligent transportation, and intelligent security. From the perspective of cybernetics, the logic of the whole smart city is actually the cyber-physical system (CPS) transformation of the urban space with new technological methods centering on information and communication technology (ICT). As shown in Fig. 14, the goal follows the basic logic of cybernetics; that is, the information acquired based on the perception system reveals the difference between the effect and standard, and corrective measures are taken to stabilize the system in the predetermined target state through cyclic feedback. Perception and intervention are the two core links[129]. However, a smart society is a complex open system. Due to complex connections and interactions among social elements, the change of each variable will lead to a series of chain reactions. In addition, the randomness and freedom of the crowd behavior lead to the weak perception and intervention ability of the smart society at the macro level.

From the perspective of CPS or degree of control, a society can be decomposed into three systems: natural ecological environment, AI-built environment, and crowd behavior[12, 13]. However, people still cannot fully understand and explain, let alone intervene, the natural ecological environment. Researchers mainly focus on understanding the laws of pollutant production and transmission and the discovery and tracing of sudden man-made environmental pollution events. An AI-built environment consists of all kinds of engineering infrastructure and buildings, landscapes, streets, and other surface- and underground-built environments. In theory, this is a completely controllable system. Although the above two systems (ecological environment system, with strong perception and weak intervention; AI-built environment, with strong perception and strong intervention) are closely related to human activities, human behavior often determines only the input variables of the system. Another kind of system is centered on human needs and behaviors (human behavior, with strong perception and medium intervention), including education, medical care, retail, tourism, and government affairs. At present, the vast majority of smart city construction projects are concentrated in this field.

In terms of smart societies with crowd intelligence, the operation of a service ecosystem is not a simple collection and integration of data, but it will be the basic operation logic of future cities. The impact of the service ecosystem at the macro level is mainly embodied in whether it can improve the level of social governance and whether its intervention can balance the contradiction between top-down planning and bottom-up emergence. In terms of data privacy and profit model, the implementation of the service ecosystem needs to coordinate the interests of the government, enterprises, and citizens. As the advocates and most direct beneficiaries of technology, enterprises are always motivated to promote its implementation. The government's duty requires it to defend the boundary of social equity and public interest through policies and regulations. Public demands are relatively diverse. Therefore, although the top-down top-level design is important, bottom-up market-oriented innovation and extensive public participation are also indispensable.

According to the requirements of the Law of Requisite

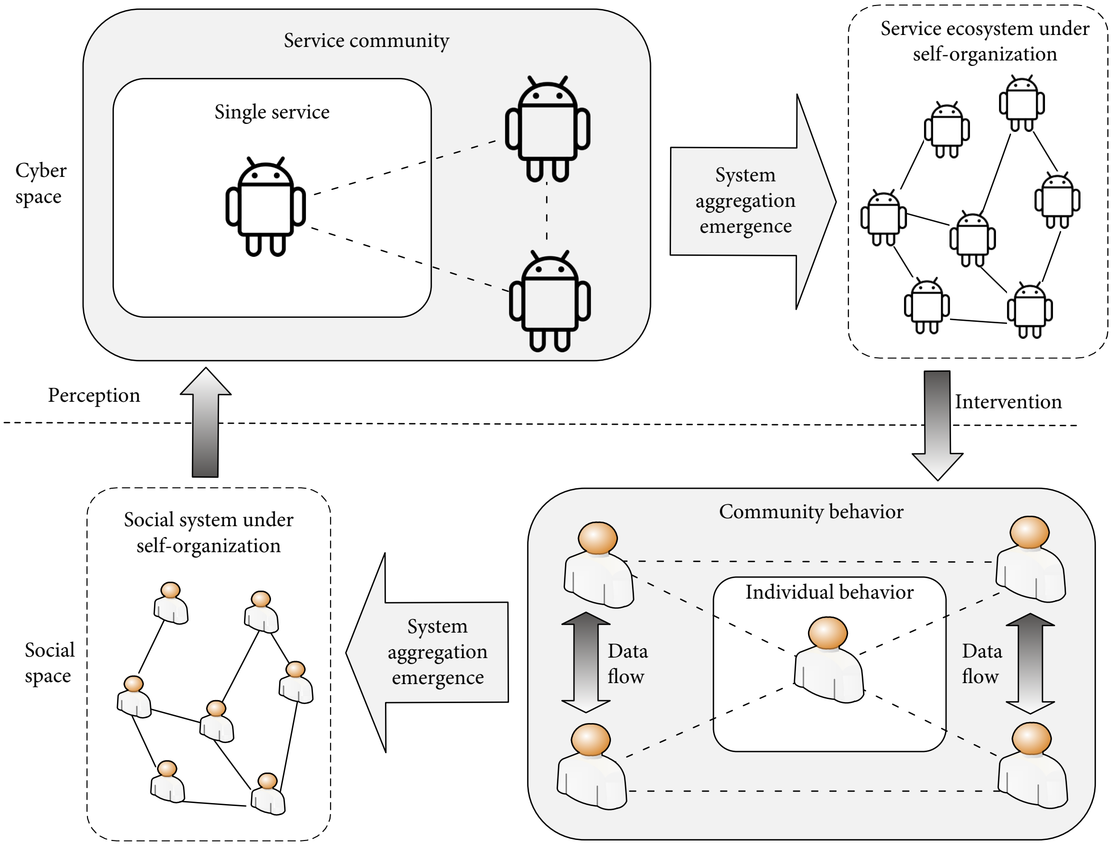


**Fig. 14 Loop feedback of the service ecosystem.**

Variety[157], to ensure effectiveness, the service ecosystem must be as "complex" enough as the environment so that the system can make appropriate responses to the interactions in the environment. If the environment has 100 different behaviors that need responses and a system can make different responses to these different behaviors, the system is effective. However, if the system has only ten possible behaviors, the system is not effective for the environment. However, due to complexity, such a system cannot be established. Therefore, we need to define the boundaries of the service ecosystem. What we really need is not to accurately predict the behavior of each individual or even society but to make correct decisions. That is, even if unpredictable, wise decisions can still be made.

To ensure the effectiveness, the service ecosystem must match the complexity of the environment at all behavioral interaction scales. For a service ecosystem, to increase its complexity on a large scale, the complexity of its constituent individuals should be reduced. For example, if the services in the service ecosystem only have collaboration without competition, then the entire system can run efficiently. However, an efficient and large-scale service ecosystem is built at the expense of low-scale complexity. In the end, such a service ecosystem will lack adaptability in the face of the new situation of the changeable environment. The impact of the service ecosystem on the social governance ability lies not in data collection and processing ability but in how to balance the intervention scale and complexity of intervention objects. Therefore, the governance of a smart society with crowd intelligence needs to focus on where the boundaries of the service ecosystem are, that is, how to make rules on a reasonable scale, rather than interfering with the autonomous behavior of each service.

## 5 Outlook

Undeniably, our society is fully affected, transformed, and shaped by ubiquitous, interconnected, and personalized services. We can make reasonable and limited interventions only by capturing the evolutionary laws and expansion boundaries of smart services in human society. In this setting, we need a new interdisciplinary research field: the service ecosystem. For the smooth development of this discipline, the following issues should be given special attention.

First, the service ecosystem involves a dynamic evolution, with novel services continuously emerging. These novel technological species will affect the current operating mode of society in various ways. As the diagram of the smart society has crowd intelligence, the service ecosystem needs to identify and predict the impact of various new smart services on existing social systems so that our understanding of the smart society can keep pace with the times.

Second, most scientists put emphasis just on technical aspects of smart services, leaving apart social elements involved in it. Due to the huge differences in social systems and local cultures, the performance of smart services greatly varies in different environments. Therefore, researchers should pay more attention to the influence of localization characteristics on the evolution of the service ecosystem. The perfect working process might lie somewhere between local characteristics and general regulations.

Third, in the construction of smart services, a low level of investment will be insufficient, but a high level of investment may get its own benefit impaired a lot when it considerably improves users' utility. Therefore, a critical research issue of the service ecosystem is how to find a delicate balance between social affordability and expected benefits. Regardless of how ambitious the target is, it should follow the principle of gradual improvement to prevent the ratio of returns to costs from continuously decreasing.

Fourth, it is too early to tell whether the positive changes wrought by smart services will outweigh the perils. The essence of evolution is to constantly produce random "errors" in response to unforeseen situations. The elimination of uncertainties by smart services will enable the entire society to achieve great developments in a short period of time, but it may be at the expense of future changes and innovation capabilities. Therefore, the research on service ecosystems should pay more attention to how to implement the interventions of appropriate scales to avoid overkill.

Fifth, the research on service ecosystems always requires mapping relationships between the physical space and virtual space to be accurate, comprehensive, and dynamic. Even the trajectory of entity objects should also be included in the research. Because these "social laboratories" may bring privacy violations, ethical considerations should be under strict supervision.

Finally, the exploration of this discipline will require joint efforts from related disciplines because these studies are accompanied by challenges brought about by interdisciplinary cooperation. Hence, it is essential to meet these challenges. Universities, governments, and funding agencies should play an important role in developing large-scale, equal, and credible interdisciplinary research.

To summarize, smart services are promoting refined social governance to an unprecedented level, which can facilitate our life significantly and improve the utilization of social resources to a large extent. Studying service ecosystems can support us in examining technological and environmental sustainability dimensions jointly with the social justice perspective.

## Acknowledgment

This work was supported in part by the National Key Research and Development Program of China (No. 2021YFF0900800), the National Natural Science Foundation of China (Nos. 61972276, 61832014, and 62032016), Open Research Fund of The State Key Laboratory for Management and Control of Complex Systems (No. 20210101)， New Liberal Arts Reform and Practice Project of National Ministry of Education (No. 2021170002), and Shandong Key Laboratory of Intelligent Buildings Technology (No. SDIBT202001).

## Dates

Received: 6 April 2022; Revised: 23 June 2022; Accepted: 27 June 2022

## References

[1] N. McKeown, Software-defined networking, *INFOCOM Keynote Talk*, vol. 17, no. 2, pp. 30–32, 2009.

[2] B. Lantz, B. Heller, and N. McKeown, A network in a laptop: Rapid prototyping for software-defined networks, in *Proc. 9th ACM SIGCOMM Workshop Hot Topics in Networks*, Monterey, CA, USA, 2010, pp. 1–6.

[3] H. Mei, Understanding "software-defined" from an OS perspective: Technical challenges and research issues, *Sci. China Inf. Sci.*, vol. 60, no. 12, pp. 271–273, 2017.

[4] I. Foster, Service-oriented science, *Science*, vol. 308, no. 5723, pp. 814–817, 2005.

[5] M. P. Papazoglou, P. Traverso, S. Dustdar, and F. Leymann, Service-oriented computing: A research roadmap, *Int. J. Coop. Inf. Syst.*, vol. 17, no. 2, pp. 223–255, 2008.

[6] D. Bhamare, R. Jain, M. Samaka, and A. Erbad, A survey on service function chaining, *J. Netw. Comput. Appl.*, vol. 75, pp. 138–155, 2016.

[7] J. H. Lee, R. Phaal, and S. H. Lee, An integrated service-device-technology roadmap for smart city development, *Technol. Forecast. Soc. Chang.*, vol. 80, no. 2, pp. 286–306, 2013.

[8] C. Villalba and F. Zambonelli, Towards nature-inspired pervasive service ecosystems: Concepts and simulation experiences, *J. Netw. Comput. Appl.*, vol. 34, no. 2, pp. 589–602, 2011.

[9] M. Weiser, Ubiquitous computing, *Computer*, vol. 26, no. 10, pp. 71–72, 1993.

[10] G. Bell and P. Dourish, Yesterday's tomorrows: Notes on ubiquitous computing's dominant vision, *Pers. Ubiquitous Comput.*, vol. 11, no. 2, pp. 133–143, 2007.

[11] F. -Y. Wang, The emergence of intelligent enterprises: From CPS to CPSS, *IEEE Intell. Syst.*, vol. 25, no. 4, pp. 85–88, 2010.

[12] Y. Zhou, F. R. Yu, J. Chen, and Y. Kuo, Cyber-physical-social systems: A state-of-the-srt survey, challenges and opportunities, *IEEE Commun. Surveys Tuts.*, vol. 22, no. 1, pp. 389–425, 2019.

[13] X. Xue, Y. -D. Guo, S. -Z. Chen, and S. -F. Wang, Analysis and controlling of manufacturing service ecosystem: A research framework based on the parallel system theory, *IEEE Trans. Serv. Comput.*, doi: 10.1109/TSC.2019.2917445.

[14] K. Manikas and K. M. Hansen, Software ecosystems–a systematic literature review, *J. Syst. Softw.*, vol. 86, no. 5, pp. 1294–1306, 2013.

[15] A. Corallo, G. Passiante, and A. Prencipe, *The Digital Business Ecosystem*. Northampton, MA, USA: Edward Elgar Publishing, 2007.

[16] A. Abellá-García, M. O. De-Urbina-Criado, and C. De-Pablos-Heredero, The ecosystem of services around smart cities: An exploratory analysis, *Procedia Comput. Sci.*, vol. 64, pp. 1075–1080, 2015.

[17] M. Ford, *Rise of the Robots: Technology and the Threat of a Jobless Future*. New York, NY, USA: Basic Books, 2015.

[18] A. Paulin, Technological ecosystems' role in preventing neo-feudalism in smart-city informatization, in *Proc. 25th Int. Conf. Companion on World Wide Web* (*WWW*), Montreal, Canada, 2016, pp. 333–337.

[19] J. Thornhill, The big data revolution can revive the planned economy, *Financial Times*, https://www.ft.com/content/6250e4ec-8e68-11e7-9084-d0c17942ba93, 2017.

[20] J. F. Moore, Predators and prey: A new ecology of competition, *Harv. Bus. Rev.*, vol. 71, no. 3, pp. 75–86, 1999.

[21] S. L. Vargo and R. F. Lusch, Evolving to a new dominant logic for marketing, *J. Mark.*, vol. 68, no. 1, pp. 1–17, 2004.

[22] S. L. Vargo and R. F. Lusch, Service-dominant logic: Continuing the evolution, *J. Acad. Mark. Sci.*, vol. 36, no. 2, pp. 1–10, 2008.

[23] D. G. Messerschmitt and C. Szyperski, *Software Ecosystem: Understanding an Indispensable Technology and Industry*. Cambridge, MA, USA: MIT Press Books, 2003.

[24] M. Peltoniemi and E. Vuori, Business ecosystem as the new approach to complex adaptive business environments, presented at Frontiers of e-Business Research 2004 (FeBR 2004), Tampere, Finland, 2004.

[25] M. Fowler, and J. Lewis, Microservices, http://martinfowler.com/articles/microservices. html, 2014.

[26] S. L. Vargo, P. P. Maglio, and M. A. Akaka, On value and value co-creation: A service systems and service logic perspective, *Eur. Manag. J.*, vol. 26, no. 3, pp. 145–152, 2008.

[27] J. M. Smith, *Evolution and the Theory of Games*. Cambridge, UK: Cambridge University Press, 1982.

[28] M. T. Hannan and J. Freeman, The population ecology of organizations, *Am. J. Sociol.*, vol. 82, no. 5, pp. 929–964, 1977.

[29] S. L. Vargo and R. F. Lusch, Institutions and axioms: An extension and update of service-dominant logic, *J. Acad. Mark. Sci.*, vol. 44, no. 1, pp. 5–23, 2016.

[30] M. A. Akaka, S. L. Vargo, and R. F. Lusch, The complexity of context: A service ecosystems approach for international marketing, *J. Int. Market.*, vol. 21, no. 4, pp. 1–20, 2013.

[31] M. M. Mars, J. L. Bronstein, and R. F. Lusch, The value of a

metaphor: Organizations and ecosystems, *Organ. Dyn.*, vol. 41, no. 4, pp. 271–280, 2012.

[32] M. Kenney and J. Zysman, The rise of the platform economy, *Issues Sci. Technol.*, vol. 32, no. 3, pp. 61–69, 2016.

[33] K. Kim and J. Altmann, Platform provider roles in innovation in software service ecosystems, *IEEE Trans. Eng. Manage.*, vol. 69, no. 4, pp. 930–939, 2020.

[34] R. W. Schulte and Y. V. Natis, SSA research note SPA-401-068, Service oriented architectures, Part 1 & 2, Technical report, The Gartner Group, Stamford, CT, USA,1996.

[35] R. Perrey and M. Lycett, Service-oriented architecture, in *Proc. 2003 Symp. Appl. Internet Workshops* (*SAINTW*), Orlando, FL, USA, 2003, pp. 116–119.

[36] C. M. MacKenzie, K. Laskey, F. McCabe, P. F. Brown, R. Metz, and B. A. Hamilton, Reference model for service oriented architecture 1.0, *OASIS Standard*, vol. 12, no. S18, pp. 1–31, 2006.

[37] K. Manikas, Revisiting software ecosystems research: A longitudinal literature study, *J. Syst. Softw.*, vol. 117, pp. 84–103, 2016.

[38] J. Yin, B. Zheng, S. Deng, Y. Wen, M. Xi, Z. Luo, and Y. Li, Crossover service: Deep convergence for pattern, ecosystem, environment, quality and value, in *Proc. 2018 IEEE 38th Int. Conf. Distrib. Comput. Syst.* (*ICDCS*), Vienna, Austria, 2018, pp. 1250–1257.

[39] Z. Wu, J. Yin, S. Deng, J. Wu, Y. Li, and L. Chen, Modern service industry and crossover services: Development and trends in China, *IEEE Trans. Serv. Comput.*, vol. 9, no. 5, pp. 664–671, 2016.

[40] X. Xu, Q. Z. Sheng, L. -J. Zhang, Y. Fan, and S. Dustdar, From big data to big service, *Computer*, vol. 48, no. 7, pp. 80–83, 2015.

[41] X. Xu, G. Motta, Z. Tu, H. Xu, Z. Wang, and X. Wang, A new paradigm of software service engineering in big data and big service era, *Computing*, vol. 100, no. 4, pp. 353–368, 2018.

[42] S. -Z. Chen, Z. -Y. Feng, and H. Wang, Service relations and its application in services-oriented computing, *Chin. J. Comput.*, vol. 33, no. 11, pp. 2068–2083, 2010.

[43] S. Vandermerwe and J. Rada, Servitization of business: Adding value by adding services, *Eur. Manag. J.*, vol. 6, no. 4, pp. 314–324, 1988.

[44] F. Tao, L. Zhang, V. C. Venkatesh, Y. Luo, and Y. Cheng, Cloud manufacturing: A computing and service-oriented manufacturing model, *Proc. Inst. Mech. Eng. Part B: J. Eng. Manuf.*, vol. 225, no. 10, pp. 1969–1976, 2011.

[45] A. Zimmermann, M. Pretz, G. Zimmermann, D. G. Firesmith, I. Petrov, and E. El-Sheikh, Towards service-oriented enterprise architectures for big data applications in the cloud, in *Proc. 2013 17th IEEE Int. Enterp. Distrib. Object Comput. Conf. Workshops* (*EDOC*), Vancouver, Canada, 2013, pp. 130–135.

[46] M. R. Rasouli, An architecture for IoT-enabled intelligent process-aware cloud production platform: A case study in a networked cloud clinical laboratory, *Int. J. Prod. Res.*, vol. 58, no. 12, pp. 3765–3780, 2020.

[47] H. Bouzary and F. F. Chen, Service optimal selection and composition in cloud manufacturing: A comprehensive survey, *Int. J. Adv. Manuf. Technol.*, vol. 97, pp. 795–808, 2018.

[48] L. Zhang, H. Guo, F. Tao, Y. Luo, and N. Si, Flexible management of resource service composition in cloud manufacturing, in *Proc. 2010 IEEE Int. Conf. Ind. Eng. Eng. Manage.* (*IEEM*), Macao, China, 2010, pp. 2278–2282.

[49] X. Xiao, S. Wang, L. Zhang, and C. Qin, Complexity analysis of manufacturing service ecosystem: A mapping-based computational experiment approach, *Int. J. Prod. Res.*, vol. 57, no. 2, pp. 357–378, 2019.

[50] A. Treadgold and J. Reynolds, *Navigating the New Retail Landscape: A Guide for Business Leaders*. Oxford, UK: Oxford University Press, 2016.

[51] X. Xue, J. -J. Gao, S. Wu, S. -F. Wang, and Z. -Y. Feng, Value based analysis framework of crossover service: A case study of new retailer in China, *IEEE Trans. Serv. Comput.*, vol. 15, no. 1, pp. 83–96, 2019.

[52] S. Guo, C. Xu, X. Xue, Z. -Y. Feng, and S. -Z Chen, Research on trans-boundary convergence of different service chains in health service ecosystem, *J. Med. Imaging Health Inform.*, vol. 10, no. 7, pp. 1734–1745, 2020.

[53] Y. -F. Huang, P. Liu, Q. Pan, and J. -S. Lin, A doctor recommendation algorithm based on doctor performances and patient preferences, in *Proc. 2012 Int. Conf. Wavelet Active Media Technol. Inf. Process.* (*ICWAMTIP*), Chengdu, China, 2012, pp. 92–95.

[54] H. Jiang and W. Xu, How to find your appropriate doctor: An integrated recommendation framework in big data context, in *Proc. 2014 IEEE Symp. Comput. Intell. Healthc. e-Health* (*CICARE*), Orlando, FL, USA, 2014, pp. 154–158.

[55] C. W. Phang, C. -H. Tan, J. Sutanto, F. Magagna, and X. Lu, Leveraging O2O commerce for product promotion: An empirical investigation in mainland China, *IEEE Trans. Eng. Manage.*, vol. 61, no. 4, pp. 623–632, 2014.

[56] X. Xue, G. Gao, S. -F. Wang, and Z. -Y. Feng, Service bridge: Transboundary impact evaluation method of internet, *IEEE Trans. Computat. Soc. Syst.*, vol. 5, no. 3, pp. 758–772, 2018.

[57] C. -J. Lin, T. -T. Lee, C. Lin, Y. -C. Huang, and J. -M. Chiu, Establishing interaction specifications for online-to-offline (O2O) service systems, in *Proc. Inst. Ind. Eng. Asian Conf.*, Taipei, China, 2013, pp. 1137–1145.

[58] G. Lawton, Developing software online with platform-as-a-service technology, *Computer*, vol. 41, no. 6, pp. 13–15, 2008.

[59] S. Bhardwaj, L. Jain, and S. Jain, Cloud computing: A study of infrastructure as a service (IAAS), *Int. J. Inf. Technol. Web Eng.*, vol. 2, no. 1, pp. 60–63, 2010.

[60] M. Turner, D. Budgen, and P. Brereton, Turning software into a service, *Computer*, vol. 36, no. 10, pp. 38–44, 2003.

[61] S. Wu, S. Shen, X. Xu, Y. Chen, X. Zhou, D. Liu, X. Xue, and L. Qi, Popularity-aware and diverse web APIs recommendation based on correlation graph, *IEEE Trans. Comput. Soc. Syst.*, doi: 10.1109/TCSS.2022.3168595.

[62] L. Qi, W. Lin, X. Zhang, W. Dou, X. Xu, and J. Chen, A correlation graph based approach for personalized and compatible web APIs recommendation in mobile APP development, *IEEE Trans. Knowl. Data Eng.*, doi: 10.1109/TKDE.2022.3168611.

[63] H. Wang, X. Chi, Z. Wang, X. Xu, and S. Chen, Extracting fine-grained service value features and distributions for accurate service recommendation, in *Proc. 2017 IEEE Int. Conf. Web Serv.* (*ICWS*), Honolulu, HI, USA, 2017, pp. 277–284.

[64] M. Qian, Z. Liu, L. Yao, and W. Zhang, A coordination-theory driven approach for manufacturing Web services composition process, in *Proc. 2018 IEEE Int. Conf. Ind. Eng. Eng. Manage.* (*IEEM*), Singapore, 2008, pp. 2071–2076.

[65] D. Peidro, J. Mula, R. Poler, and F. -C. Lario, Quantitative models for supply chain planning under uncertainty: A review, *Int. J. Adv. Manuf. Technol.*, vol. 43, nos.3&4, pp. 400–420, 2009.

[66] W. Shen, Q. Hao, H. J. Yoon, and D. H. Norrie, Applications of agent-based systems in intelligent manufacturing: An updated review, *Adv. Eng. Inform.*, vol. 20, no. 4, pp. 415–431, 2006.

[67] P. Wohlleben, *The Secret Network of Nature: The Delicate Balance of All Living Things*. London, UK: Vintage Digital, 2018.

[68] F. S. Chapin III, M. S. Torn, and M. Tateno, Principles of ecosystem sustainability, *Am. Nat.*, vol. 148, no. 6, pp. 1016–1037, 1996.

[69] E. Handoyo, S. Jansen, and S. Brinkkemper, Software ecosystem modeling: The value chains, in *Proc. Fifth Int. Conf. Manage. Emergent Digit. EcoSyst.* (*MEDES*), Luxembourg, Luxembourg, 2013, pp. 17–24.

[70] M. H. Sadi, J. Dai, and E. Yu, Designing software ecosystems: How to develop sustainable collaborations? in *Proc. Int. Conf. Adv. Inform. Syst. Eng.* (*ICAIS*), Stockholm, Sweden, 2015, pp. 161–173.

[71] W. Vorraber, M. Mueller, S. Voessner, and W. Slany, Analyzing and managing complex software ecosystems: A framework to understand value in information systems, *IEEE Software*, vol. 36, no. 3, pp. 55–60, 2018.

[72] M. Valverde and A. Flynn, More buzzwords than answers—To

sidewalk labs in Toronto, *Landsc. Archit. Front.*, vol. 6, no. 2, pp. 115–123, 2018.

[73] I. Argyriou, Planning the smart city in China: Key policy issues and the case of dream town in the city of Hangzhou, in *Proc. 25th Int. Conf. Comp. World Wide Web* (*WWW*), Montreal, Canada, 2016, pp. 339–343.

[74] P. Frow, J. R. McColl-Kennedy, T. Hilton, A. Davidson, A. Payne, and D. Brozovic, Value propositions: A service ecosystems perspective, *Mark. Theory*, vol. 14, no. 3, pp. 327–351, 2014.

[75] Y. Zheng, L. Capra, O. Wolfson, and H. Yang, Urban computing: Concepts, methodologies, and applications, *ACM Trans. Intell. Syst. Technol.*, vol. 5, no. 3, pp. 1–55, 2014.

[76] H. Habibzadeh, C. Kaptan, T. Soyata, B. Kantarci, and A. Boukerche, Smart city system design: A comprehensive study of the application and data planes, *ACM Comput. Surv.*, vol. 52, no. 2, pp. 1–38, 2019.

[77] T. Shinbrot, C. Grebogi, J. A. Yorke, and E. Ott, Using small perturbations to control chaos, *Nature*, vol. 363, no. 6428, pp. 411–417, 1993.

[78] X. Xue, S. Huangfu, L. Zhang, and S. Wang, Research on escaping the big-data traps in O2O service recommendation strategy, *IEEE Trans. Big Data*, vol. 7, no. 1, pp. 199–213, 2019.

[79] D. Lazer, R. Kennedy, G. King, and A. Vespignani, Big data. The parable of Google flu: Traps in big data analysis, *Science*, vol. 343, no. 6176, pp. 1203–1205, 2014.

[80] I. Prigogine and I. Stengers, *The End of Certainty*. New York, NY, USA: Free Press, 1997.

[81] D. Nikolov, D. F. M. Oliveira, A. Flammini, and F. Menczer, Measuring online social bubbles, *PeerJ Comput. Sci.*, vol. 1, p. e38, 2015.

[82] S. Flaxman, S. Goel, and J. M. Rao, Filter bubbles, echo chambers, and online news consumption, *Public Opin. Q.*, vol. 80, no. S1, pp. 298–320, 2016.

[83] S. Hajian, F. Bonchi, and C. Castillo, Algorithmic bias: From discrimination discovery to fairness-aware data mining, in *Proc. 22nd ACM SIGKDD Int. Conf. Knowl. Discov. Data Min.*, San Francisco, CA, USA, 2016, pp. 2125–2126.

[84] D. Danks and A. J. London, Algorithmic bias in autonomous systems, in *Proc. 26th Int. Joint Conf. Artif. Intell.* (*IJCAI*), Melbourne, Australia, 2017, pp. 4691–4697.

[85] R. Li, L. Dong, J. Zhang, X. Wang, W. -X. Wang, Z. Di, and H. E. Stanley, Simple spatial scaling rules behind complex cities, *Nat. Commun.*, vol. 8, no. 1, p. 1841, 2017.

[86] N. F. Johnson, R. Leahy, N. J. Restrepo, N. Velasquez, M. Zheng, P. Manrique, P. Devkota, and S. Wuchty, Hidden resilience and adaptive dynamics of the global online hate ecology, *Nature*, vol. 573, no. 7773, pp. 261–265, 2019.

[87] P. Kristensen, The DPSIR framework, *Natl. Environ. Res. Inst.*, vol. 10, pp. 1–10, 2004.

[88] E. Schrödinger, *What is Life?: With Mind and Matter and Autobiographical Sketches*. Cambridge, UK: Cambridge University Press, 1992.

[89] P. Skålén, J. Gummerus, C. V. Koskull, and P. R. Magnusson, Exploring value propositions and service innovation: A service-dominant logic study, *J. Acad. Mark. Sci.*, vol. 43, no. 2, pp. 137–158, 2015.

[90] M. A. Akaka and S. L. Vargo, Technology as an operant resource in service (eco)systems, *Inf. Syst. E-Bus. Manag.*, vol. 12, no. 3, pp. 367–384, 2014.

[91] J. Yuan, Y. Zheng, X. Xie, and G. Sun, Driving with knowledge from the physical world, in *Proc. 17th ACM SIGKDD Int. Conf. Knowl. Discov. Data Min.*, San Diego, CA, USA, 2011, pp. 316–324.

[92] M. Balabanović and Y. Shoham, Fab: Content-based, collaborative recommendation, *Commun. ACM*, vol. 40, no. 3, pp. 66–72, 1997.

[93] M. J. Pazzani and D. Billsus, Content-based recommendation systems, in *The Adaptive Web: Methods and Strategies of Web Personalization*, P. Brusilovsky, A. Kobsa, and W. Nejdl, eds. Berlin, Germany: Springer-Verlag, 2007, pp. 325–341.

[94] B. Sarwar, G. Karypis, J. Konstan, and J. Riedl, Item-based collaborative filtering recommendation algorithms, in *Proc. 10th Int. Conf. World Wide Web* (*WWW*), Hong Kong, China, 2001, pp. 285–295.

[95] G. Cachon and C. Terwiesch, *Matching Supply with Demand*. New York, NY, USA: McGraw-Hill Publishing, 2008.

[96] D. Renzel, M. Behrendt, R. Klamma, and M. Jarke, Requirements bazaar: Social requirements engineering for community-driven innovation, in *Proc. 2013 21st IEEE Int. Requir. Eng. Conf.* (*RE*), Rio de Janeiro, Brazil, 2013, pp. 326–327.

[97] Y. Cheng, F. Tao, L. Zhang, and Y. Zuo, Supply-demand matching of manufacturing service in service-oriented manufacturing systems, *Comput. Integr. Manuf. Syst.*, vol. 21, no. 7, pp. 1930–1940, 2015.

[98] N. Nag and R. Jain, A navigational approach to health: Actionable guidance for improved quality of life, *Computer*, vol. 52, no. 4, pp. 12–20, 2019.

[99] J. Zhao, J. Wu, X. Feng, H. Xiong, and K. Xu, Information propagation in online social networks: A tie-strength perspective, *Knowl. Inf. Syst.*, vol. 32, no. 3, pp. 589–608, 2012.

[100] F. Hacklin and M. W. Wallin, Convergence and interdisciplinarity in innovation management: A review, critique, and future directions, *Serv. Ind. J.*, vol. 33, nos.7&8, pp. 774–788, 2013.

[101] J. Peppard and A. Rylander, From value chain to value network: Insights for mobile operators, *Eur. Manag. J.*, vol. 24, nos. 2&3, pp. 128–141, 2006.

[102] L. Liu, M. Shen, and C. Li, The extension of the application domain of value engineering is a challenge to the theory and method system of value engineering, *J. Beijing Inst. Mach.*, vol. 21, no. 1, pp. 60–63, 2006.

[103] C. Alves, J. A. P. D. Oliveira, and S. Jansen, Software ecosystems governance: A systematic literature review and research agenda, in *Proc. 19th Int. Conf. Enterp. Inf. Syst.* (*ICEIS*), Porto, Portugal, 2017, pp. 215–226.

[104] N. Haile and J. Altmann, Value creation in IT service platforms through two-sided network effects, in *Proc. 9th Int. Conf. Econ. Grids, Cloud. Syst. Serv.* (*GECON*), Berlin, Germany, 2012, pp. 139–153.

[105] K. Touliou and E. Bekiaris, Building an inclusive ecosystem for developers and users: The role of value propositions, in *Advances in Ergonomics Modeling, Usability & Special Populations*, M. Soares, C. Falcão, and T. Z. Ahram, eds. Cham, Switzerland: Springer, 2017, pp. 339–346.

[106] N. Haile and J. Altmann, Structural analysis of value creation in software service platforms, *Electron. Mark.*, vol. 26, no. 2, pp. 129–142, 2016.

[107] S. Panda, N. M. Modak, M. Basu, and S. K. Goyal, Channel coordination and profit distribution in a social responsible three-layer supply chain, *Int. J. Prod. Econ.*, vol. 168, pp. 224–233, 2015.

[108] V. Pant and E. Yu, Modeling strategic complementarity and synergistic value creation in competitive relationships, in *Proc. 8th Int. Conf. Softw. Bus.* (*ICSOB*), Essen, Germany, 2017, pp. 82–98.

[109] P. Cong, L. Li, J. Zhou, K. Cao, T. Wei, M. Chen, and S. Hu, Developing user perceived value based pricing models for cloud markets, *IEEE Trans. Parallel Distrib. Syst.*, vol. 29, no. 12, pp. 2742–2756, 2018.

[110] Y. Duan, K. Huang, A. Kattepur, and W. Du, Towards value-driven business modelling based on service brokerage, in *Proc. Int. Conf. Service-Oriented Comput.*, Berlin, Germany, 2013, pp. 163–176.

[111] H. Kil, S. -C. Oh, E. Elmacioglu, W. Nam, and D. Lee, Graph theoretic topological analysis of web service networks, *World Wide Web*, vol. 12, no. 3, pp. 321–343, 2009.

[112] K. Huang, Y. Fan, and W. Tan, An empirical study of programmable web: A network analysis on a service-mashup system, in *Proc. 2012 IEEE 19th Int. Conf. Web Serv.* (*ICWS*), Honolulu, HI, USA, 2012, pp. 552–559.

[113] R. S. Burt, *Structural Holes: The Social Structure of Competition*. Cambridge, MA, USA: Harvard University Press, 1995.

[114] B. Bai, Y. Fan, W. Tan, and J. Zhang, SR-LDA: Mining effective representations for generating service ecosystem knowledge maps,

in *Proc. 2017 IEEE Int. Conf. Serv. Comput.* (*SCC*), Honolulu, HI, USA, 2017, pp. 124–131.

[115] W. Tan, J. Zhang, R. Madduri, I. Foster, D. D. Roure, and C. Goble, ServiceMap: Providing map and GPS assistance to service composition in bioinformatics, in *Proc. 2011 IEEE Int. Conf. Serv. Comput.* (*SCC*), Washington, DC, USA, 2011, pp. 632–639.

[116] D. Achlioptas, R. M. D'Souza, and J. Spencer, Explosive percolation in random networks, *Science*, vol. 323, no. 5920, pp. 1453–1455, 2009.

[117] T. Bohman, Emergence of connectivity in networks, *Science*, vol. 323, no. 5920, pp. 1438–1439, 2009.

[118] X. Xue, Z. Chen, S. Wang, Z. Feng, Y. Duan, and Z. Zhou, Value entropy: A systematic evaluation model of service ecosystem evolution, *IEEE Trans. Serv. Comput.*, doi: 10.1109/TSC.2020. 3016660.

[119] J. A. Schumpeter and U. Backhaus, *The Theory of Economic Development*, J. A. Schumpeter, ed. Boston, MA, USA: Springer, 2003, pp. 61–116.

[120] B. Angelova and J. Zekiri, Measuring customer satisfaction with service quality using American customer satisfaction model (ACSI model), *Int. J. Acad. Res. Bus. Soc. Sci.*, vol. 1, no. 3, pp. 232–258, 2011.

[121] P. Belleflamme and M. Peitz, Platform competition and seller investment incentives, *Eur. Econ. Rev.*, vol. 54, no. 8, pp. 1059–1076, 2010.

[122] J. -C. Rochet and J. Tirole, Cooperation among competitors: Some economics of payment card associations, *Rand J. Econ.*, vol. 33, no. 4, pp. 549–570, 2002.

[123] R. Berk, *Machine Learning Risk Assessments in Criminal Justice Settings*. Cham, Switzerland: Springer, 2019.

[124] H. E. Brady, Models of causal inference: Going beyond the Neyman-Rubin-Holland theory, presented at 2003 Midwest Political Science Association Annual Meeting, Chicago, IL, USA, 2003.

[125] G. Sugihara, R. May, H. Ye, C. Hsieh, E. Deyle, M. Fogarty, and S. Munch, Detecting causality in complex ecosystems, *Science*, vol. 338, no. 6106, pp. 496–500, 2012.

[126] P. Dowe, A counterfactual theory of prevention and 'causation' by omission, *Australas. J. Philos.*, vol. 79, no. 2, pp. 216–226, 2001.

[127] D. Gasking, Causation and recipes, *Mind*, vol. 64, no. 256, pp. 479–487, 1955.

[128] H. Zenil, N. A. Kiani, A. A. Zea, and J. Tegnér, Causal deconvolution by algorithmic generative models, *Nat. Mach. Intell.*, vol. 1, no. 1, pp. 58–66, 2019.

[129] Z. Shen, W. -X. Wang, Y. Fan, Z. Di, and Y. -C. Lai, Reconstructing propagation networks with natural diversity and identifying hidden sources, *Nat. Commun.*, vol. 5, no. 1, pp. 1–7, 2014.

[130] J. Ginsberg, M. H. Mohebbi, R. S. Patel, L. Brammer, M. S. Smolinski, and L. Brilliant, Detecting influenza epidemics using search engine query data, *Nature*, vol. 457, no. 7232, pp. 1012–1014, 2008.

[131] N. J. Yuan, Y. Zheng, L. Zhang, X. Xie, and G. Sun, Where to find my next passenger, in *Proc. 13th Int. Conf. Ubiquitous Comput.* (*UBIC*), Beijing, China, 2011, pp. 109–118.

[132] N. J. Yuan, Y. Zheng, L. Zhang, and X. Xie, T-finder: A recommender system for finding passengers and vacant taxis, *IEEE Trans. Knowl. Data Eng.*, vol. 25, no. 10, pp. 2390–2403, 2012.

[133] R. S. Sutton and A. G. Barto, *Reinforcement Learning: An Introduction*. Cambridge, MA, USA: MIT press, 2018.

[134] M. L. Littman, Markov games as a framework for multi-agent reinforcement learning, in *Proc. 11th Int. Conf. Mach. Learn.*, New Brunswick, NJ, USA, 1994, pp. 157–163.

[135] A. Ghose, P. G. Ipeirotis, and B. Li, Examining the impact of ranking on consumer behavior and search engine revenue, *Manage. Sci.*, vol. 60, no. 7, pp. 1632–1654, 2014.

[136] P. Kollock, Social dilemmas: The anatomy of cooperation, *Annu. Rev. Sociol.*, vol. 24, no. 1, pp. 183–214, 1998.

[137] D. Heckerman, D. Geiger, and D. M. Chickering, Learning Bayesian networks: The combination of knowledge and statistical data, *Mach. Learn.*, vol. 20, no. 3, pp. 197–243, 1995.

[138] N. L. Zhang and D. Poole, Exploiting causal independence in Bayesian network inference, *J. Artif. Intell. Res.*, vol. 5, pp. 301–328, 1996.

[139] S. Davey, N. Gordon, I. Holland, M. Rutten, and J. Williams, Bayesian methods in the search for MH370, doi: 10.1007/978-981-10-0379-0.

[140] J. F. Moore, The death of competition, *Fortune*, vol. 133, no. 7, pp. 90–92, 1996.

[141] J. Korhonen, F. V. Malmborg, P. A. Strachan, and J. R. Ehrenfeld, Management and policy aspects of industrial ecology: An emerging research agenda, *IEEE Eng. Manage. Rev.*, vol. 35, no. 3, p. 77, 2007.

[142] R. Fischer, U. Scholten, and S. Scholten, A reference architecture for feedback-based control of service ecosystems, in *Proc. 4th IEEE Int. Conf. Digit. Ecosyst. Technol.* (*DEST*), Dubai, United Arab Emirates, 2010, pp. 1–6.

[143] A. J. Quinn and B. B. Bederson, Human computation: A survey and taxonomy of a growing field, in *Proc. SIGCHI Conf. Hum. Fact. Comput. Syst.*, Vancouver, Canada, 2011, pp. 1403–1412.

[144] P. Michelucci and J. L. Dickinson, The power of crowds, *Science*, vol. 351, no. 6268, pp. 32–33, 2016.

[145] H. Shirado and N. A. Christakis, Locally noisy autonomous agents improve global human coordination in network experiments, *Nature*, vol. 545, no. 7654, pp. 370–374, 2017.

[146] G. Paolacci, J. Chandler, and P. G. Ipeirotis, Running experiments on Amazon mechanical turk, *Judgm. Decis. Mak.*, vol. 5, no. 5, pp. 411–419, 2010.

[147] S. Colbert, The Word –Wikiality, The Colbert report, vol. 31, https://en.wiktionary.org/wiki/wikiality, 2006.

[148] D. Wen, Y. Yuan, and X. -R. Li, Artificial societies, computational experiments, and parallel systems: An investigation on a computational theory for complex socioeconomic systems, *IEEE Trans. Serv. Comput.*, vol. 6, no. 2, pp. 177–185, 2013.

[149] F. -Y. Wang, Toward a paradigm shift in social computing: The ACP approach, *IEEE Intell. Syst.*, vol. 22, no. 5, pp. 65–67, 2007.

[150] F. -Y. Wang, Parallel control and management for intelligent transportation systems: Concepts, architectures, and applications, *IEEE Trans. Intell. Transp. Syst.*, vol. 11, no. 3, pp. 630–638, 2010.

[151] H. Oh and R. Jain, Detecting events of daily living using multimodal data, arXiv preprint arXiv: 1905.09402, 2019.

[152] Z. X. Zhang and Y. Long, Aplication of wearable cameras in studying individual behaviors in built environments, *Landsc. Archit. Front.*, vol. 7, no. 2, pp. 22–37, 2019.

[153] A. Bandura, *Social Learning Theory*. Englewood Cliffs, NJ, USA: Prentice Hall, 1977.

[154] X. Xue, S. Wang, L. Zhang, Z. Feng, and Y. Guo, Social learning evolution (SLE): Computational experiment-based modeling framework of social manufacturing, *IEEE Trans. Ind. Inform.*, vol. 15, no. 6, pp. 3343–3355, 2018.

[155] M. Cheng, Sharing economy: A review and agenda for future research, *Int. J. Hosp. Manag.*, vol. 57, pp. 60–70, 2016.

[156] G. Zervas, D. Proserpio, and J. W. Byers, The rise of the sharing economy: Estimating the impact of Airbnb on the hotel industry, *J. Mark. Res.*, vol. 54, no. 5, pp. 687–705, 2017.

[157] Y. Bar-Yam, From big data to important information, *Complexity*, vol. 21, no. S2, pp. 73–98, 2016.