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Computational Experiments: Virtual Production and Governance Tool for Metaverse

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ABSTRACT

The metaverse, as an extension of the physical world, can be described as a highly immersive digital realm constructed with technologies such as mixed reality and digital modeling. It is rooted in decentralized principles and features novel economic forms, individual identities, and institutional systems. In this architecture, the entire social landscape is redefined under the logic of service, gradually becoming a service ecosystem operated and cooperated by numerous intelligent entities. To achieve sustainable and healthy development of the metaverse ecology, this paper first analyzes the operating logic of the metaverse from the perspective of the fusion of the cyber-physical-social tripartite world and the three typical complexity characteristics faced by it: evolutionary complexity, cognitive complexity, and regulatory complexity. Next, the paper focuses on introducing the idea and technical system of computational experiments as an analysis and governance tool for the metaverse service ecosystem. Then, it explores the integration of computational experiments and metaverse technology, including how computational experiments can be applied to the metaverse and how the metaverse can support computational experiments. Finally, the paper introduces the metaverse applications of computational experiments, covering fields such as industrial design, health care, social governance, and military reform.

KEYWORDS

computational experiments; metaverse; virtual production and governance

Metaverse consists of Meta, which stands for beyond, and Verse, which stands for universe. Together, they usually mean “beyond the universe”. In terms of its external form, the metaverse is a digital world built on top of mixed reality, digital modeling, and other underlying technologies, and the augmented reality sensory experience is one of its external features. However, in terms of its connotation, the metaverse provides a vehicle for integrating different intelligent technologies and is a complex system formed by the interaction and co-evolution of intelligent technologies and social ecology, which may bring much more positive significance than mixed reality technologies:

(1) The metaverse breaks element limitations and creates incremental economic value. The metaverse creates a vibrant new realm beyond the confines of the physical world, circumventing the limitations imposed by finite land and other resource constraints in the real world and propelling robust economic growth. The land, space, and natural resources in the real world are limited and constrained by the endowment of resources and the law of conservation of matter, and the physical world’s economy cannot achieve sustainable growth. However, the resources in the metaverse, including land, facilities, equipment, and tools, exist in a digitized form and have the potential to break the constraints of land and resource supply in the physical world, providing incremental space and resources, bringing new business models, consumer demand, and scene innovation to the real world, and driving sustainable economic growth.

(2) The metaverse reconstructs production relationships and brings new collaboration models. From the perspective of production factors and production relationships, the greater appeal of the metaverse lies in its disruptive transformation of production relationships, which brings a decentralized collaboration paradigm. In the real world, society needs to bear high costs to increase trust, which is controlled by a few centralized institutions. Digital individuals, digital enterprises, and digital government agencies that interact with people, businesses, and government agencies in the real world in real-time are the basic objects of the digital world. The metaverse relies on the underlying technology of blockchain to establish “trust without trust” and Web 3.0 to establish a data exchange paradigm without centralized platforms. Furthermore, through the Decentralized Autonomous Organization (DAO) and other organizational collaboration methods, a decentralized landscape is created, which effectively reduces the cost of trust friction in society and establishes a trustworthy, secure, and transparent social system.

(3) The metaverse breaks the boundaries between the virtual and real worlds, empowering the real world. With the help of the metaverse, a symbiotic and dynamic feedback system can be formed between the digital world and the real world. The metaverse is a space where the physical world, digital world, and consciousness world are fused, enabling mutual empowerment among them. This leads to a multiplier effect on the economic and social development of the real world, as well as improvements in

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people’s material and spiritual lives, and an increase in government governance capacity. For example, designing and constructing buildings on digital land can create new building patterns and technologies that can be empowered in the real world; farming and breeding on digital land can lead to new farming and breeding patterns and technologies that can be empowered in the real world; simulating warfare on digital maps can help discover new modes of combat and technologies, etc.

Under the technical architecture of the metaverse, these intelligent technology communities continuously combine and fuse in various ways to meet complex application scenarios. “Data + computing power + AI algorithm = intelligent service” is forming a new social infrastructure. In this technical architecture, services gradually give a unified logic to everything in society, including applications, platforms, data, algorithms, resources, and “everything as a service”[1]. Furthermore, service technology plays a comprehensive role in “connecting everything”, and acts as a connector and lubricant across domains, industries, and organizations, making collaboration and integration between different elements truly possible. The entire social landscape is redefined under the service logic, gradually becoming an ecosystem that can be created and operated by many intelligent entities, constantly iterating, evolving, self-growing, and possessing energy and vitality beyond imagination.

The metaverse service ecosystem involves many areas and complex factors, and is undergoing rapid iterative evolution. On one hand, the emergence of the service ecosystem is a bottom-up, self-organizing, and self-growing process, and its overall state depends on the spontaneous interaction behavior among services. On the other hand, the service ecosystem is a product of top-down planning, and we can change the design and evolution path of the service ecosystem by utilizing the discovered patterns. The complexity of governing the service ecosystem is currently still unclear. Due to its complexity, it is difficult for us to see clearly what the service ecosystem will evolve into, and we can only think about it in scattered and vague terms.

In this context, we need to peel back from the complex phenomena and find new perspectives to observe and understand the service ecology of the metaverse, so as to strike a balance between executing planning and conforming to laws, which can ensure the diversity of the ecology while preventing the whole ecology from falling into disorderly development. In this paper, our contributions are as follows:

(1) We investigate the complexity challenges of the metaverse within the metaverse and introduce computational experimentation as an analysis and governance tool for the metaverse service ecosystem.

(2) We focus on exploring the integration of computational experimentation and the metaverse, including how computational experimentation is applied in the metaverse and how the metaverse supports computational experimentation.

(3) We present the applications of computational experimentation in the metaverse, providing novel insights for future related research.

The rest of this paper is organized as follows. First, we expound on the operational logic of the metaverse service ecosystem and the complexity issues it faces. Then, we provide a research methodology framework from a causal perspective. Finally, we bridge the virtual and real worlds using computational experiments techniques to create a collaborative and symbiotic feedback system, enabling the metaverse to empower the real world.

1 Related Work

1.1 Metaverse

In recent years, the concept of the metaverse has garnered significant attention from both academia and industries. As an extension and expansion of the physical world, the metaverse aims to construct a holographic digital realm parallel to the traditional physical world[2]. While the external form of the metaverse is built on foundational technologies such as augmented reality and digital modeling, its essence goes beyond the sensory experiences of augmented reality.

The definition and scope of the metaverse are constantly evolving. It offers immersive experiences based on extended reality technology, generates real-world replicas through digital twin, and establishes an economic system based on blockchain and decentralized principles, effectively blending the virtual world with the real world. The introduction of cryptography, blockchain technology, and decentralized thinking endows the metaverse with the potential to fundamentally disrupt existing social production relations and collaboration methods, enabling the reconstruction of societal structures from three dimensions: economic system, identity system, and governance system.

The economic system serves as the foundation of the metaverse. Almost every activity in the metaverse is intertwined with the economy. In the virtual world of the metaverse, the economic system must handle economic activities different from those in the real world, giving rise to new economic structures. Huang et al.[3] synthesized various literature to propose a blockchain-based economic framework for the metaverse, comprising three fundamental elements: digital creation, digital assets, and digital trading market. Additionally, five themes are introduced, including incentive mechanisms, monetary systems, digital wallets, decentralized finance, and cross-platform interoperability.

Identity, as the primary element in the metaverse, is also subject to continuous changes in this era. The development of digital identity has gone through stages such as centralized identity, federated identity, user-centric identity, and Self-Sovereign Identity (SSI), progressively moving from a centralized to a decentralized model[4]. Ghirmai et al.[5] addressed challenges related to security and interoperability by proposing a solution that integrates SSI with blockchain. This approach views users as the sole holders and owners of their identities, which proves to be valuable in solving issues of decentralization, trust, and interoperability in the metaverse.

The governance of the metaverse presents a high-risk challenge. Schneider et al.[6] introduced a modular, bottom-up governance approach tailored for platforms like the metaverse. This modular approach allows for the development of portable tools adaptable to different platforms and use cases. An example of a governance system that aligns with the aforementioned characteristics is the DAO. Built on blockchain technology, DAO enables self-governance within the metaverse through programmable smart contracts, facilitating the operation of decentralized organizational management models[7]. In this paper, we introduce the computational experiments method as a novel approach for the analysis and governance of the metaverse.

1.2 Computational experiment

The computational experiment method, based on distributed thinking and employing a bottom-up approach, utilizes decentralized micro-level intelligent models to simulate the micro behaviors of various entities in the real world. By designing interactions among these individual entities, complex phenomena are formed, reflecting the evolutionary patterns of the entire system at the macroscopic level. Through carefully crafted computational models and simulation environments, computational experiments serve as powerful tools for reasoning, experimentation, and gaining a comprehensive understanding of system complexity[8]. Computational experiment is a natural extension and sublimation of computer simulation. However, it differs from traditional simulation in terms of data-driven mechanisms of emergence and interpretation of multiple worlds. In addition to the traditional description and prediction functions of computer simulation, computational experiment emphasizes the guiding function of results. Compared with traditional experimental methods, computational experiment has the following characteristics. (1) Precision and controllability: By setting environmental parameters (such as geographic factors and population distribution) and triggering events (such as time, location, type, and scale), various scenarios can be accurately reproduced as the system's operating environment. (2) Simplicity of operation: In the simulation process, various extreme experiments can be easily performed to evaluate different performance indicators of the system, such as accuracy and responsiveness. (3) Reproducibility: This advantage allows researchers to design different experimental scenarios to evaluate the impact of different factors (such as geographic environment and trigger event characteristics) on system performance[9].

As a methodological approach in scientific research, computational experiment method has become one of the mainstream techniques for analyzing complex systems. It is applied in studying systems that involve high risks, high costs, or situations where direct experimentation is not feasible in reality[10], including intelligent transportation systems[11], war simulation systems[12], socio-economic systems[13], ecological and environmental systems[14], physiological/pathological systems[14,15], and political ecological systems[15,16]. Once the "computational laboratory" of a complex system is established, various research tasks can be conducted in this laboratory. The metaverse, being a platform that integrates various intelligent technologies, represents a complex system where intelligent technologies and social ecosystems interact and coevolve. Hence, computational experiments are well-suited as analytical and governance tools for the metaverse service ecosystem.

2 Operational Logic of the Metaverse Service Ecosystem

The metaverse uses information technology to integrate human society with information space and the physical world, forming a world of human-machine-material ternary integration. Unlike the human-machine symbiotic system, the human-machine-material ternary world is a dynamic open network society composed of multiple people, multiple computers, and multiple things, emphasizing the comprehensive use of human-machine and material resources. The new generation of information technology needs to provide intelligent information services that can perceive the human society and physical world and comprehensively utilize the resources of the human-machine-physical trinity world. As shown in Fig. 1, the operational mode of the metaverse service ecosystem depends on the cyclic feedback of physical space, social space, and digital space[17,18]. Physical space represents the counterpart of the metaverse in the real world, social space represents the numerous intelligent agents present in the metaverse, and digital space represents the various innovative content and services in the metaverse The value cycle represents the driving mechanism of the trinity space.

Physical space represents the external environment in which

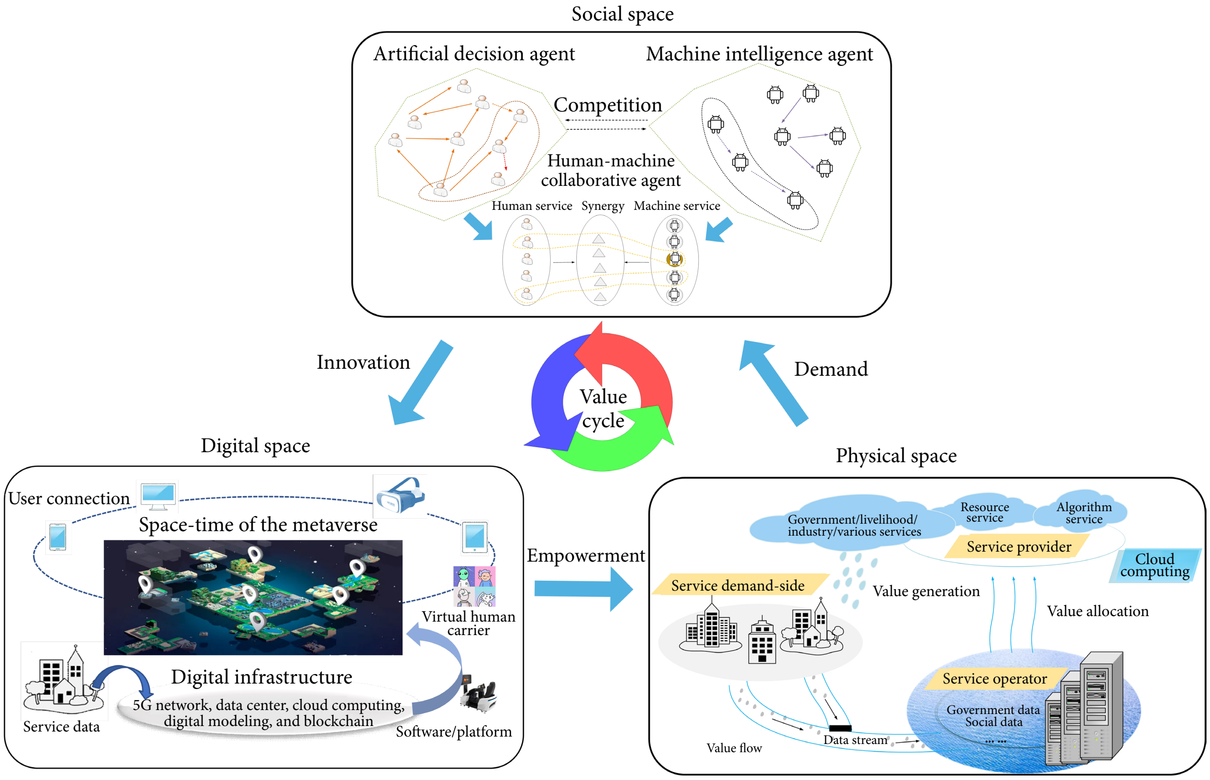


Fig. 1 Schematic diagram of the metaverse service ecosystem.

the metaverse is implemented, including population, law, culture, customs, and industry, and is used to portray different levels of demand. From the perspective of the Cyber-Physical System (CPS) or the degree of controllability, physical space can be decomposed into three major systems: natural ecological environment, artificial built environment, and crowd behavior system. For the natural ecological environment, it is not yet fully understood and explained, and the focus of attention is mainly on better understanding the laws of nature. The artificial built environment includes various engineering infrastructures and various systematic equipment systems, and the focus of attention is mainly on better design. Human behavior system is centered on human needs and behaviors, including production, life, travel, etc. Education, medical care, retail, tourism, government, etc., can be classified as such systems, and the focus of attention is mainly on better service.

Social space is a decentralized, self-organized, and ecological network of intelligence composed of many intelligent subjects such as enterprises, individuals, institutions, and algorithms interconnected online. Driven by the demand for physical space, the collaborative relationship among many intelligent subjects gradually changes, and multiple decentralized small- and medium-sized ecologies emerge, gradually forming the local prototype of metaverse. The DAO in the metaverse breaks the hierarchical management structure, and the decentralized and code-based management potential comes to the fore, breaking the information asymmetry among the participants and minimizing the cost of trust, which is expected to become the underlying paradigm for the internal governance of various organizations in the metaverse. With the support of blockchain technology, each participant (developer, user, swapper, and miner) obtains revenue, enjoys voting rights according to contribution, and uses token to motivate participants, which can reduce management costs.

Digital space refers to a network composed of all available services, and the core is services with rich physical and social information and the interaction between services. With the development of the metaverse, application scenarios emerge in large numbers, and the Internet of everything is integrated into the metaverse world. At the scene level, it extends from games to other scenes and catalyzes the digitization of various industries. In the Customer to Customer (2C) field, applications such as gaming serve as the initial use cases for the metaverse, gradually driving the transition of certain offline experiences to an online environment, including office work, education, sports, etc. Virtual beings emerge and become commercialized, reshaping content and social interactions. In the Business to Business (2B) field, digitalization and virtualization upgrades in various industries are catalyzed by the metaverse concept and related technological advancements. This includes the emergence of functional virtual entities like visual humanoid AI assistants. Industrial and urban application scenarios initially focus on scene simulation, such as simulation of assembly lines and 3D digitization of infrastructure.

Value cycle represents the process of value appreciation and circulation among the ternary space, similar to the energy cycle in natural ecological systems. The metaverse, as the successor of the mobile Internet, is in turn positioned as a platform for human leisure, labor, and survival. The success of this vision depends on whether the metaverse has a thriving economy. Creator Economy, which refers to everything that helps creators produce and monetize their results to profit from them, includes design tools, animation systems, graphic tools, and monetization technologies. Blockchain technology provides a decentralized clearing platform Decentralized Finance (DeFi), and value transfer mechanism Non-Fungible Tokens (NFT), which can guarantee the value attribution and flow of the metaverse, thus guaranteeing the stability and efficiency of the economic system and the transparency and deterministic enforcement.

3 Complexity Challenge of Metaverse

From the perspective of the structural function or state change of social systems, digital technology has created unprecedented complexity in social systems, leading to a series of challenging problems. Breakthroughs in information technologies such as mobile communications, complex networks, big data, artificial intelligence, blockchain, and cloud computing are continuously pushing the integration of the physical world and human society in terms of depth and breadth, as well as the integration of the real world and virtual world, resulting in increasingly complex and dynamic systems with a stronger coupling of cyber-physical society[19]. This, in turn, is driving profound changes in social governance models and methods.

3.1 Evolutionary complexity

The agents in the metaverse not only include individuals with autonomous consciousness and gaming behavior but also gradually include all kinds of intelligent machines, human-machine fusion systems, social organizations, and digital platform enterprises. The Artificial Intelligence (AI) system with increasing capability and the people and organizations empowered by AI are both autonomous and passive, conflicting and cooperative, forming an evolutionary system of multiagent game, and the complexity of maintaining its dynamic balance is increasing. Moreover, any sensitive event, through networked connectivity and positive feedback amplification, may rapidly associate with other events and generate a cascading “1+1>2” “emergence”, which may trigger the “polarization phenomenon” or “butterfly effect”, leading to an unprecedented complexity of social system evolution. The Internet of Things (IoT) opens the era of interconnectedness of everything, which may lead to the transmission, interweaving, and superposition of different spatial risks, far exceeding the security risks of traditional society.

3.2 Cognitive complexity

With the gradual maturity of Artificial Intelligence Generated Content (AIGC) technology, traditional human forms cannot enter virtual worlds like the metaverse. The future subjects of the metaverse will be digital humans, which are modeled digital humans presented in code form through AIGC technology, particularly integrating ChatGPT[20] technology. As the level of human-machine collaboration continues to improve and the depth of human-machine fusion continues to strengthen, digital humans will gradually evolve from human assistants and tools to staff assistants, forming a complementary “mutual assistance relationship” with humans. In long-term human-machine interaction, humans may form an intangible dependence on various algorithm-based intelligent systems. This may lead humans to fall into the “information cocoon” circumscribed by algorithm preferences, where people believe they are seeing the objective world, but in fact they are only seeing a “curated” world chosen by algorithms.

3.3 Regulatory complexity

In the metaverse, centralization and decentralization coexist.

Centralization manifests as the concentration of data and technology as well as the possibility of greater power concentration, while decentralization is manifested as the increasing autonomy of distributed behaviors and evolution of various entities. How to achieve the unity of system functionality in the dynamic game between centralization and decentralization involves adapting and adjusting the boundaries of the service ecosystem governance, which is an important reflection of regulating complexity. Game regulation may be an area of research that requires special attention, with macro-regulation variables at the upper level and multiple intelligent subsystems with interrelated and different functional or goal pursuits at the lower level, enabling the unification of centralized and distributed regulation.

4 Computational Experiment Method

4.1 Core idea of computational experiments

The essence of computational experiments is to algorithmize counterfactuals and create a digital and computational method for quantitatively analyzing complex systems[8]. As shown in Fig. 2, this method starts from the microscopic scale of a reference system in the real world, constructs individual models with autonomous characteristics and interaction rules, and abstracts the conceptual model of the reference system. By combining the theoretical framework of complex scientific systems with computer simulation technology, a “digital twin”[21] of the real system can be cultivated in the information world. The rules, parameters, and external interventions that the system follows can be easily modified, and various experiments can be repeatedly performed. Based on the experimental results, the causal relationship between the intervention variables and the emergence of the system can be explored, providing a new tool and means for explaining, understanding, guiding, and regulating macroscopic phenomena in the real world.

4.2 Computational experiments technology system

With the increasing maturity of complex system science and computer simulation technology, in 2004, researcher Wang[22] officially proposed the concept of “computational experiments” and formed the ACP method of “Artificial Systems + Computational Experiments + Parallel Execution”, emphasizing the feedback relationship between artificial systems and actual systems. In 2020, Professor Xue[23] published *Computational Experiment Methods for Complex Systems: Principles, Models and Cases*, systematically combing and elaborating on the computational experiments method. According to Ref. [23], the research framework and technical system of the method of computational experiments method can be summarized in Fig. 3, which includes five steps: modeling of artificial society (digital twin + digital human), construction of experimental systems, design of computational experiments, analysis of computational experiments, and verification of computational experiments, forming a feedback loop[24,25].

(1) Modeling of artificial society (digital twin + digital human)

Modeling of artificial society (digital twin + digital human) is a method of simulating human society in the computer, which includes individual model, environmental model, and social model[26]. Compared to general simulation models, artificial society (digital twin + digital human) model describes more complex systems, where not only individual behavior is uncertain, but also individuals have complex interaction behaviors.

(2) Construction of experimental systems

Construction of experimental systems is mostly based on distributed thinking, using a bottom-up approach and utilizing dispersed micro-intelligence models to simulate the entire complex system. The focus of experimental system construction is on how to use data-driven approaches to complete the initialization of artificial social systems and design data pipelines to achieve model integration.

(3) Design of computational experiments

In computational experiments with a large number of factors, if these factors are arbitrarily tested and observed in combination, the number of experiments will exponentially increase, making it impossible to scale. Reasonable experimental design ensures that ideal experimental results can be obtained in the most rapid and economical way possible.

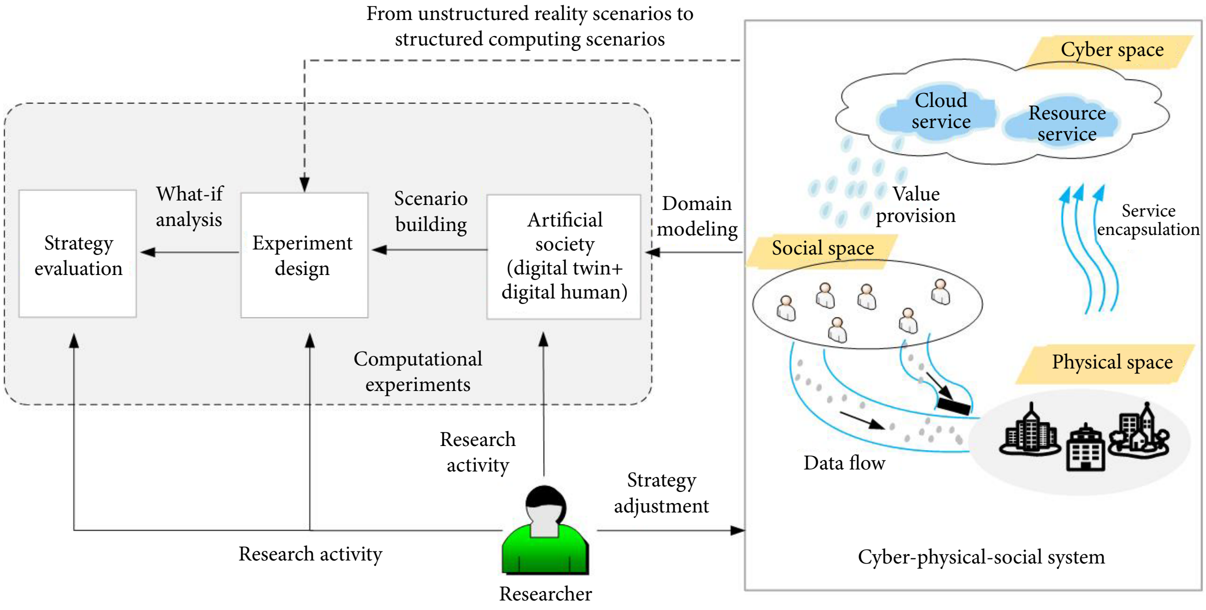
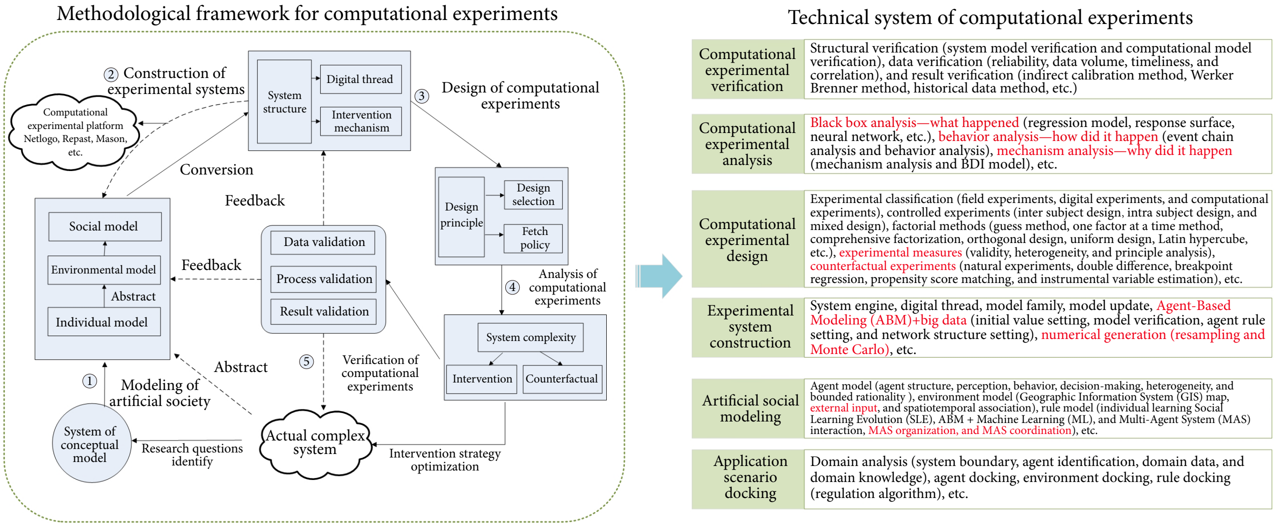


Fig. 2 Schematic diagram of the computational experiments method.



Technical system of computational experiments

Computational experimental verification	Structural verification (system model verification and computational model verification), data verification (reliability, data volume, timeliness, and correlation), and result verification (indirect calibration method, Werker Brenner method, historical data method, etc.)
Computational experimental analysis	Black box analysis—what happened (regression model, response surface, neural network, etc.), behavior analysis—how did it happen (event chain analysis and behavior analysis), mechanism analysis—why did it happen (mechanism analysis and BDI model), etc.
Computational experimental design	Experimental classification (field experiments, digital experiments, and computational experiments), controlled experiments (inter subject design, intra subject design, and mixed design), factorial methods (guess method, one factor at a time method, comprehensive factorization, orthogonal design, uniform design, Latin hypercube, etc.), experimental measures (validity, heterogeneity, and principle analysis), counterfactual experiments (natural experiments, double difference, breakpoint regression, propensity score matching, and instrumental variable estimation), etc.
Experimental system construction	System engine, digital thread, model family, model update, Agent-Based Modeling (ABM)+big data (initial value setting, model verification, agent rule setting, and network structure setting), numerical generation (resampling and Monte Carlo), etc.
Artificial social modeling	Agent model (agent structure, perception, behavior, decision-making, heterogeneity, and bounded rationality), environment model (Geographic Information System (GIS) map, external input, and spatiotemporal association), rule model (individual learning Social Learning Evolution (SLE), ABM + Machine Learning (ML), and Multi-Agent System (MAS) interaction, MAS organization, and MAS coordination), etc.
Application scenario docking	Domain analysis (system boundary, agent identification, domain data, and domain knowledge), agent docking, environment docking, rule docking (regulation algorithm), etc.

Fig. 3 Technology of computational experiment method.

(4) Analysis of computational experiments

In computational experiments, multiple control experiments can be set up at the same time, targeted changes to the parameters of artificial social systems can be made, or specific intervention measures can be applied to compare experimental results. When necessary, multiple repetitions of large-scale simulations can be conducted to explore the underlying causes of complex phenomena.

(5) Verification of computational experiments

High confidence is the foundation for the application of computational experiments. Only by making breakthroughs in model verification can computational experiments methods become mainstream methods in the field of social and economic development, complementing and enhancing other methods and becoming a powerful tool for understanding the operational rules of complex systems.

5 Integration of Computational Experiments and Metaverse

The metaverse challenges the physical rules of the real world, redefines production and lifestyle in the digital world, and improves overall productivity and cooperation with new methods, including economic and social development and the improvement of material and spiritual well-being. However, as the metaverse continues to develop, its "double-edged sword" nature will become more apparent. Maintaining a positive interaction between the real world and the metaverse and maximizing its positive effects while minimizing negative ones are significant challenges that the metaverse will face in the future. The issues that need to be studied include: how to empower the real world through the digital world, providing reference, estimation, and guidance for possible situations in reality; how to determine and predict where the expansion boundary of the metaverse is, continuously improving and regulating the ecological system of the metaverse, so as to know what to do and what not to do.

The metaverse belongs to the social complex system, and due to its involvement of human and social factors, its design, analysis, management, control, and integration face unprecedented challenges. Restricted by many factors such as economy, law, and morality, traditional technical means are often powerless in studying such problems[27,28]. Therefore, the study of the metaverse can only rely on "counterfactual experiments" to analyze the dynamic evolution trend of social complex systems under hypothetical conditions. The computational experiment, by algorithmizing the counterfactual and conducting research on the metaverse, provides a solution to the above problems by integrating the two approaches.

In general, computational experiments can be integrated with metaverse in different ways. As shown in Fig. 4, the metaverse integrates infrastructure technologies such as blockchain, interaction, electronic game, AI, intelligent network, and the IoT to provide an environment for experimental design and analysis of computational experiments, while computational experiments design rules that affect data and the environment of digital humans in the metaverse. The digital humans in the metaverse can be formed directly by modeling data in the metaverse environment, or they can be generated directly through AIGC technology. The integration of metaverse and computational experiments provides technical support for virtual production and virtual governance. Due to the different technical architectures contained in computational experiments, their functions after integration with metaverse are also different. Computational experiments has two main functions for the metaverse, which mainly involves both empowerment and regulation.

(1) Empowering the real world (production)

By conducting computational experiments in a cognitive space similar to the real world in the metaverse, the decision-making process in the real world can be analyzed, evaluated, and optimized to achieve accurate deduction of the real world and generate new technologies applicable to the real world. "Computational experiments + metaverse" provides a new method for interpreting, understanding, and guiding the real world, thereby achieving new scenarios for production-oriented enterprises, namely virtual production. Using virtual agriculture[29] as an example, various agriculture-related data, such as climate data, crop data, and economic data, are collected and processed to set up computational experiments in the digital space. By utilizing plant models, agricultural models[30], and other relevant models, a virtual agricultural system can be constructed to simulate diverse agricultural production scenarios and facilitate virtual agricultural production. This virtual system runs parallel to the real scenario, and can be used to interpret and analyze real agricultural production. By conducting a large number of repetitive

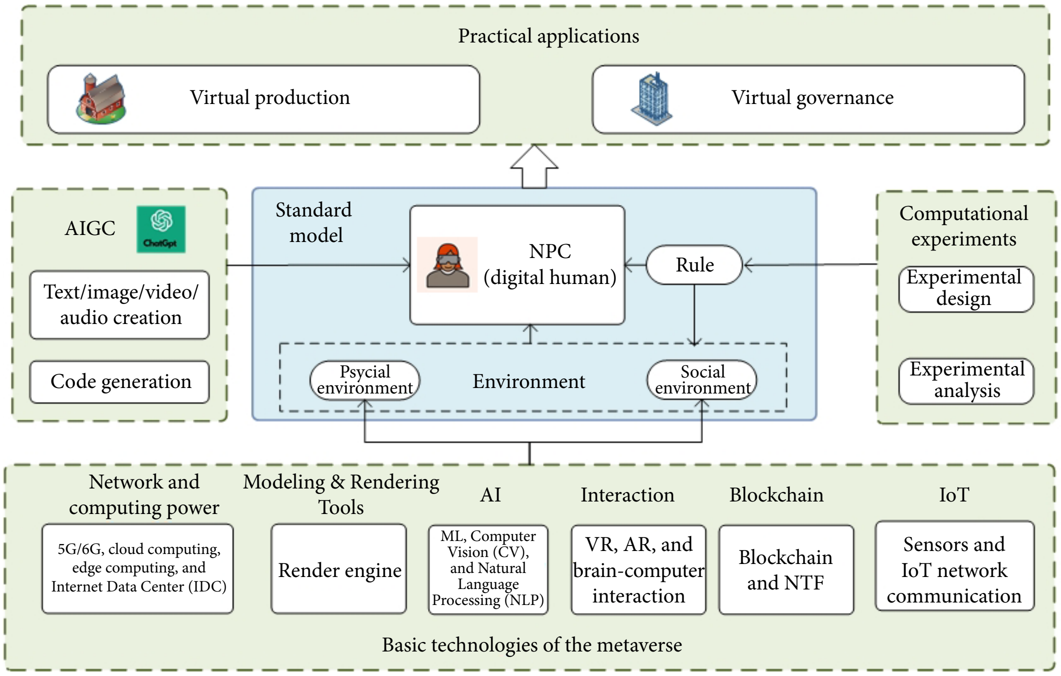


Fig. 4 Integration of metaverse and computational experiments.

experiments in this virtual system using computational experiments, it is expected to generate new planting patterns and technologies to empower the real world.

(2) Regulating the digital world (governance)

As a massively complex system, the metaverse incorporates the achievements of the information revolution (5G/6G), the internet revolution (Web 3.0), the artificial intelligence revolution, and the virtual reality technology revolution (VR, AR, etc.), attempting to construct a holographic digital world parallel to the traditional physical world. This will make the metaverse more integrated into people's daily lives than the internet, and any damage to the metaverse ecosystem will have a serious impact on the real world. By designing and repeating a large number of computational experiments in the metaverse, we can help to identify potential social risks and crises related to technological governance and effectively build the metaverse ecosystem. At the same time, computational experiments can break down the barriers between the digital and real worlds, eliminate unfeasible strategies through counterfactual reasoning in the digital world, and transfer optimized strategies to the real world to guide the operation of real systems, thus achieving dynamic guidance or control of decision-making in the real world and conducting reliable virtual governance, such as emergency management. Through digital cities in the metaverse, people can use computational experiments to conduct various social experiments that are difficult to carry out in reality, including simulating how to evacuate and rescue people in major disaster situations[31].

The metaverse also provides support for the implementation of computational experiments, serving as a specific implementation of Cyber-Physical-Social System (CPSS)[32]. It offers an experimental environment in which various rules can be designed to alter the environment and achieve experimental goals. This environment encompasses both physical and social aspects. Taking Didi Dache as an example, the physical environment includes modeling information such as roads, traffic lights, and Non-Player Characters (NPCs) (digital humans) participating in the interaction. The social environment includes social knowledge such as traffic rules and interactive information related to the network of relationships among intelligent agents in various scenarios. These elements are critical throughout the experimental process of computational experiments and support the extension of the application scope and depth of computational experiments methodology, fostering innovation in its application.

6 Application of Computational Experiments in Metaverse

The metaverse is an open complex system. From virtual reality, augmented reality, and mixed reality to extended reality, the ambition of the metaverse is no longer limited to simulate reality but to further integrate reality and virtuality or to dissolve the boundary between reality and virtuality, ultimately enabling the digital world to extend and empower the real world. As shown in Fig. 5, by utilizing the metaverse, we can fully leverage the integration advantages of virtual scenes and real subjects and conduct "virtual-real integration, humans in the loop" computational experiments to study the real world, especially in scenarios where risks are high, scales are large, or costs are high, and field experiments are difficult or impossible to conduct. As a fundamental technology for virtual production and governance, computational experiments will shine in fields such as industrial design, healthcare, military reform, social governance, and online learning and education. The details are as follows:

(1) Industrial design

The metaverse offers an innovative and collaborative space where designers, engineers, and users can work together on designs. For instance, you could explore a virtual showroom with your family and try out a vehicle before deciding on a purchase. In fields such as architecture, mechanical manufacturing, and autonomous technology, highly accurate and physically realistic 3D simulations can be achieved, enabling products to exist virtually before they are produced in the physical world. This makes digital simulation verification and virtual collaboration among users possible. NVIDIA has established a platform called Omniverse that supports real-time virtual collaboration in industrial design and visualization, allowing for multiple tests and

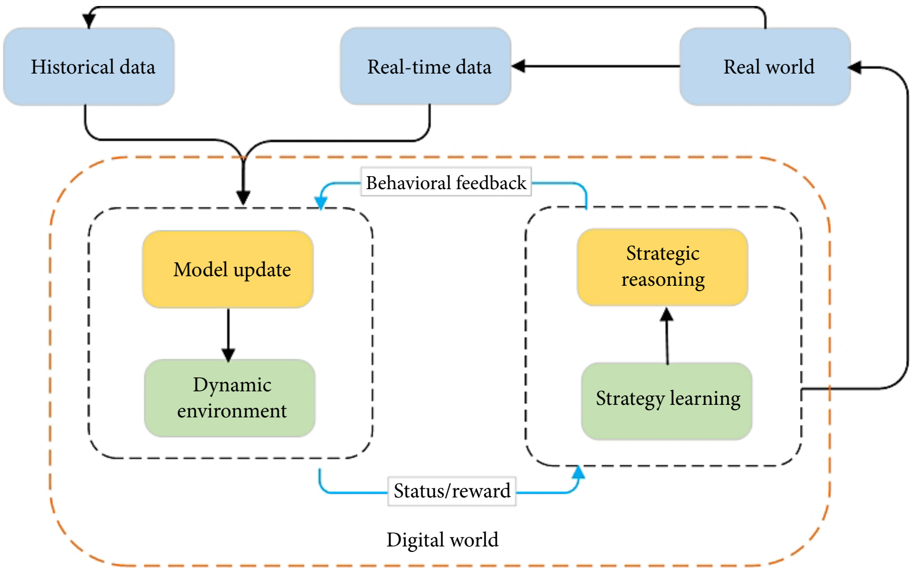


Fig. 5 Feedback loops for computational experiments in metaverse.

experiments in simulated virtual worlds[33]. This can help reduce costs, optimize designs, and enhance development efficiency in industrial production.

(2) Healthcare

In the metaverse, the use of augmented reality and virtual reality technology to establish digital patients, enabling bi-directional data flow between the physical entity and its digital twin, can have a significant impact on the training and improvement of future healthcare professionals' skills and knowledge base[34]. For example, medical equipment manufacturers can perform various parameter adjustments based on digital patients to identify potential issues, greatly reducing research and development costs while enhancing the performance and safety of the final product; doctors rely on customized digital patients to track each patient's response to different treatment plans, thereby improving the overall accuracy of treatment plans. Integrating a large number of digital patients can also improve our understanding of population diseases and lead to more insightful public health decisions.

(3) Military reform

War exercises are very important for military. The real battlefield is full of various uncertainties, so it is necessary to be well prepared by constantly conducting war exercises. Traditional field exercises are costly and difficult to simulate real combat scenarios, especially extreme situations. Pure computer simulation, on the other hand, is difficult to model the uncertainty on the battlefield and the subjective initiative of combatants. By creating a dedicated synthetic training environment[35], the advantages of combining virtual and real can be fully utilized. The computer generates virtual military training sites, equipment and facilities, tasks, weapons, other environments, and battlefields, while soldiers in the virtual battlefield can be played by real people, fully demonstrating their combat skills. On the virtual battlefield, soldiers and decision-makers in combat can go beyond existing conditions, simulate imagined concepts, combat operations, formations, and so on, and repeatedly rehearse. In future metaverse war exercises, the combination of data capture, storage, analysis technology, and new synthetic virtual environment technology will be more conducive to summarizing errors, failures, and achievements.

(4) Social governance

The metaverse is the integration and incorporation of the real world into a virtual world. Using a generated digital city as a carrier, social management personnel can conduct various social experiments that are difficult to carry out in reality. This will have unprecedented positive effects on simulating and modeling events such as floods, fires, and energy demand[36]. In the metaverse, it is possible to achieve the integration of real subjects and virtual identities, thereby greatly improving the credibility of social experiment results. For example, in emergency rescue, firefighters can also use real data to reproduce past fire scenes, providing an immersive digital twin environment for emergency responders, operators, and engineers to evaluate the effectiveness of their firefighting actions.

(5) Online learning and education

With the help of metaverse technology, teachers can also display teaching materials that are difficult to display in reality, such as complex experiments. The metaverse environment can add a new dimension to the field of educational technology[37], which means that education is no longer just a matter of theory but can be practiced in the metaverse. For example, when learning astrophysics, one can observe stars in the metaverse; when learning to repair vehicles, medical students or doctors can use VR to learn new surgical techniques and practice. The metaverse can provide teachers with tools to unleash their creativity, and using everything learned from games can make the experience more interesting. Skills training, including for pilots and astronauts, can be conducted using fully immersive VR/AR equipment. The metaverse will transform education into a more immersive and social experience and will greatly impact traditional education, corporate training, and skills learning.

7 Conclusion

Based on the current situation, it is impossible to achieve a fully-realized metaverse that encompasses everything and allows us to live inside it all at once. Instead, it is more likely that various scenarios with a rudimentary metaverse will develop first and gradually evolve towards the final form as various technologies reach a certain level of development. In this context, we need to delve into the complexity of the phenomenon and search for unique perspectives to construct, understand, and govern the metaverse. We need to find our own path of technological innovation, with distinct characteristics, by peeling off the layers of complexity.

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