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Research on Data-Driven Dynamic Decision-Making Mechanism of Mega Infrastructure Project Construction

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Abstract: The construction of mega infrastructure projects has the characteristics of repeatability, long duration, and high complexity. Therefore, it is particularly important to implement dynamic decision-making in projects. This study takes data-driven decision-making mechanisms as the entry point and constructs a dynamic decision-making system for mega infrastructure projects consisting of an information collection subsystem, an information processing and transformation subsystem, a human–computer collaborative decision-making subsystem and an evaluation and feedback subsystem. On this basis, we established a system dynamics model of dynamic decision-making for mega infrastructure projects. Vensim PLE 9.3.5 software was used to simulate and analyze the operation law of dynamic decision-making for mega infrastructure projects from a data-driven perspective, and the sensitivity of the application rate of information management technology, the application rate of data analysis methods, the participation rate of experts in decision-making, the historical case information on this project, and the information on similar projects on the effectiveness of program implementation were simulated and analyzed. The results of the study showed that all five key influencing factors have a positive impact on the effectiveness of program implementation. In addition, the application rate of information management technology and the application rate of information analysis methods have a higher sensitivity to the effectiveness of program implementation, the participation rate of experts in decision-making and historical case information on this project have average sensitivity to the effectiveness of program implementation, and information on similar projects has lower sensitivity to the effectiveness of program implementation. This study provides some ideas and suggestions to promote the effective use of information technology and digital technology by each participant in the construction of mega infrastructure projects while improving their dynamic decision-making efficiency, scientificity, and accuracy.

Keywords: mega infrastructure projects; data-driven; dynamic decision-making; system dynamics

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1. Introduction

The dynamic decision-making in this article refers to the decision-making in the process of mega infrastructure project construction.

The world has entered the "Trillion Era" of mega infrastructure projects [1,2]. According to a report on global consulting by McKinsey, the total investment in infrastructure will reach up to USD 57 trillion by 2030 [3]. It is estimated that the global annual investment in mega infrastructure projects will reach up to USD 6–9 trillion [1], accounting for 8% of the global gross domestic product (GDP). Mega infrastructure projects are large, complex engineering projects, often costing USD 1 billion or more, requiring years of development and construction, involving multiple public and private stakeholders, are transformative, and affect millions of people [1]. Major infrastructure projects are engineering projects of great significance to the economic and social development of a country under a certain background of the times [4,5]. Mega infrastructure projects are understood differently by scholars and practitioners in different cultural contexts, but generally, they refer to large-scale and complex architectural, engineering, and construction (AEC) projects in spaces with significant investment and broad social and economic impact [6,7]. Compared with general engineering projects, mega infrastructure projects are characterized by large scale, high complexity, and a wide range of significance [8]. These bring great challenges to decision-making and project management. There are many problems in the field of mega infrastructure project construction today. "Over-investment, over-schedule, and low investment profit" have become the international "iron law" for mega infrastructure projects [9,10]. The economic benefits of contracted works are mostly unstable and low. The implementation of technological innovation in the field of mega infrastructure projects is slow and inactive, as evidenced by the statistics [11,12]. Flyvbjerg et al. investigated 258 large-scale projects in 20 countries across 5 continents and found that 90% of megaprojects were subjected to cost overruns and delays in schedules, resulting in being, on average, over budget by 28% [13]. Traditional project management concepts and strategies have proven less efficient for modern mega infrastructure projects [13]. There is an urgent need for the research and development of cutting-edge technologies in mega infrastructure project fields and scientific and effective management methods [14]. The construction process of mega infrastructure projects often generates many problems involving environmental pollution and ecological damage, and a moment earlier to propose a decision plan can be a moment earlier to reduce pollution of the environment. Therefore, to improve the efficiency of decision-making is key. The implementation of dynamic decision-making is imperative [15]. Therefore, in order to cope with these challenges in the process of mega infrastructure projects, dynamic management has become an effective means in recent years. Dynamic decision-making, as the core of dynamic management, plays a crucial role in the efficient and high-quality operation of mega infrastructure projects [16]. Dynamic decision-making implies real-time, circular feedback, sustainability, and environmental adaptability [17]. The purpose of the decision-making mechanism studied in this paper is mainly three-fold: first, to introduce the information on similar projects to support dynamic decision-making in mega infrastructure projects and reduce the uncertainty of decision-making in the process of mega infrastructure project construction; second, to design a dynamic decision-making mechanism model with real-time monitoring, circular feedback, sustainability, and environmental adaptability to cope with the problem of high risk in the process of mega infrastructure project construction; and third, to cope with the problem of long processing cycles and inefficient decision-making during the construction of mega infrastructure projects, reduce the uncertainty of decision-making, and make full use of the massive data generated during mega infrastructure project construction.

2. Literature Review

2.1. The Basic Process of Dynamic Decision-Making in Mega Infrastructure Projects

Decisions are at the heart of engineering projects; better decisions will lead to better engineering design [18]. Effective decision-making program functions are important tasks for decision-making [19]. The formation of the decision-making program is an instant regulation and design based on the current needs, industry standards, geological survey accuracy, technology and equipment maturity, and enterprise capabilities [20]. In the whole life cycle of a project, the function of the decision-making will be continuously optimized and expanded with the deepening of people's understanding of the decision-making problem, environmental changes, and new functional requirements [21].

The decision-making process of mega infrastructure projects not only reflects path dependence but is also full of uncertainties and dynamic evolution, which makes the core decision-making process of mega infrastructure projects have various complex phenomena.

Various models of the decision-making process have been proposed, such as single-criterion models [22], multiple-criteria models [23], Sutherland's model [24], Holt's model [25], models based on operational studies [26], cybernetic decision models [27], fuzzy data models [28], etc., as shown in Table 1.

Table 1. Models of decision-making processes [29].

Single-criterion models:	Multiple-criteria models:
1. Discovering the difficulty. Applying to evaluate problem solution variants; 2. Identifying the problem; 3. Determining the criterion; 4. Setting a list of solutions; 5. Describing effects of the implementation of each solution; 6. Selecting the best solution; 7. Implementing the decision.	1. Identifying the problem; 2. Identifying decision criteria; 3. Assigning weights to criteria; 4. Elaborating alternative solutions; 5. Evaluating alternative solutions; 6. Selecting the best solution; 7. Implementing the chosen solution; 8. Evaluating the efficiency of the decision implemented.
Sutherland's model:	**Holt's model:**
1. The need to make a decision (goal); 2. Primary information (opinions, theories); 3. Empirical studies; 4. Building a model; 5. Generating solutions; 6. Selecting criteria for evaluation; 7. Evaluation of variants; 8. Selection of the solution; 9. Making a decision; 10. Implementation; 11. Feedback to correct the model.	1. Identification of the problem; 2. Analysis of the context; 3. Definition of the problem; 4. Elaboration of solutions; 5. Evaluation of variant solutions; 6. Selection of a solution; 7. Implementation; 8. Evaluation of effects.
Model based on operational studies:	**Cybernetic decision model:**
1. Building a model (describing the situation using mathematical language); 2. Solving the problem presented in the form of a mathematical model; 3. Verification of the model—possible corrections; 4. Monitoring—feedback and correction of the decision made.	1. Input—primary, raw information; 2. Transformation—a decision-making process; 3. Output—secondary information in the form of a decision.
Fuzzy data model:	
1. Data collection stage—input signals; 2. The fuzzification stage; 3. The stage of fuzzy inference;	4. The stage of defuzzification; 5. Making a decision.

The aforementioned models of the decision-making process can be broadly divided into two categories. The first category consists of models that utilize single-criterion and multi-criteria approaches that aim to evaluate several alternative solutions to determine the best solution by assessing the possible effects of their implementation. The second category consists of methods that build mathematical models that present the implementation of previous decisions through mathematical language. These modeling methods collect and analyze information about the current situation in order to determine the goal and the measures that will be applied to determine to what extent this goal will be achieved. The final stage provides feedback that allows the user to correct the model or decision if necessary. The models given in the table vary in their approach to problem-solving and subsequent procedures, but, in each case, the completed procedures lead to problem-solving. In different areas of business activity, different approaches may be applicable to different decision situations. An analysis of the literature related to decision-making revealed the lack of decision models adapted to mega infrastructure construction activities.

The decision-making model process for mega infrastructure projects is to analyze the environment and gather information, define the problem that causes difficulties, determine the evaluation criteria for the solution of the problem, develop different solutions, select a method, evaluate possible solutions, evaluate all alternatives and select one, make a decision, implement the decision, obtain feedback, and correct input data and basic assumptions [29].

2.2. Support Conditions for Dynamic Decision-Making of Mega Infrastructure Projects

Information is the basis of decision-making, and dynamic decision-making in mega infrastructure projects is inseparable from the collection of real-time information. The decision-making process also includes how to collect and analyze new information [30], and the empowerment of any decision-making program as a man-made system is set by the subject through the theoretical thinking at the virtual engineering level, preceding the entity. However, the functional value and role of the decision-making program cannot exist separately from the system entity and must ultimately be realized through the engineering entity [19]. The more complex the core decision-making problem, the more relations of "gene" and "bloodline" it has to the situation, and the more we need to look at the problem, think about the problem, and analyze the problem in the overall situation where the problem is located to find a decision-making solution to solve the problem [5]. This requires us to build a sound survey, a forecasting, monitoring, and inspection system, and an information processing and analysis platform in the process of mega infrastructure project construction [31] and to design a sound decision-making program formation mechanism. Analyzing and solving such decision-making problems generally require cross-field, interdisciplinary, and cross-professional technologies, means, and methods, so it is necessary for decision-makers to build a holistic cognitive platform with complete knowledge and a good working mechanism [32]. The dynamic management of mega infrastructure projects is based on the information platform, with the information platform as the core [33].

Expert knowledge information is a source of learning, and information that is organized and processed to the right people will benefit project decision-making [34]. The organizational structure in the process of mega infrastructure projects is very complex. For example, a mega infrastructure project under construction in Southwestern China is a three-level management system; each level has a very complex organizational structure, mainly including the owner, construction units, design units, consulting units, etc., where the construction units have many companies. These units have experts in the field under the jurisdiction of the unit. These experts in the project decision-making process contribute their knowledge for different issues and provide strong support for decision-making [18]. Dynamic decision-making in the process of mega infrastructure project construction must not only be supported by factual information and data but also have the intelligence of decision-making experts. The participation of decision-making experts is indispensable in the stage of cause analysis, the decision-making program design, and the decision-making plan evaluation of mega infrastructure project construction decisions [5]. With a deep theoretical foundation and practical experience, experts have keen insight into the handling and response of emergencies, professional analysis and judgment, and accurate intelligence decision-making ability [35,36]. The intelligence of experts is essential for architectural and engineering organizations, as the characteristics of each project are dynamic and unique [35].

Although experts usually operate within a bounded range where they are knowledgeable and comfortable, they sometimes confidently give information outside their range of expertise [20]. They can also miss the bigger picture. Furthermore, the outcome of decision-making is affected by various factors, such as the professional background, knowledge, experience, personality, and emotions of the decision-maker [37], and has strong subjectivity and uncertainty. Therefore, it is necessary for human–computer collaboration to make decisions.

The core problem of dynamic decision-making in mega infrastructure projects is to propose the relevant decision-making program, and the process of the subject proposing the decision-making program is actually through the combination of theoretical thinking and engineering thinking on the basis of respecting the general law and reflecting the unique intention of the subject [29].

In summary, dynamic decision-making has a very far-reaching significance for the construction of mega infrastructure projects. The information collection team (fact data), information analysis team (tools and methods), and decision-making team (expert intelligence) of mega infrastructure project construction work together on the information management platform to jointly provide support for the dynamic decision-making of mega infrastructure projects, which will be a development trend and more conducive to giving full play to the substantive role of fact data and expert intelligence in the dynamic decision-making of mega infrastructure projects and realize the interactive interconnection and harmonization of various subjects. However, there is currently a lack of a systematic framework to determine the dynamic decision-making process architecture in the construction process of mega infrastructure projects. From the project survey, monitoring, inspection, data analysis, and expert discussion to the formation of the final decision-making plan, the decision-making path needs to be further designed and clarified. In this paper, we will use the system dynamics method to design and construct the dynamic decision-making mechanism path of mega infrastructure projects, take human–computer collaborative intelligent decision-making thinking as the core, describe the dynamic complexity of the system through causal feedback, and simulate the dynamic evolution process of the system using computer simulation technology.

3. Overview of System Dynamics

3.1. Concept of System Dynamics

System dynamics is a discipline of analysis and research based on information feedback and is comprehensive in its understanding and solution of problems [38,39]. System dynamics proposes that its behavior patterns and properties are determined by the internal dynamic structure and feedback mechanisms [40,41]. For the study of complex problems, system dynamics is solved using a qualitative combined with a quantitative approach; that is, the construction of the models is based on the theory of system dynamics and the use of computers to perform simulations and, thus, the study of the problem [42].

3.2. Composition of System Dynamics Model

3.2.1. Cause-and-Effect Diagram

Before simulating a system, the cause–effect relationship needs to be analyzed, which is a necessary condition for successful modeling, and the relationship between different factors is represented with the help of a cause–effect diagram, as shown in Figure 1. The cause–effect diagrams are used to represent the logical relationships between the different factors, i.e., to represent them qualitatively. Arrows are used to connect the different factors so that each factor forms a certain relationship and, thus, becomes a whole. If there is a positive sign at the arrow, it means that the variable at the end of the arrow increases, causing the variable at the arrow to increase; if the variable at the end of the arrow decreases, the variable at the arrow decreases, i.e., the variables at both ends increase or decrease in the same direction. If there is a negative sign at the arrow, it means that an increase in the variable at the end of the arrow will cause a decrease in the variable of the arrow, and a decrease in the variable at the end of the arrow will cause an increase in the variable of the arrow.

If arrows connect the factors to each other to form a closed path, then it is called a feedback loop, and there are positive feedback and negative feedback loops. If a loop has an even number of negative signs, it is a positive feedback loop and is indicated by "+" in the center of the loop; when a loop has an odd number of negative signs, it is a negative feedback loop and is indicated by "-" in the center of the loop.

As shown in Figure 1, Figure 1a indicates that when A increases, B increases; and when A decreases, B decreases. Figure 1b shows that when A increases, B decreases; and when A decreases, B increases. Figure 1c,d are causal loop diagrams, and it is difficult to determine the beginning and end of the loop. Figure 1c has two negative signs, which is a positive feedback loop and is expressed as A increases → B increases → C decreases → A increases or A decreases → B decreases → C increases → A decreases. Figure 1d has one negative sign, which is a negative feedback loop, and the causal relationship is expressed as A increases → B increases → C increases → A decreases or A decreases → B decreases →

C decreases → A increases. The arrows of the cause–effect diagram only reflect the logical relationship of different factors, and there is no quantitative relationship.

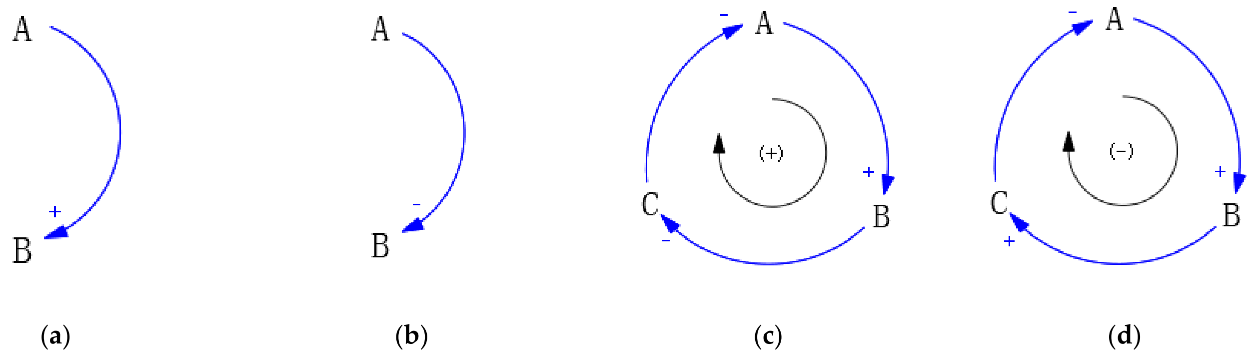

Figure 1. Example diagram of cause-and-effect relationship. (**a**) represents positive feedback, (**b**) represents negative feedback, (**c**) represents positive feedback loop, (**d**) represents negative feedback loop. (A,B,C represent different events.)

3.2.2. System Flow Diagram

The cause–effect diagram only reflects the increase or decrease among variables and cannot reflect the specific quantity of change, which is a qualitative description of different variables. Therefore, in order to quantitatively analyze the system and describe the whole change process, the first step is to transform the cause–effect diagram into a system flow diagram. A system flow diagram can quantitatively describe each variable in the system and make up for the lack of causality diagrams by assigning values to the variables and defining the variable relationships using formulas.

A stock–flow diagram captures the amount of accumulation resulting from a change in one variable leading to a change in another variable. Here, the main elements contained in the stock–flow diagram are described, as shown in Figure 2.

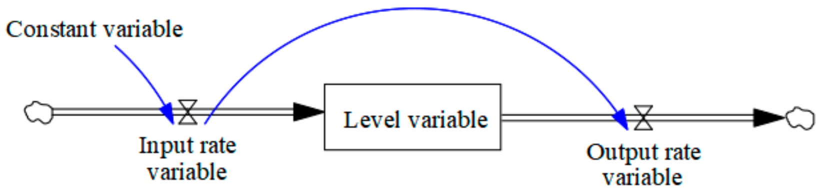

Figure 2. General form of system flow diagram.

(1) Level variable

The level variable is a variable that provides a description of the cumulative effect of the system. As time accumulates, this variable can demonstrate that the value at this moment is equal to the value at other previous moments plus the amount of effect accumulated during this time. The magnitude of the resulting value can reflect the actual state of the variable at a given moment in time. In the system flow diagram, the level variables are represented as rectangular boxes;

(2) Rate variable

The rate variable can reflect the rate of input or output of the state variable and is also a variable that can reflect the cumulative effect of the system. The rate of change of the system is also a variable that can reflect the rate of change of the system accumulation effect. In the system flow diagram, the rate variable is represented by a double arrow line with a funnel symbol together with the funnel symbol;

(3) Constant variable

Constants do not change as they accumulate over time. Constants can either point to rate variables or point to rate variables on top of auxiliary variables. However, no variable will point to a constant. There is no special notation for the representation of constants in the system flow diagram.

3.2.3. Equation

Before performing the simulation, equations are needed to establish the relationships between the variables, which are used to calculate the values of each variable. The equations to be used in this paper are:

$$Stock(t) = \int_{t_0}^{t} [Inflow(t) - Outflow(t)]dt + Stock(t_0) \quad (1)$$

$Stock(t)$ is the number of stocks at time t. $Inflow(t)$ is the inflow volume. $Outflow(t)$ is the outflow volume. $Stock(t_0)$ is the volume of stock at the initial moment. System dynamics expresses time as a continuous quantity. The equation is represented in the software Vensim PLE 9.3.5 by INTEG = (x, initial), with initial being the initial value.

3.3. The Modeling Process of System Dynamics

System dynamics can be analyzed based on actual problems, modeled based on the analysis results, and then simulated using software to analyze the obtained simulation results and finally provide relevant suggestions. The modeling process is shown in Figure 3.

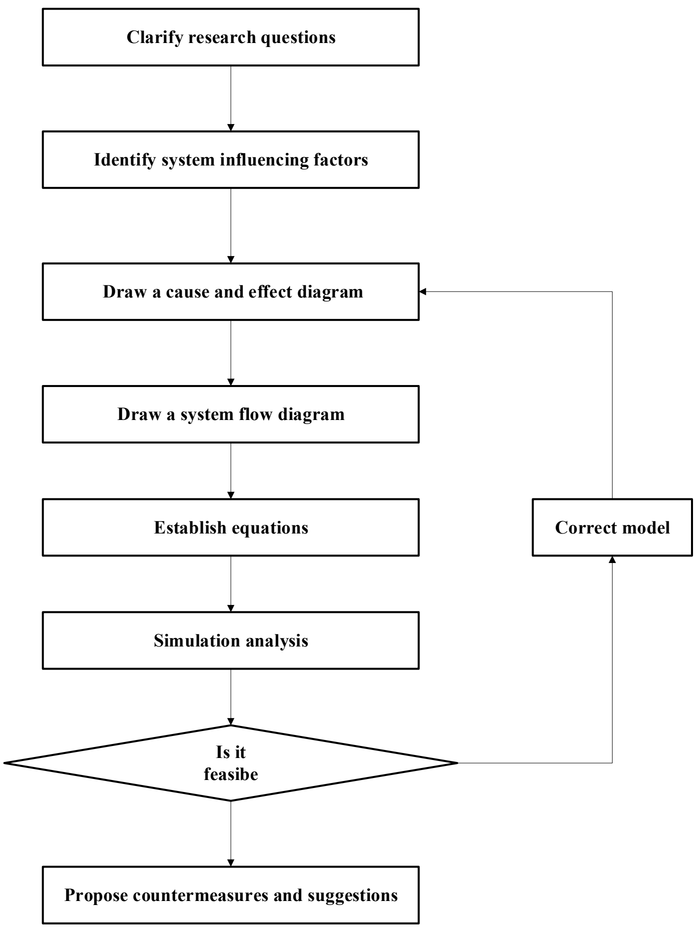

Figure 3. Modeling process of system dynamics.

The first step is to analyze and understand the problem in all aspects with the theory and method of system dynamics and to identify the problem to be studied. In the second step, the influencing factors of the system are clarified, and the relationship between the factors is analyzed. In the third step, a cause–effect diagram is drawn based on the analysis results. In the fourth step, on the basis of the cause–effect diagram, the system flow diagram is drawn. In the fifth step, the appropriate function is selected to establish the equation. In the sixth step, on top of the system dynamics theory, the software is used to simulate the model and analyze the results. If the simulation results are found to be contrary to the reality, it is necessary to return to make modifications to the model. In the seventh step, sensitivity analysis is performed on key elements to discover their influence laws.

4. System Construction

In the traditional dynamic decision-making system for the construction of mega infrastructure projects, it is difficult to complete the collation and analysis of massive data, while the dynamic decision-making information system for the construction of mega infrastructure projects in the information environment can break through the limitations of time and space, break through the constraints of funds and equipment, and carry out comprehensive and accurate data collation and analysis. The construction of mega infrastructure projects should follow the trends, seize the advantages, and use information management technology to analyze construction information data. In addition, the experience and intelligence of relevant industry experts are indispensable as leading roles in the dynamic decision-making process of mega infrastructure projects. Humans lead dynamic decision-making for mega infrastructure projects with the assistance of computers. Before using the system dynamics method to build the model, it is first necessary to establish a dynamic decision-making system for mega infrastructure project construction. According to the development and characteristics of mega infrastructure project construction, the dynamic decision-making system of engineering construction is divided into four subsystems: a decision support subsystem, an information processing and transformation subsystem, a human–computer collaborative decision-making subsystem, and a subsystem for evaluating the effect of the program. The four subsystems are described below, as shown in Figure 4.

4.1. Information Collection Subsystem

The collection of project implementation information is the basis for dynamic decision-making in mega infrastructure projects, and the comprehensiveness and accuracy of the collected information directly determine the smoothness of the project implementation information data analysis. Increasingly often, cutting-edge information technologies are a source of information and datasets supporting the process of arriving at a decision [35,43]. The collection of information on mega infrastructure project construction is inseparable from advanced space–sky–earth integrated information collection technology and equipment. In recent years, with the promotion of mega infrastructure projects and the rapid development of information technology, cutting-edge technologies, such as the ubiquitous Internet of Things [44], mobile Internet [45], GIS [46], and satellite remote sensing [47,48], have effectively supported the collection of information for mega infrastructure projects. Especially in the context of big data, when analyzing project information and making decisions, it is necessary to combine the information resources of other project cases [20,49] and policies, regulations, and industry codes. Therefore, by analyzing the source of project information and the mechanism of information acquisition, the project information collection can be divided into two aspects: static information data and dynamic information data. Static information data mainly includes the collection of historical case information, project plans and strategies, policies, regulations, and industry codes. Dynamic information data mainly includes project advance survey information, project monitoring, and inspection information [34,49]. Figure 4 shows the analysis of real-time dynamic information data to find problems combined with static information data to analyze the causes of the problems to design a decision-making program. For example, regarding investment information indicators, monthly investment information on the construction process of mega infrastructure projects is monitored and counted, and then the quarterly investment information on the construction process of mega infrastructure projects, annual investment information, and cumulative investment information from the start of construction are counted.

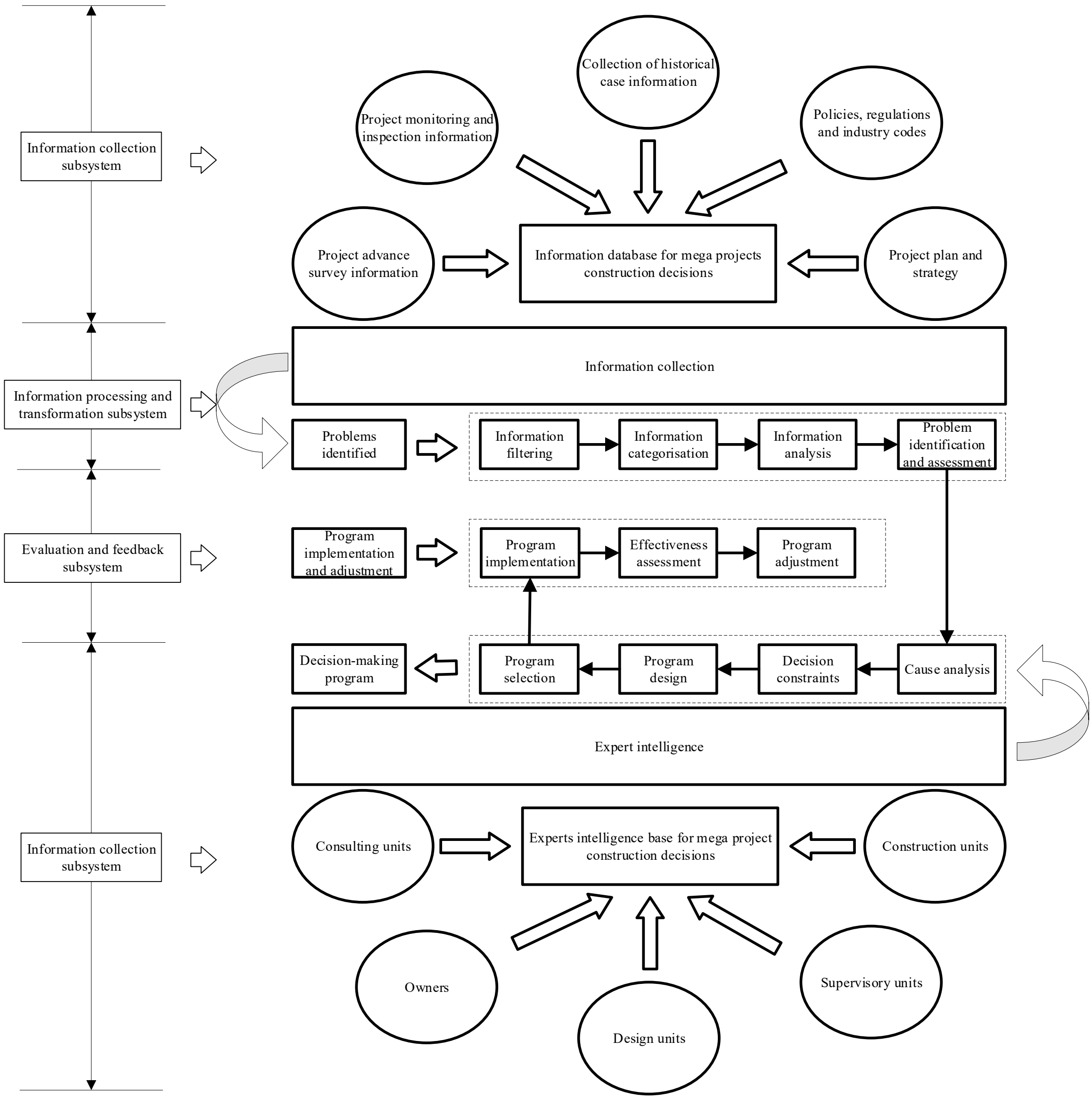

Figure 4. Decision-making and dynamic operation mechanism of mega infrastructure projects based on human–computer collaborative thinking.

4.2. Information Processing and Transformation Subsystem

The project information processing and transformation subsystem is an important part of the dynamic decision-making of mega infrastructure projects, which is led by human intelligence and assisted by computers. Using decision-making information pre-processing methods, decision-making information analysis methods, decision-making information evaluation methods, logical thinking, creative thinking, and accumulated knowledge and experience, the filtering and categorization of information data is achieved. In addition, statistical analysis methods are used to transform information into analysis results [50], from which problems can be identified and evaluated. In view of the complexity and long-term nature of the construction of mega infrastructure projects, the collected information data often have significant characteristics, such as being massive, multi-source, heterogeneous, and interdisciplinary. Moreover, it is increasingly difficult to process and analyze the information data of project implementation. The integrated application of "tool methods" is the "core" of mega infrastructure project decision-making. Therefore, project decision-making relies on the integration and innovation of new data processing analysis tools and methods. According to the existing research results, the information processing and transformation subsystem of mega infrastructure projects can be divided into four parts: information filtering, information categorization, information analysis, and problem identification and assessment. This is shown in Figure 4.

4.3. Human–Computer Collaborative Decision-Making Subsystem

Human–computer collaboration refers to the process of processing, transforming, and analyzing the massive monitoring and inspection information in the process of mega infrastructure projects by computer networks using modeling methods, from which problems can be identified. Then, experts from each unit can evaluate and make decisions. "Factual data" and "tool methods" have laid the foundation for the dynamic decision-making of mega infrastructure projects. However, each link of dynamic decision-making still relies on expert intelligence. The scientific nature of dynamic decision-making cannot be separated from the support of expert intelligence. Generally speaking, expert intelligence is mainly used in information analysis and evaluation, decision-making program formulation, and selection [51]. Therefore, under human–computer collaborative thinking, the real-time participation and collaboration of expert intelligence is particularly important. Scientific and efficient interdisciplinary expert selection and opinion integration are conducive to maximizing the positive role of expert intelligence in mega infrastructure project decision-making. The specific operating mode is shown in Figure 4.

The dynamic decision-making mentioned in this paper mainly refers to the dynamic decision-making carried out in response to the problems encountered in the construction process of mega infrastructure projects. Through consulting experts in the related fields and the relevant literature, it was determined that the decision-making expert database in this paper mainly refers to the decision-making expert team composed of owners, design units, supervisory units, construction units, consulting units, etc., as shown in Figure 4. These experts contribute intelligence and knowledge in the dynamic decision-making process.

4.4. Evaluation and Feedback Subsystem

In the process of mega infrastructure project construction, the successful implementation of a decision-making program often requires trial and error. The evaluation and feedback of the implementation effect of the decision-making program are important parts of the dynamic decision-making process of mega infrastructure projects. Both the Holt's decision model [25] and the multi-criteria decision models [23] mentioned the evaluation and adjustment of the effect of the implemented decision program. Although the theoretical decision-making program combines "factual data", "tool methods", and "expert intelligence", the construction of mega infrastructure projects is dynamically changing, and various environmental factors are intertwined and complex. There is a certain uncertainty in the implementation of the decision-making program. Timely evaluation and adjustment are required. This process of the effectiveness of assessment and program adjustment is also repetitive and dynamic. This is shown in Figure 4.

5. Model Construction and Simulation

5.1. System Objective

The simulation research of the dynamic decision-making operation mechanism of mega infrastructure projects based on human–computer collaborative thinking starts from the establishment of the system objective. This paper mainly studies the dynamic decision-making service mechanism of mega infrastructure project construction led by an operation mechanism under the thinking of human–computer collaboration. Therefore, the goal of the system dynamics model is to comprehensively grasp the dynamic decision-making process of mega infrastructure projects, accurately identify the key elements that affect its operation process, explore the interaction between the key elements, and provide guidance for the owners of mega infrastructure projects to carry out the design and selection of decision-making programs and continuously optimize the operation process of dynamic decision-making of mega infrastructure projects.

5.2. System Boundary Determination

The dynamic decision-making system of mega infrastructure projects is a system with a complex structure and many influencing factors, which is affected by various constraints of the project, information management (collection, processing, and analysis) technology, expert intelligence, and other factors. Its internal structure is complex, and there is multi-level causal feedback among various factors, which is manifested as a nonlinear system with multiple complex feedback loops [52]. Due to the complexity of this multi-loop feedback and non-linear analysis, this feature fully meets the characteristics of system dynamics modeling and simulation. Therefore, this paper uses the system dynamics method to analyze the relationship between the factors of the dynamic decision-making system of mega infrastructure projects.

Under the influence of various factors in the dynamic decision-making of mega infrastructure projects, the system boundary was first defined. Combined with the work of the relevant departments of mega infrastructure projects, this paper uses the Delphi method, questionnaire survey method, field investigation of mega infrastructure projects, and consultation with experts in the industry to analyze the system boundary. The operational process, influencing factors, and participating subjects of the dynamic decision-making of mega infrastructure projects were delineated into the system. We invited experts from universities involved in the scientific research of mega infrastructure projects and industry experts involved in the construction of a mega infrastructure project in Southwest China—a total of eight people—to set up an expert group to define the boundaries of the dynamic decision-making system for the construction of mega infrastructure projects. Eight experts put forward their personal opinions; after three lots of feedback, we understood that the system mainly involves an information collection system, an information processing and transformation platform, a decision support information base, and a decision expert team.

5.3. Cause-and-Effect Diagram of Dynamic Decision-Making System for Mega Infrastructure Projects

In the analysis of the dynamic decision-making information system for mega infrastructure projects, a change in each factor has an impact on the results of the analysis. There is also interaction and mutual influence among various factors. In this paper, the system dynamics software Vensim PLE was used to establish a cause-and-effect diagram of the influencing factors, as shown in Figure 5.

As can be seen from Figure 5, there are two positive feedback loops in the dynamic decision-making operation of mega infrastructure projects, as shown in Table 2.

(1) Loop 1 represents the most basic process of the dynamic decision-making and operation of mega infrastructure projects. Information collection focuses on comprehensiveness and accuracy. By virtue of using the existing scientific and technological level and staffing situation, the implementation of the project is monitored and inspected to collect information. In addition, information is uploaded to the information management platform in a timely manner. The information management platform is used to process and analyze information in conjunction with historical cases of this project and similar projects' cases to improve the efficiency of mega infrastructure project decision-making. After that, the problem identification and assessment are carried out. The problem identification is carried out by the decision-making experts according to the project plan and strategy, policies, regulations, and industry codes. The problem assessment is carried out according to the relevant assessment methods and rules. The decision-making experts carry out the cause analysis by combining the historical cases of this project and the historical cases of

similar projects. The decision-making experts combine the problem assessment results, the causes of the problems, and the decision-making constraints, using certain decision-making models and methods to design programs, among which the owners select the best program. Finally, the construction unit implements the decision-making program and the owners evaluate the effectiveness of program implementation;

(2) Loop 2 represents the process of updating the historical case database when the dynamic decision-making of mega infrastructure projects runs. Firstly, the reasons for the problem are identified by searching and matching from the historical case database of this project. It provides reference ideas for the decision-making program. Once the decision-making programs are completed, the optimal program needs to be selected and implemented and its effectiveness evaluated. Finally, the decision-making process is formed into a case to update the historical case database of the project, and it further improves and enriches the historical case database of the project.

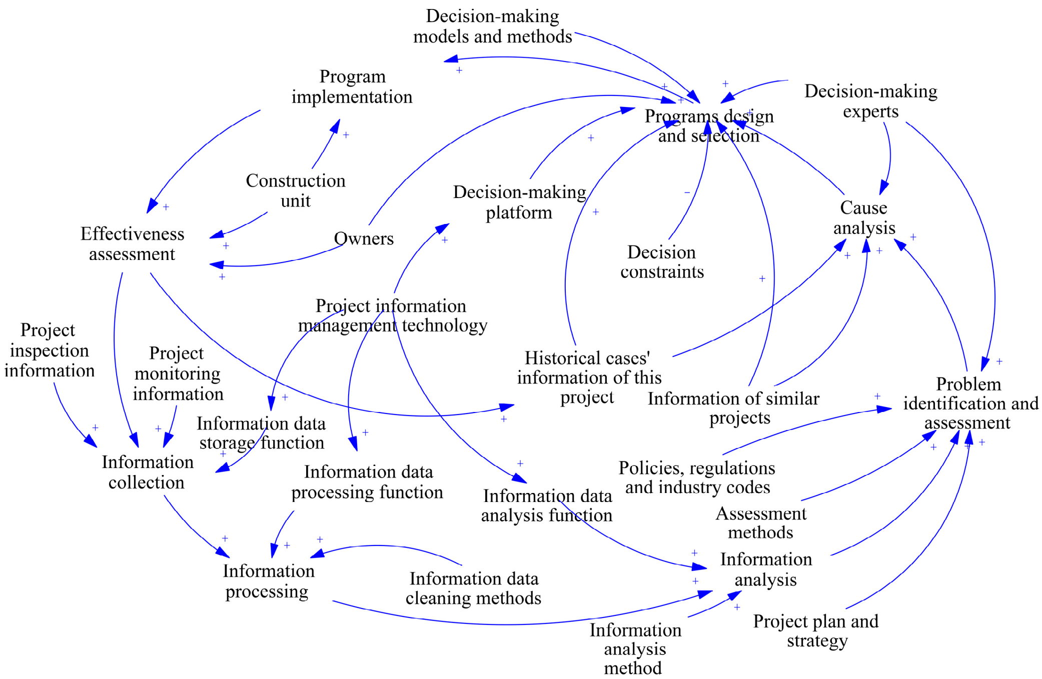

Figure 5. The cause-and-effect diagram of the dynamic decision-making mechanism for mega infrastructure projects based on human–computer collaborative thinking.

5.4. Simulation Flow Diagram of Dynamic Decision-Making System for Mega Infrastructure Projects

Although the logical relationship and feedback loops among the elements are clarified through the cause-and-effect diagram, the essence and structural relationship of the system elements cannot be fully revealed [53]. The system flow diagram has the ability to reflect the interaction form of various variables in the system. A dynamic system model with a feedback structure can be established after quantifying each feedback loop. Human–computer collaborative intelligent decision-making thinking has a guiding effect on the dynamic decision-making mechanism of mega infrastructure projects. The change of thinking leads to the application of related technologies and measures. The presentation of the influence of human–computer collaborative thinking is mainly based on the performance of relevant measures. Therefore, this paper comprehensively considers the reality of the dynamic decision-making practice of mega infrastructure projects and the scientific nature of data and constructs a system flow diagram of the dynamic decision-making mechanism of mega infrastructure projects based on human–computer collaborative decision-making thinking according to the cause-and-effect diagram, as shown in Figure 6.

Table 2. Dynamic decision-making operation feedback loop of mega infrastructure projects.

Loop Number	Type of Feedback	Loop Details
Loop 1	Positive feedback	Information collection → Information processing → Information analysis → Problem identification and assessment → Causes analysis → Solution design and selection → Decision-making solution implementation → Implementation effect evaluation → Information collection
Loop 2	Positive feedback	Historical case information on this project → Analysis of causes → Solution design and selection → Decision-making solution implementation → Evaluation of implementation results →Historical case information on this project

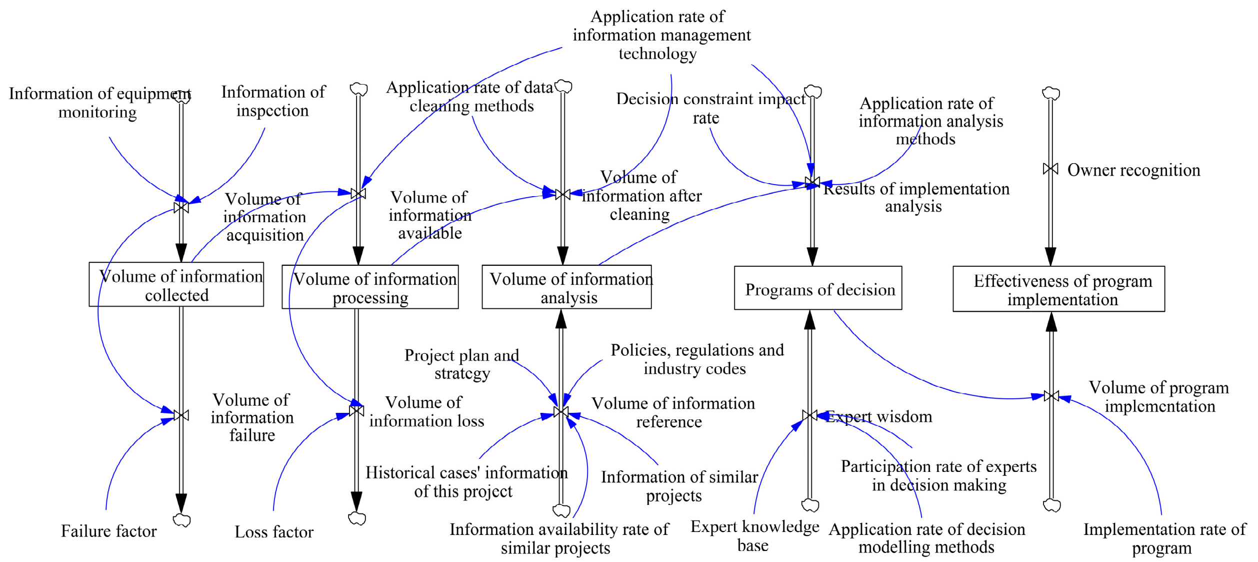

Figure 6. Flowchart of dynamic decision-making mechanism for mega infrastructure projects based on human–computer collaborative thinking.

According to Figure 6, the system is mainly composed of 32 variables, including 5 level variables, 10 rate variables, and 17 constants, as shown in Table 3.

Establishing system variable equations and setting parameters are digital representations oriented to the interaction and the way they act among the elements of the system [58]. The dynamic decision-making mechanism of mega infrastructure projects based on human–computer collaborative thinking is characterized by complexity and dynamism. It has certain theorization, broadness, and geographical differences in terms of quantifying the influencing factors. It is difficult to obtain specific data that can express the relationship and influence among the elements through questionnaires, research interviews, or historical data in a single way in concrete implementation. In addition, the process of simulation is not about how realistic it is but about its usefulness and the extent to which it reveals how things change. Although the parameters in the model, in many cases, lack accurate data, the system dynamics model reveals changes in the evolutionary trend of the whole system and does not require precise results [40]. The correctness of the structure of the system dynamics model is more important than the choice of the parametric values. Therefore, in this paper, the initial assignment of parameters was performed through the review of historical mega infrastructure project construction-related materials and interviews with experts in the field, who have participated in the construction of mega infrastructure projects. For example, the initial values of level variables and rate variables were determined by consulting 56 experts within the construction industry, and some constants were derived on the basis of reference to the existing research results and expert opinions. Based on the initial parameter settings, the final model was determined after several times of debugging and verification. Information on the consulting experts is shown in Table 4. The specific equation design and parameter descriptions are shown in Table 5.

Table 3. Names and types of variables.

Variable Type	Name of Variables	Reference
Level variables (5)	Volume of information collected (y_1), volume of information processing (y_2), volume of information analysis (y_3), programs of decision-making (y_4), effectiveness of program implementation (y_5)	[29,54,55]
Rate variables (10)	Volume of information acquisition (x_1), volume of information failure (x_2), volume of information available (x_3), volume of information loss (x_4), volume of information after cleaning (x_5), volume of information reference (x_6), results of implementation analysis (x_7), expert intelligence (x_8), owner recognition (x_9), volume of program implementation (x_{10})	[29,56,57]
Constants (17)	Information on equipment monitoring (c_1), information on inspection (c_2), failure factor (c_3), application rate of information management technology (c_4), application rate of data cleaning methods (c_5), loss factor (c_6), project plan and strategy (c_7), policies, regulations, and industry codes (c_8), historical case information on this project (c_9), information on similar projects (c_{10}), information availability rate of similar projects (c_{11}), decision constraint impact rate (c_{12}), application rate of information analysis methods (c_{13}), expert knowledge base (c_{14}), participation rate of experts in decision-making (c_{15}), application rate of decision modeling methods (c_{16}), implementation rate of program (c_{17})	[11,20,57]

5.5. Model Simulation

The purpose of validity testing is to check the validity of the model results and verify whether the information and behavior associated with the model reflect the characteristics and change patterns of the actual system. Therefore, Vensim PLE 9.3.5 software was needed to check the dynamic decision system model of the mega infrastructure projects to ensure the proper operation of the system model simulation. After constructing the system dynamics model, it was necessary to perform simulation tests according to the pre-set equations and initial values of the parameters. We used Vensim PLE software to test the simulation effect of the system dynamics model and then analyzed the validity and rationality of the simulation results. On this basis, we selected the main variables to complete the sensitivity analysis operation to understand its effect on the dynamic decision-making operation mechanism of mega infrastructure projects.

5.5.1. Model Simulation Analysis

Validity testing was required to verify that the information and behavior associated with the model reflect the characteristics and patterns of change in the actual system. This paper uses Vensim PLE software to test the validity of the model of the dynamic decision-making system operation mechanism of mega infrastructure projects. With reference to the existing related research, the simulation time was limited to 12 months, and the time step was 1 month. The five main variables of the volume of information collected, the volume of information processing, the volume of information analysis, the programs of decision-making, and the effectiveness of program implementation were selected for monitoring. The change patterns of the above variables in the system were observed, and the simulation results of the main variables of the model under the established parameters are shown in Figure 7.

Table 4. Information on consulting experts.

	Variable	Category	Number	Percentage (%)
Project information	Project type	Railway	30	53.57
		Road	9	15.71
		Public building	11	19.11
		Hydropower	4	6.79
		Others	2	3.57
	Project duration (years)	1~3	10	18.21
		4~6	15	27.32
		7~9	17	30.36
		10~12	13	23.04
		>12	1	2.14
Information on respondents	Types of respondent firms	Owner	13	23.75
		Designer	11	19.64
		Contractor	15	26.79
		Supervisor	7	11.96
		Government	4	6.43
		Supplier	6	10.71
	Gender	Men	46	82.14
		Women	10	17.86
	Education background	College or below	7	12.32
		Bachelor	0	0.00
		Master	32	57.50
		Doctor	14	25.18
	Work experience (years)	<5	3	5.18
		5~10	4	7.14
		11~15	17	30.71
		16~20	23	40.89
		>20	8	14.11
	Professional qualification	Project manager	4	6.43
		Department manager	11	19.64
		Project engineer	9	15.71
		Professional technician	23	40.89
		Others	10	17.86

(1) The volume of information collected is increasing.

During the construction of a mega infrastructure project, the operation of the project is monitored by various monitoring equipment at all times, and there will also be supervisory units and owners visiting the site regularly to check the construction situation. All these means are carried out to collect information. On the one hand, the information can be collected by a variety of space–sky–earth integrated intelligent sensing technology and equipment to monitor the implementation process of mega infrastructure projects in real time. On the other hand, the information can be collected through the construction unit personnel self-inspection and the inspection of supervisory units and owners. The construction situation of mega infrastructure projects is complex and changeable, which will make some of the acquired information data lose its own value as time goes by and then lead to data failure. However, in this information and digitalization environment, efficient data acquisition technology and multi-source data collection channels can still make the amount of data collected by the project management information system increase continuously;

(2) The volume of information processing and analysis are growing in tandem.

The growth rate of information processing volume is slightly flat at first compared with the later stages due to the low popularity of information processing technology and tools and the impact of the data loss factor. It also restricted by the speed of information analysis. With the increasing maturity of information processing technology and the deepening and improvement of the scope of project information monitoring and inspection, the speed of information processing is improved. The historical case information on this project and the information on similar projects provide useful supplements for information analysis. Information analysis experts transform existing information resources by applying professional information analysis methods and the powerful information data analysis function of the information management platform, and the quality and quantity of information analysis results are continuously improved;

(3) The effectiveness of program implementation is positively correlated with the programs of decision-making, and both show an increasing trend.

Table 5. The description of equation design and parameter.

Variables	Equations and Initial Values	Description
Volume of information collected (y_1),	INTEG ($x_1 - x_2$, 5000)	Using integral functions
Volume of information processing (y_2)	INTEG ($x_3 - x_4$, 0)	
Volume of information analysis (y_3)	INTEG ($x_5 + x_6$, 0)	
Programs of decision − making (y_4)	INTEG ($x_7 + x_8$, 0)	
Effectiveness of program implementation (y_5)	INTEG ($x_9 \times x_{10}$, 0)	
Volume of information acquisition (x_1)	$c_2 + c_1$	Using linear correlation functions
Volume of information failure (x_2)	$x_1 \times c_3$	
Volume of information available (x_3)	$y_1 \times c_4$	
Volume of information loss (x_4)	$x_3 \times c_6$	
Volume of information after cleaning (x_5)	$y_2 \times c_4 \times c_5$	
Volume of information reference (x_6)	$c_7 + c_8 + c_9 + c_{10} \times c_{11}$	
Results of implementation analysis (x_7)	$y_3 \times c_{13} \times c_{12} \times c_4$	
Expert intelligence (x_8)	$c_{14} \times c_{15} \times c_{16}$	
Owner recognition (x_9)	0.6	Consulting with experts in the field of mega infrastructure project construction
Volume of program implementation (x_{10})	$y_4 \times c_{17}$	
Information on inspection (c_2)	1000	Based on existing research and experience in the construction of mega infrastructure projects
Information on equipment monitoring (c_1)	4000	
Failure factor (c_3)	0.03	
Loss factor (c_6)	0.02	
Application rate of information management technology (c_4)	0.5	
Application rate of data cleaning methods (c_5)	0.8	
Project plan and strategy (c_7)	1000	
Policies, regulations, and industry codes (c_8)	3000	
Historical case information on this project (c_9)	7000	
Information on similar projects (c_{10})	15,000	
Information availability rate of similar projects (c_{11})	0.05	
Application rate of information analysis methods (c_{13})	0.6	
Decision constraint impact rate (c_{12})	0.2	
Expert knowledge base (c_{14})	10,000	
Participation rate of experts in decision − making (c_{15})	0.7	
Application rate of decision modeling methods (c_{16})	0.6	
Implementation rate of program (c_{17})	0.8	

Programs of decision-making are influenced by factors such as the participation rate of experts in decision-making, the expert knowledge base, the application rate of decision modeling methods, the decision constraint impact rate, etc. The increase in the information analysis volume of mega infrastructure projects continuously promotes the output of implementation analysis results. These analysis results combined with expert intelligence jointly promote the output of decision-making programs. The programs of decision-making discussed and reasoned by relevant experts are approved by owners and then passed through docking to each unit of the project to implement. Constrained by the quality and quantity of the pre-decision programs, the volume of program implementation is low, which leads to less effective program implementation. With the continuous output of high-quality programs of decision-making, the effectiveness of program implementation is improving continuously. The improvement from the implementation of the program further enhances the influence of the dynamic decision-making system. Therefore, the effectiveness of program implementation is weak in the early stage and significantly enhanced in the middle and late stages.

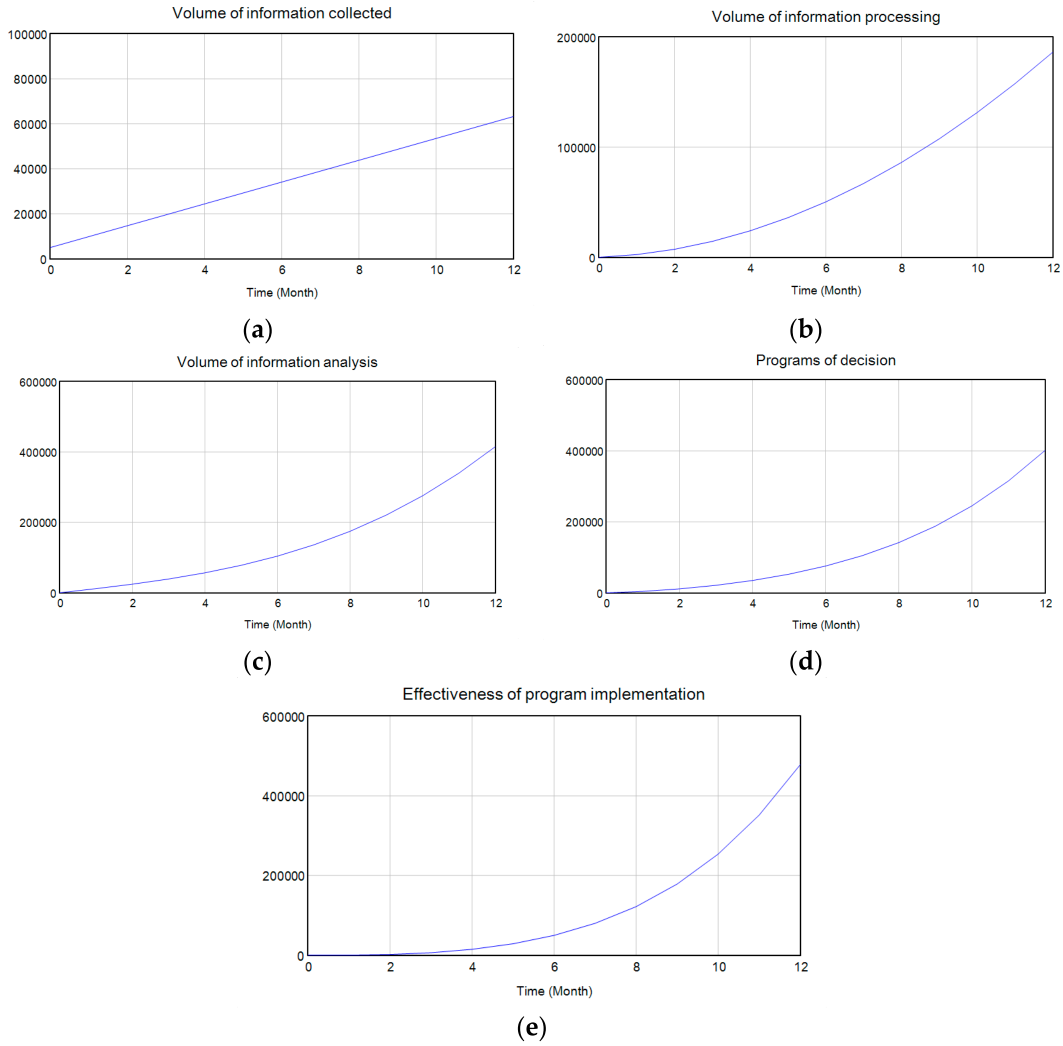

Figure 7. Simulation results of main variables of the system model. (**a**) represents Volume of information collected, (**b**) represents Volume of information processing, (**c**) represents Volume of information analysis, (**d**) represents Programs of decision, (**e**) represents Effectiveness of program implementation.

Thus, it can be seen that the performance of the volume of information collected, the volume of information processing, the volume of information analysis, the programs of decision-making, and the effectiveness of the program implementation is consistent with the reality of the dynamic decision-making operation of mega infrastructure projects, indicating that the model can accurately reflect the operation system of the dynamic decision-making mechanism of mega infrastructure projects based on human–computer collaborative thinking. It has a certain significance for the design of dynamic decision-making programs for mega infrastructure projects.

5.5.2. Sensitivity Analysis

Sensitivity analysis was performed by changing the parameter values of important variables to observe the resulting dynamic changes in the simulation results, thus analyzing the impact of the adjusted variables on the system and the degree of influence. On the basis of the analysis of the dynamic decision-making mechanism of the project, combined with the constructed cause–effect diagram and system flow diagram, five elements were selected for sensitivity analysis. They were the application rate of information management technology, the application rate of data analysis methods, the participation rate of experts in decision-making, the historical case information on this project, and the information on similar projects. In this paper, four subsystems were constructed, and five key factors are the key representative elements of the four subsystems, among which the application rate of information management technology has a key influence on all five subsystems. The data analysis method is the key element of the data processing and transformation subsystem. Expert wisdom, historical case information on this project, and the information on similar projects are the keys of the human–computer collaborative decision-making subsystem. The implementation effect of the engineering decision program is closely related to the information analysis and result production links, and the above five elements, as important factors supporting the output of information products and decision results, can significantly show their effect on the role of the system model.

(1) The application rate of information management technology

The parameter values of the application rate of the information management platform were set to 0.5, 0.1, and 0.9 to obtain three simulation curves, as shown in Figure 8. By comparing and analyzing the simulation results, it is concluded that the change of application rate of information management technology has an obvious positive impact on the implementation effect of the engineering decision-making program. The process of mega infrastructure project construction is filled with a huge amount of complex data, which needs to be collected, processed, and analyzed using information management technology. High-quality data are the source and basis of outputting high-quality decision-making programs, which can influence the effectiveness of program implementation. Therefore, mega infrastructure project construction should actively introduce information technology and digital technology to enhance operation efficiency and quality and strive to improve the impact of decision-making programs;

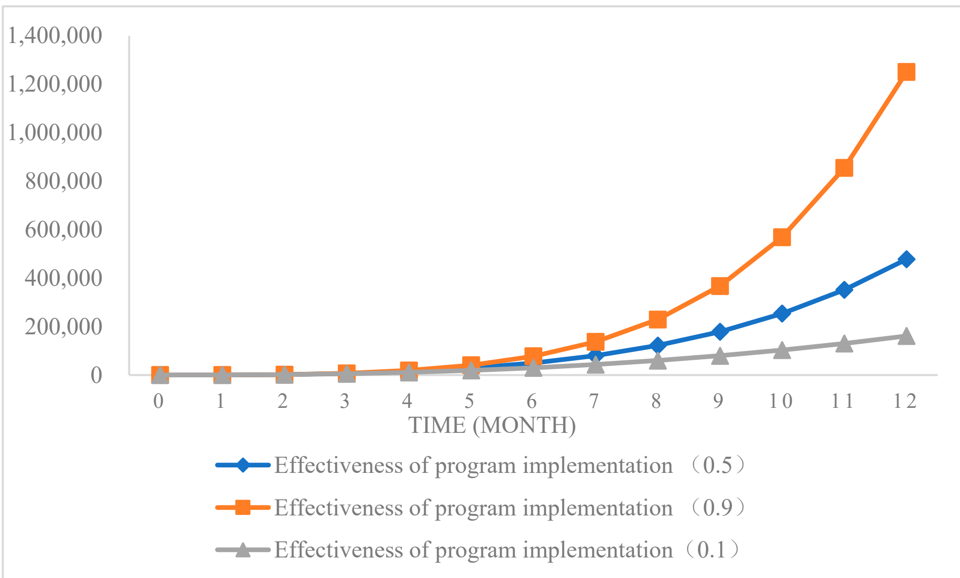

Figure 8. Changes in the sensitivity of the application rate of information management technology on the effectiveness of program implementation.

(2) Application rate of information analysis methods

The parameter values of the application rate of information analysis methods were set to 0.6, 0.2, and 0.9, and three simulation curves were obtained, as shown in Figure 9. By comparing and analyzing the simulation results, it is concluded that the application of information analysis methods can significantly improve the implementation effect of decision results. A variety of information analysis methods, such as information measurement analysis and content analysis, can improve the efficiency of information data result transformation under combined use with the information management platform and provide support for the engineering decision-making program design. Therefore, the construction of mega infrastructure projects should pay attention to the application of information analysis methods and combine the scientific and reasonable use of information analysis methods with the needs of mega infrastructure projects to promote the output of decision-making results;

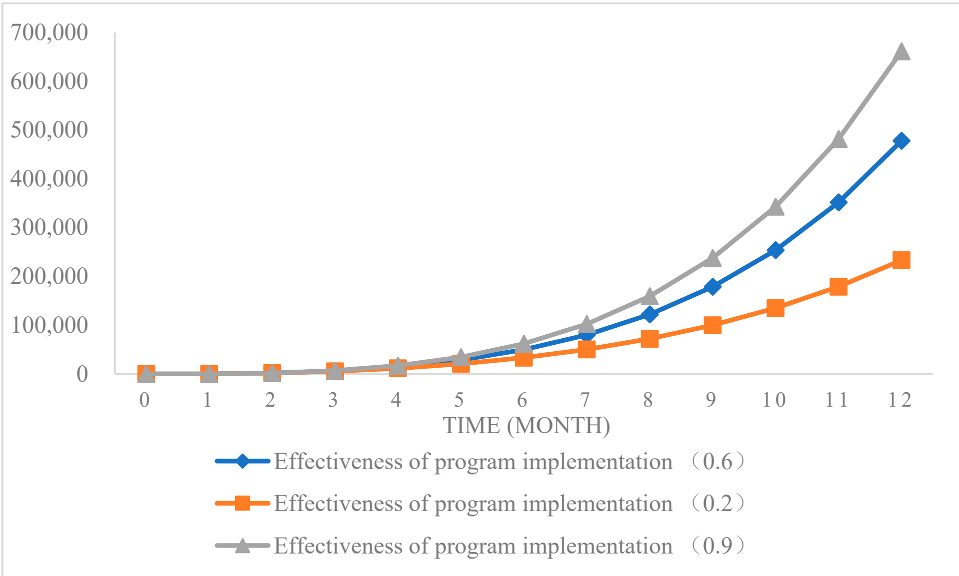

Figure 9. Changes in the sensitivity of the application rate of information analysis methods on the effectiveness of program implementation.

(3) Participation rate of experts in decision-making

The parameter values of the experts' participation rate in decision-making were set to 0.7, 0.2, and 1, and three simulation curves were obtained, as shown in Figure 10. By comparing and analyzing the simulation results, it is concluded that the experts' participation rate in decision-making and the effectiveness of program implementation are positively correlated. In addition, the implementation effect of the dynamic decision-making program of mega infrastructure projects needs the support of a construction expert team. The project information analysis results need to be sublimated with the participation of the expert team and processed into a decision-making program that can be delivered to the owners through the experts' empirical reasoning and deliberative thinking. Therefore, the construction of mega infrastructure projects should pay attention to the selection and application of an expert team and gather experts with both theoretical foundation and practical experience in the construction of mega infrastructure projects based on research projects. Through the synergy of the information management system and expert intelligence, the intelligent decision-making of mega infrastructure projects is carried out to enhance the effectiveness of decision-making program implementation;

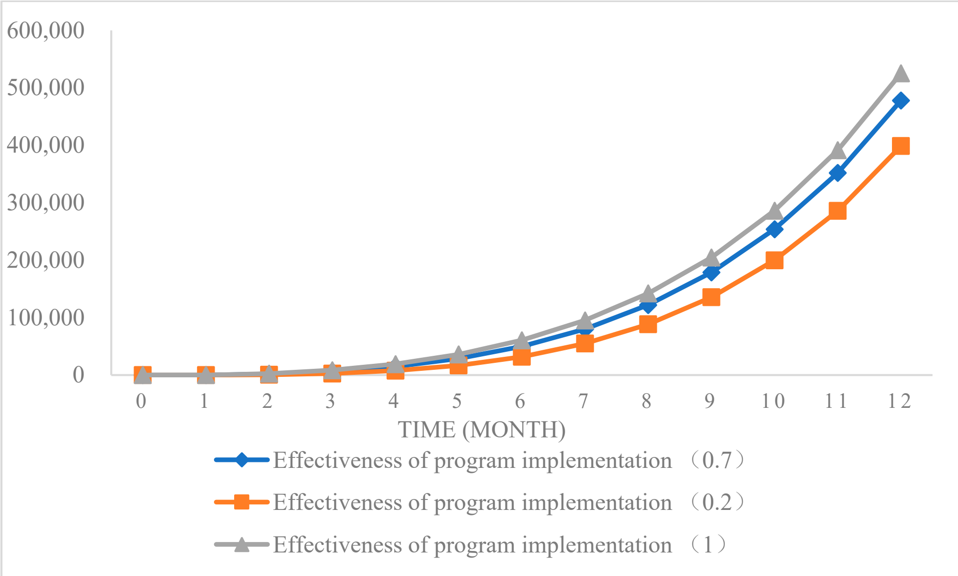

Figure 10. Sensitivity change of participation rate of experts in decision-making on the effectiveness of program implementation.

(4) Historical case information on this project

The parameter values of historical case information on this project were set to 7000, 2000, and 10,000, and three simulation curves were obtained, as shown in Figure 11. By comparing and analyzing the simulation results, it is concluded that the effectiveness of mega project construction decision-making program implementation is influenced by the historical case information on this project. The more available information obtained from it, the more significant the influence is. As they are decisions in the same project, the decision environment, influencing factors, and constraints have a high degree of fit. Therefore, the historical case information on this project has a direct and close connection with the new problems and decisions. Therefore, the usability is high, which can give reliable information support to the decision experts. Therefore, it can serve as a useful supplement to decision information analysis, shorten the information analysis time, and accelerate the output of results. It has a more obvious impact on project decision-making in the later information analysis and result production stages;

(5) Information from similar projects

The parameter values of information on similar projects were set to 15,000, 2000, and 30,000, and three simulation curves were obtained, as shown in Figure 12. Through the comparative analysis of the simulation results, it is concluded that the effectiveness of program implementation is related to the information on similar projects. In addition, the information on similar projects can promote the effectiveness of program implementation. Through the curve changes caused by the numerical changes, we found that the available information provided by the similar project cases is significantly reduced due to the influence of the information availability rate of similar projects. The information provided by the similar project cases can have an impact on the effectiveness of program implementation to a certain extent, but it does not cause too much fluctuation. The information on similar projects is composed of various types of construction project information, which can meet the cross-discipline information resource demand of mega infrastructure project construction decision-making by breaking the information barrier and alleviating the problem of an "information silo". Therefore, regardless of the amount of information provided, the information on similar projects will have a positive impact on the effectiveness of program implementation.

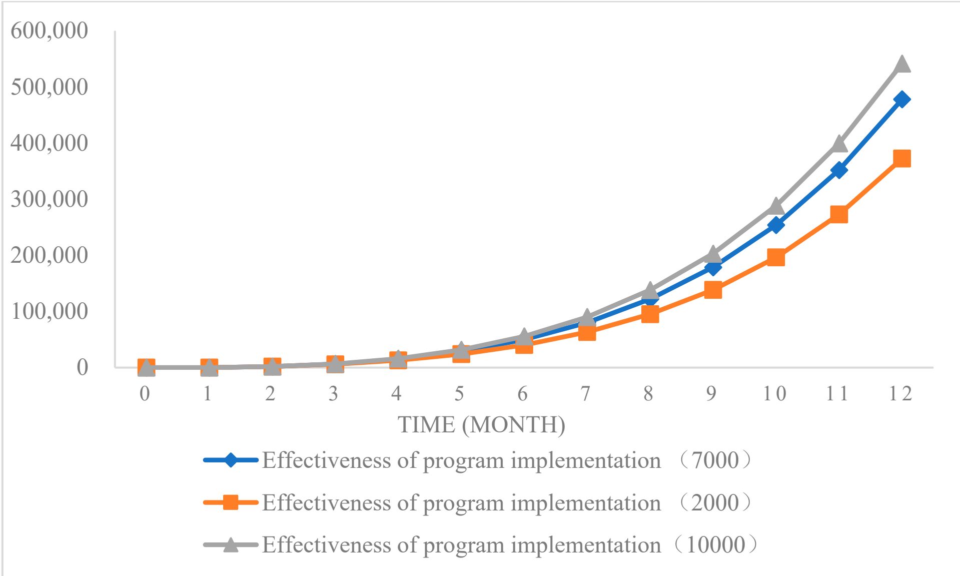

Figure 11. Sensitivity change of the historical case information on this project on the effectiveness of program implementation.

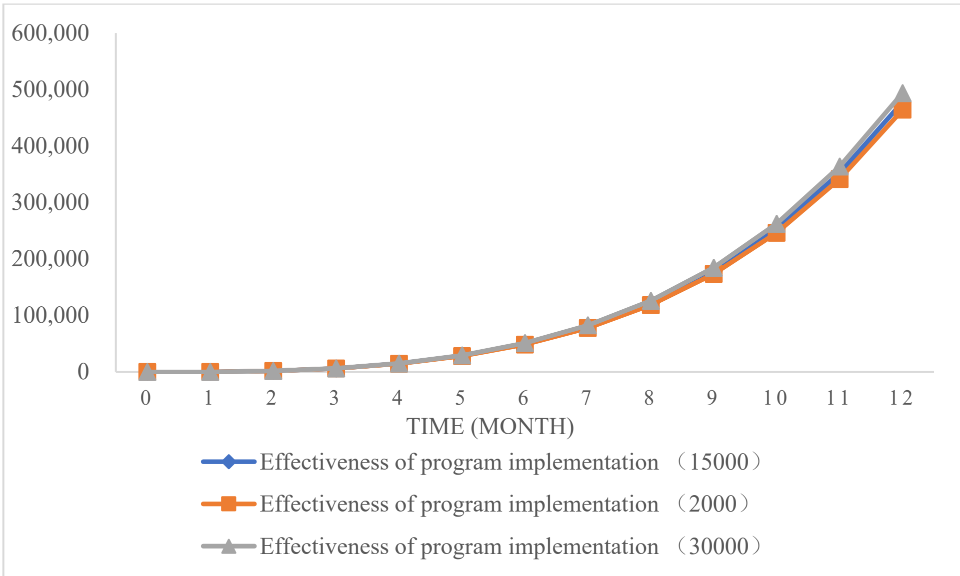

Figure 12. Sensitivity change of the information on similar projects on the effectiveness of program implementation.

6. Discussion

6.1. About Model Construction

Szafranko, E [28] considered decision-making to be a process that includes activities such as expressing decision-making needs, collecting and processing data to support decision-making, measuring results, and finally, evaluating the implementation of the chosen program and the extent to which it meets the evaluation criteria at the beginning of the process. The dynamic decision-making model of mega infrastructure projects constructed in this paper basically agrees with the views of the scholar, but there are still different views in some aspects. For example, this paper believes that the first step of dynamic decision-making in major projects should be collecting information and discovering problems through the analysis of actual information, rather than expressing decision-making needs first and then collecting and processing data. This is related to the characteristics of mega infrastructure projects; the major strategic position of mega infrastructure projects and their complexity determines that they must be monitored and inspected in real time, from which problems are identified, and then decisions are made. In addition, this paper not only specifies the content of information collection but also further refines the information data processing process into four processes: information filtering, information categorization, information analysis, and problem identification and assessment.

6.2. About Key Influencing Factors

The results of the sensitivity analysis of the five key influencing factors show that the application rate of information management technology and the application rate of information analysis methods have higher sensitivity to the effectiveness of program implementation, the participation rate of experts in decision-making, and the historical case information on this project have average sensitivity to the effectiveness of program implementation, and the information on similar projects has lower sensitivity to the effectiveness of program implementation. Therefore, more attention should be paid to the improvement of the application rate of information management technology and the application rate of information analysis methods in the process of mega infrastructure project decision-making. This is consistent with the idea mentioned by Sheng, Z. in his book [5], which is verified in this paper using model simulation and sensitivity analysis.

7. Conclusions

This paper researches the dynamic decision-making mechanism in the construction process of mega infrastructure projects based on the perspective of human–computer collaboration and intelligent decision-making thinking and constructs the dynamic decision-making mechanism of mega infrastructure projects based on intelligent decision-making thinking in three aspects: the organization mechanism, the operation mechanism, and the guarantee mechanism. On this basis, a simulation and sensitivity analysis were carried out by establishing a system dynamics model. The results show that the performance of key variables, such as the volume of information collected, the volume of information processing, the volume of information analysis, the programs of decision-making, and the effectiveness of program implementation is in line with the reality of the mega infrastructure project dynamic decision-making operation. In addition, the five elements of the application rate of information management technology, the application rate of information analysis methods, the participation rate of experts in decision-making, the historical case information on this project, and information from similar projects all have a positive impact on improving the effectiveness of the program implementation of mega infrastructure projects. The mechanism construction and simulation analysis provide useful reference for optimizing the design process of the decision-making program of mega infrastructure projects.

Based on the inheritance of the overall idea of traditional engineering decision-making, this study integrates the technical means of information and digitalization into the framework of the decision-making mechanism for the construction of mega infrastructure projects. It also introduces dynamic decision-making theory into the field of mega infrastructure project construction. This study clarifies the system of influencing factors and their interaction influence paths that affect the dynamic decision-making of mega infrastructure project construction from a data-driven perspective and establishes a theoretical model of the dynamic decision-making mechanism of mega infrastructure project construction based on the data. It further improves the framework of the theoretical system of dynamic decision-making for the construction of mega infrastructure projects.

Finally, there are two main limitations of the dynamic decision mechanism model for mega infrastructure project construction constructed in this paper. One is that it still needs to rely on expert knowledge and experience for brand-new and never-before-seen problems that arise during the construction of mega infrastructure projects. Second, this study has currently constructed a theoretical level decision-making mechanism based on the existing literature and actual research on mega infrastructure projects, but if it is to be implemented in the construction process of large infrastructure projects, it needs to be combined with the actual situation of the project's organizational structure and information collection technology. For example, the organizational structure of a mega infrastructure project in Southwest China is a three-level management mechanism, and the problems arising in the process of project implementation are subject to hierarchical decision-making, and the weight of decision experts is also considered in the decision-making process. These limitations will be further studied in depth in our subsequent research.

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