博 士 論 文

Study of factors influencing the practical application of parametric design and robotic automated construction

パラメトリック設計とロボットによる自動化施工の実用化に影響を与える要因に関する研究

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ABSTRACT

The construction industry has always been an important part of human economic activity. As time goes on, building techniques and construction methods are changing. However, with the increasing acceleration of social development, traditional construction methods have reached their limits. Both in China and Japan are facing the problem of aging population structure and low birth rate. The human demand for complex forms of construction is growing, yet experienced workers are in short supply. The construction industry continues to undergo industrial upgrading, while the rise of digital design and the widespread use of robotics point the way to the future of the construction industry. We hope to explore the possibilities of parametric design and robotic automated construction through two practical projects. W At the same time, a tripartite evolutionary game model is developed to explore the factors that influence the implementation of automated robotic construction under normal circumstances, based on the interests between the government, construction companies and public universities. Then, we analyze the interests of the construction industry under the influence of COVID-19 pandemic, establish the evolutionary game model of the government and construction companies, and explore the impact of the pandemic on the industrial upgrading of the construction industry.

In Chapter 1, RESEARCH BACKGROUND AND PURPOSE OF THE STUDY. Chapter 1 presents the research background of parametric design and robotic automated construction, including the current status and bottlenecks of integrated technology development. and the significance of digital transformation in the construction industry. Then, the development and current status of robotic automated construction in the world and China are presented. It is pointed out that the combination of parametric design and robotic construction is crucial to achieve digital transformation in the construction industry. Finally, the purpose of the study and the logical framework are presented to help reviewers understand the content of this paper.

In Chapter 2, LITERATURE REVIEW OF PARAMETRIC DESIGN AND ROBOTIC AUTOMATED CONSTRUCTION. This chapter provides a review of the relevant studies in this paper. It includes the development and current status of parametric design, the current development of robotic automated construction and the development of digital-related technologies in the construction industry. In addition, the significance and scope of use of the evolutionary game model is explained. Based on the previous studies, this paper helps to combine them to understand and explore the influencing factors that affect the application of robotic automated construction and

is explained. Based on the previous studies, this paper helps to combine them to understand and explore the influencing factors that affect the application of robotic automated construction and contribute to its development and implementation.

In Chapter 3, FOR THE EVOLUTIONARY GAME ANALYSIS OF RAAC IMPLEMENTATION UNDER NORMAL CONDITIONS. This chapter begins with an analysis of the current problems in the construction industry, namely low productivity and poor sustainability, while noting that both China and Japan are facing the challenges of low population growth and increasing aging. While there have been many studies that point to robotics and automated construction as the key to breaking the ice, there has been little practical application. This paper analyzes the interests of the government, construction companies, and public universities by analyzing the relationship between them. A three-way evolutionary game model is developed to analyze the evolutionary trends of decision making under different conditions and explore the influencing factors that affect the actual adoption of RAAC. It provides a reference for the decision making of stakeholders.

In Chapter 4, EVOLUTIONARY GAME ANALYSIS FOR RAAC IMPLEMENTATION IN THE CONTEXT OF COVID-19. This section builds on the previous chapter by introducing COVID-19 as an influencing factor. In the face of the COVID-19 pandemic, the global construction industry received an unprecedented shock, with the epidemic leading to labor shortages, expenditures on epidemic prevention costs and changes in the labor environment, leaving a large number of construction companies facing bankruptcy. However, the pandemic also brought new opportunities. On one hand, the high cost of pandemic prevention made construction companies desperately in need of new construction models, and on the other hand, it also broke the traditional concept of construction mode change. This chapter analyzes the interests of the government and construction companies in the context of COVID-19 and develops an evolutionary game model. The evolutionary trends under different conditions are analyzed to explore the key parameters affecting the evolution. Theoretical references are provided for the decision-making choices of the government and construction companies.

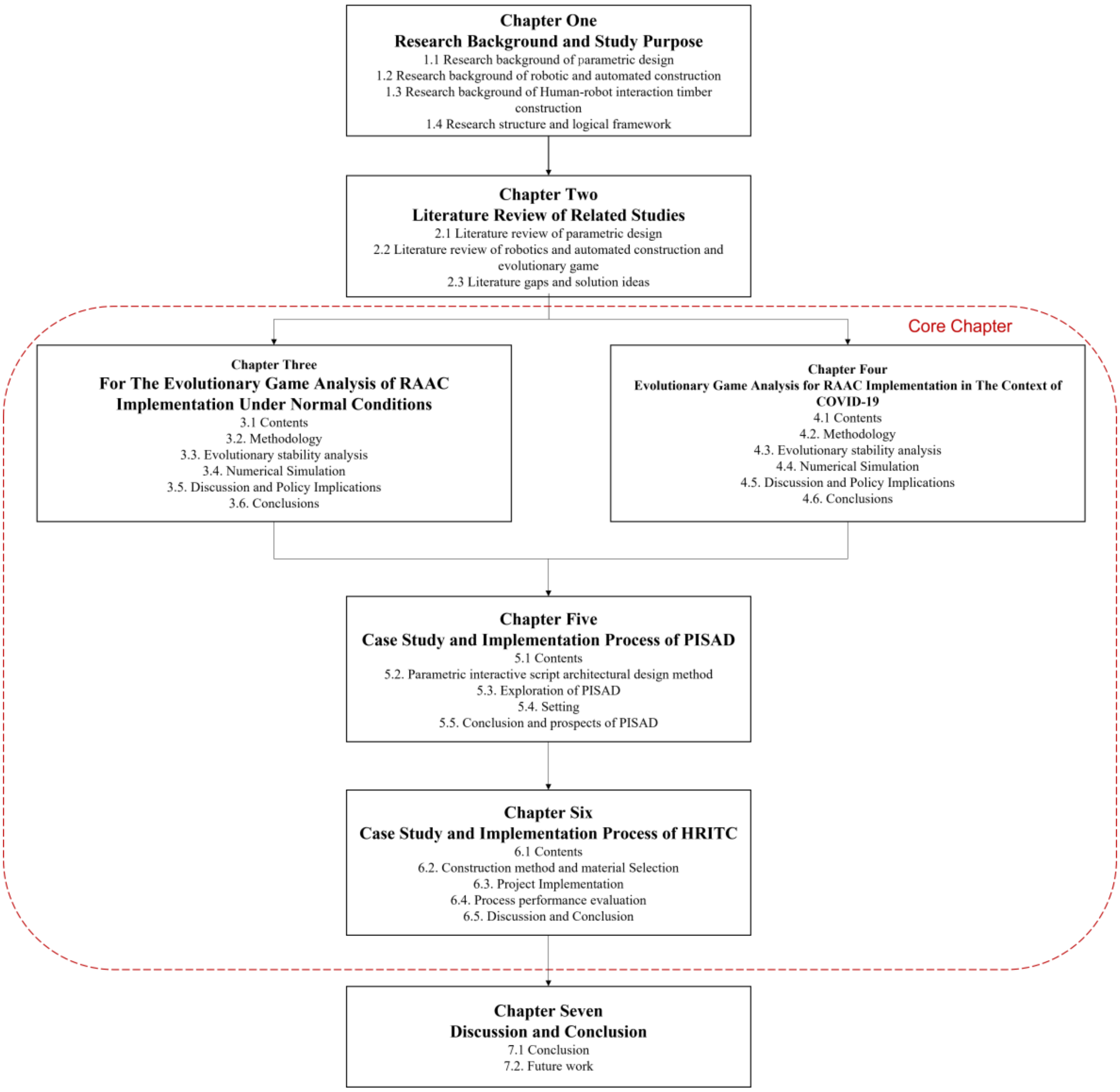
In Chapter 5, CASE STUDY AND IMPLEMENTATION PROCESS OF PISAD. This section presents a rapid interaction design process based on parametric design that allows designers to invite users to participate in design decisions. The feasibility of the flow is verified through an example. The aim is to address the challenge of insufficient design cost and design time faced by small design projects, but users have individual customization needs.

In Chapter 6, CASE STUDY AND IMPLEMENTATION PROCESS OF HRITC. This chapter goes through a practical construction case. A building process for collaborative human-robot construction of complex wood structures is presented, allowing inexperienced laymen to build complex wood structures simply, efficiently, and accurately with the assistance of robots. It allows for the actual construction of parametrically designed 3d models. The purpose of this chapter is to first resolve the paradox that parametric design solutions are too complex and difficult to achieve with manual construction. The second is to verify the potential of robotic and automated construction to improve the efficiency, productivity and sustainability of the construction process. Finally, the problems of high cost of full automation, too much technical difficulty and too many restrictions on construction sites are solved by human-machine collaboration.

In Chapter 7, CONCLUSION AND FUTURE WORK. Conclusion and future work of the chapters are concluded.

冷 逸 博士論文の構成

Study of The Factors Influencing The Practical Application of Parametric Design and Robotic Automated Construction



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Chapter 1

RESEARCH BACKGROUND AND PURPOSE OF THE STUDY

CHAPTER ONE: RESEARCH BACKGROUND AND PURPOSE OF THE STUDY

1.1 Research background of parametric design

After the industrial revolution, modern architectural forms focused more on their functionality in consideration of social and economic development. However, as modernization intensified, aesthetic demands were made on architectural design that went beyond functionality. In the late 1990s, the emergence of mass custom production models met individual needs that were ignored by standard industrial production. At the same time, attempts were made to use digital building technologies to make mass custom production as economical as standardized prefabricated production. Designing for an entire population with diverse needs is challenging and stimulating. Designing to meet the needs of different users according to fit, function, safety, budget, sustainability, regulatory requirements, physio psychological and social needs as the basic variables of the architectural design process[1, 2]. However, limited by factors such as production technology and design cost, the application and promotion of personalized custom production presents certain limitations. As parametric design and other emerging design technologies update and upgrade the architectural design industry, personalized custom production is expected to break through the boundaries of economy and efficiency and become a useful model for current architectural design and construction. In the traditional design process, the generation of design results requires four elements: starting conditions and control parameters (inputs), generation logic (rules and algorithms), generation variables (outputs), and selection of the best variant[3]. The design result is often realized in the fourth step, the early design process highly depends on the designer's perception, cognitive ability, and aesthetic taste to the continuous and dynamic process is the basis of the emergent form[4]. Architecture design entails complex analytical issues. Early conceptual design quality plays a vital role in the entire design life cycle. Typically, architects first translate his/her ideas into architectural sketches or drawings by considering functional requirements, surroundings and spatial constraints (e.g. land area, height). The conceptual design is then converted into initial design. Subsequently, experts and engineers are engaged in detailed planning: at this stage, the design continues to be fluid, often going through multiple rounds of changes and modifications. Ideally, however, the intent and perspective of the conceptual design is preserved through these changes[5].

Architects continue to face challenges related to the interwoven and complex nature of design projects, especially as design demands increase and they need to deal with integrating more and more information from the very beginning of the process. To meet these challenges, designers are seeking newer and more powerful tools. The technological wave of digitalization, which sometimes stimulates them but sometimes overwhelms them, depends largely on their digital culture and context (socio-economic, structural, organizational)[6, 7]. Because of the complexity and variability of architectural design, some architects are seeking design processes that can document change[8]. Although the efficiency of computer-aided drafting tools and computer-aided design tools currently on the market is high, Ger does not satisfy all designers. ref[7] points out that after a survey about 16.5% of designers are not satisfied with the existing design tools. Therefore, this group of designers started using very unusual design tools, level parametric modeling software (e.g. Rhinoceros 3D, Grasshopper). These modelling tools offer the possibility of considering and generating variations in numerous parameters. When implemented, this process is, by its nature and efficiency, quite different from the static characteristics of the more traditional modeling methods used to instantiate models[9]. In response to this phenomenon, researchers have been studying the impact of parametric modeling tools on architectural design for the past decade or so. The scope of the research has focused on optimizing workflows[10], exploring the diversity of building forms[11] and mastering constructability[12].

Parametric design methods are useful for solving specific design problems. Parametric algorithmic design methods are used to explore various design forms for buildings[13]. One of the benefits of using parametric design methods is that design solutions can be easily adjusted based on feedback from the design process, thus allowing for a great deal of flexibility[14]. The flexibility of parametric design methods makes the design process more efficient in terms of time and cost than traditional design methods; this is due to the fact that parametric design methods can automatically generate various design solutions based on the established design logic[15]. These advantages have facilitated the implementation of parametric design methods in sustainable design approaches for various building types[16].

A number of designers have already applied these results to large commercial projects. A large portion of these studies were conducted on stable practices that have been established in large building offices for several years. internationally known. Others, on the other hand, have been conducted in experimental settings, including controlled design conditions (e.g., teaching) that sometimes seem far removed from field reality. Parametric modeling tools have profoundly reshaped the practices of large construction firms[17]. However, for smaller buildings architects are still struggling to cope with the rapid digital transformation[18]. Considering parametric modeling tools, the attitude of these small and medium-sized "everyday architects" that we identify with is still slowly changing. These architects, according to their ability to act, are slowly ready to explore how parametric modeling tools can contribute to project development, better adapted to their expectations and creativity[19, 20].

In the field of small building design research and practice, parametric design methods have been used to solve and evaluate various design problems[21]. For instance, using parametric design to improve the lighting efficiency of residences[22]; Or use parametric design to reduce the energy consumption of the house[23]. There are also attempts to explore the characteristics and relevance of architectural structural design through mathematical modeling, and to concretize abstract aesthetic issues by studying the formation and evolution of the intersection surface generated by the

Mobius belt[24]. The above cases are all trying to simplify the complicated design process, trying to pass the complicated factors that need to be considered in the design process to the computer calculation through the parametric design method, but parametric modeling does not reduce design complexity [25]. Compared with traditional design methods, the introduction of design calculations can help designers make complex decisions with more confidence[26]. Nevertheless, Aesthetics is related to the knowledge and understanding of factors that contribute to the perception of objects or processes, which are considered to be beautiful or a pleasant experience[27] that cannot be described by rational mathematical formulas, in order to content the increasing individual aspirations, architects need to involve users in their designs[28]. Parametric design tools have profoundly influenced the workflow and design thinking of large architectural firms and have enabled many crazy ideas to come to fruition[17]. Now attention needs to be paid to the digital practices and work orientation of architects in small architectural firms. Although studies point to these designers as the largest community of participants in the architectural design industry, their digital transformation needs are rarely considered[29].

In addition, current research addressing digital transformation appears to focus on the development of tools rather than an appreciation of the alignment strategies and workflow adjustments required when integrating these tools. However, the concerns that architects may express may limit them in the adoption process and may also reshape workflows and models that emphasize the early stages of their architectural design process. Therefore, the coexistence of these two scientific approaches is essential and therefore unsustainable in the long run if our goal is to avoid developing technologies that do not fit into the daily reality of architectural small and medium-sized enterprises. This paper proposes a new design process based on parametric design: Parametric interactive script architectural design (PISAD) method is different from the traditional design process(Figure 1-1). While the designer completes the overall logic of the design according to requirements, it reserves adjustable Determine the input parameters of aesthetic details, visualize the adjustment process, allow users to adjust parameters while visually observing the changes in design results, helping users make decisions in a variety of design patterns, saving design time and reducing design costs.

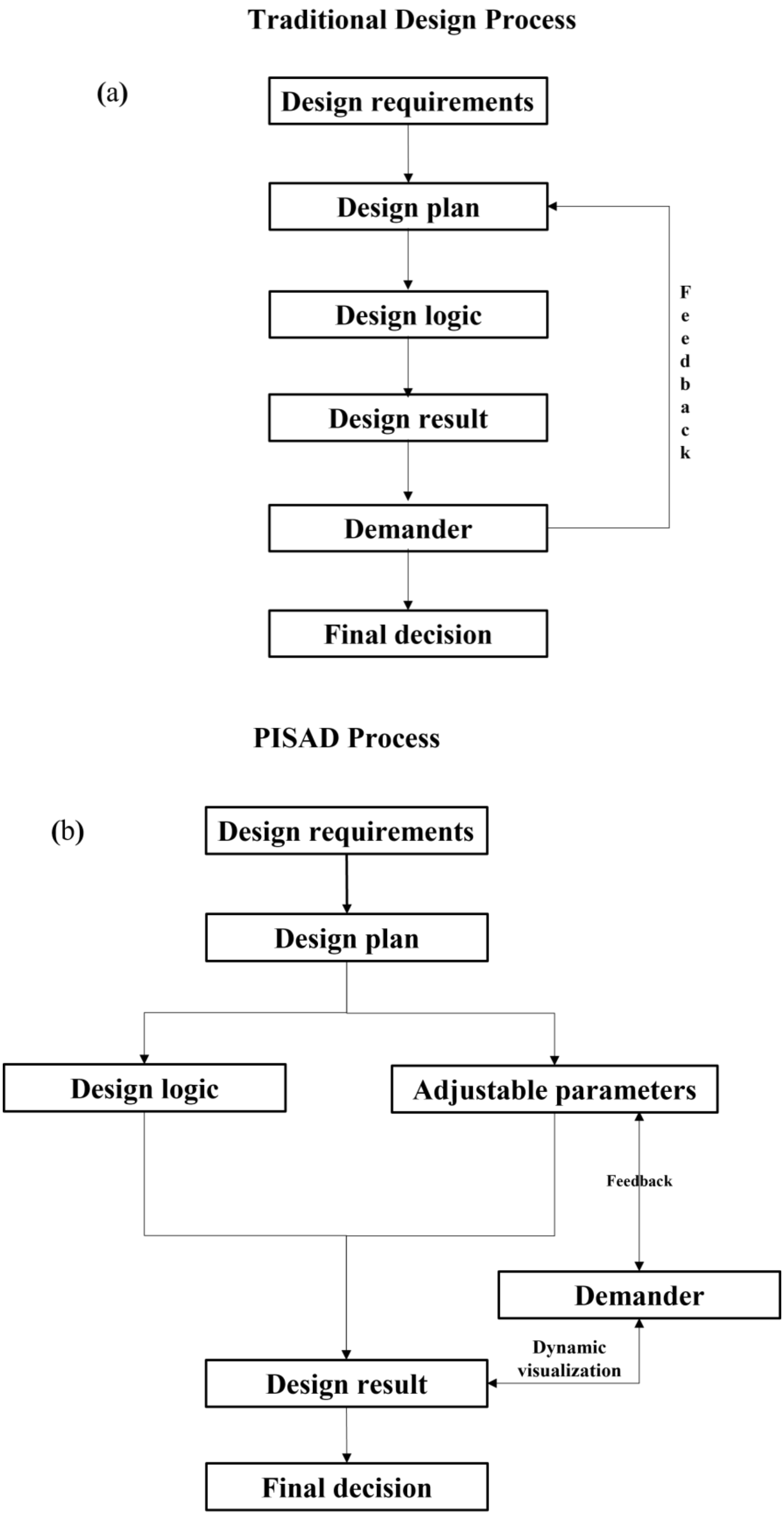

Fig. 1-1 (a)Traditional Design Process. (b)PISAD Process

1.2 Research background of robotic and automated construction

1.2.1 The construction industry faces a shortage of labor

The harmonization of environmental, economic, and socio-cultural development is essential for modern society to pursue sustainability[30-32]. [33, 34] argue that the industry's sustainability can be improved by increasing productivity and economic efficiency. Among all industries, the construction industry has been a significant part of the world's economy and contributes significantly to each country or region's gross domestic product(GDP). However, slow productivity growth is a crucial challenge for the industry[35]. However, the global construction industry has been perceived as tardy in adopting new technologies[36-39], according to McKinsey Global Institute[39]. Over the past few decades, labor productivity in the construction industry has grown at only 1%. Despite generating more than 10 trillion dollars in value annually, the industry faces a shortage of skilled workers, insufficient investment in research and development of advanced technologies, and slow productivity growth[40]. Research strongly suggests that productivity in the global construction industry has been declining in recent decades[41].

In countries with advanced societies (such as China and Japan), the natural aging of societies will continue to exacerbate this situation by reducing human capital and the ability to implement change and promote economic growth. According to the United Nations World Population Prospects Report 2019, the age distribution of China's population is 54.37% of the population aged 15-64, 13.79% under the age of 15, and 31.85% of the elderly population aged 65 or older(Figure 1-2). The age distribution of Japan's population is 50.51% of the population aged 15-64, 12.21% under the age of 15, and 37.28% of the elderly population aged 65 or older(Figure 1-3). The net population growth rates in China and Japan are also not promising(Figure 1-4).

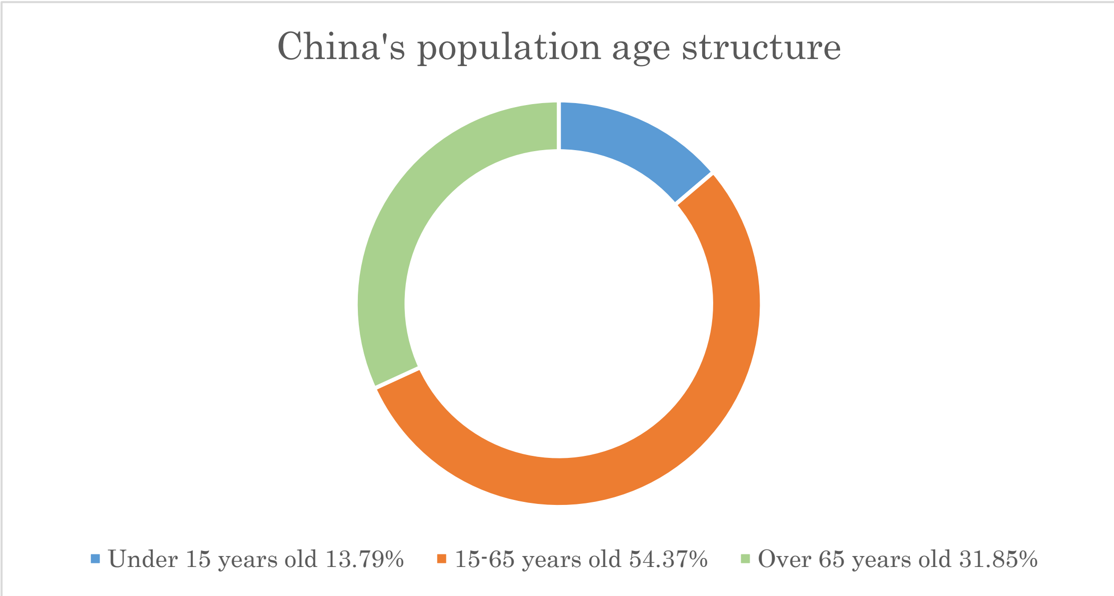

Fig. 1-2 China's population age structure[42]

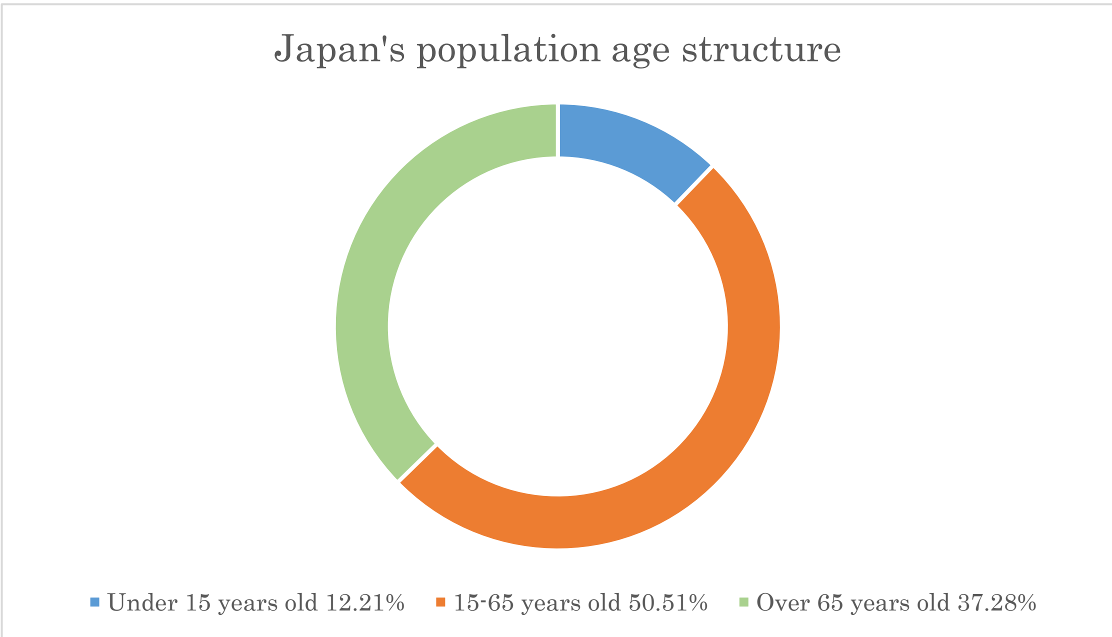

Fig. 1-5 Japan's population age structure[42]

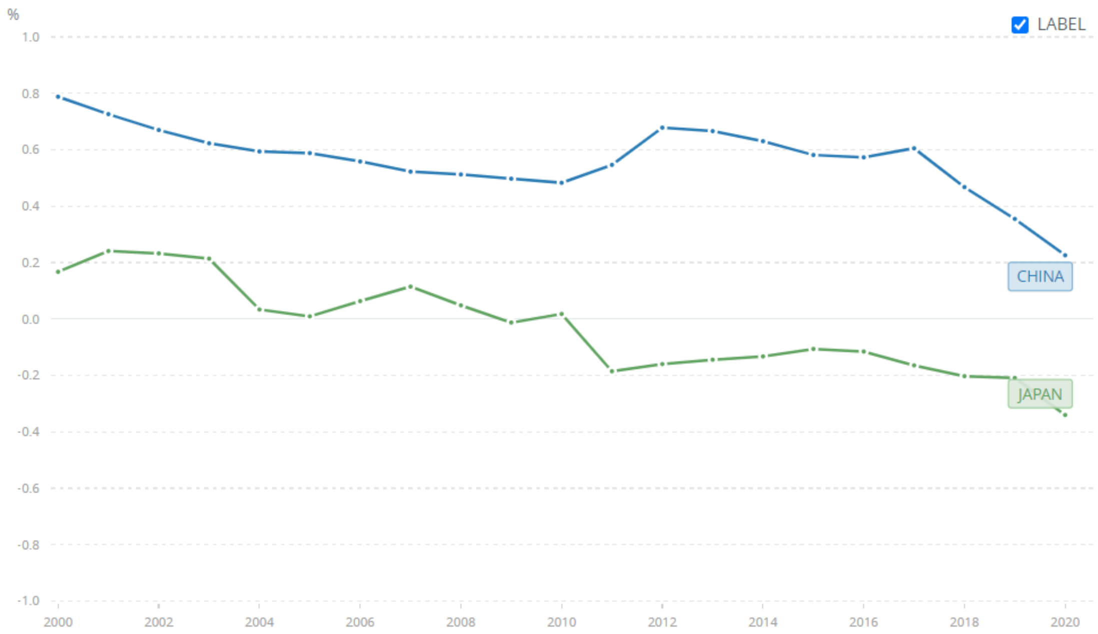

Fig. 1-4 Net population growth rates in China and Japan[43]

1.2.2 Barriers to robotic and automated construction implementation

With the accelerated development of China, the demand for sustainability and the desire for personalization in new building forms are increasing day by day for Chinese users. However, compared to other industries, the construction industry has a low productivity increase, low efficiency in material use, and low levels of automation in design and construction[44]. In parallel, the production model of the construction industry is outdated. The construction industry is still considered to be in the Industrial 1.0 era. Construction is still a labor-intensive industry[45]. Bock Thomas[41] believes that traditional construction methods have reached their limits and are unable to satisfy the current demands of the construction industry for productivity, cost, safety, and sustainability. Many researchers point out that the total factor productivity growth brought about by technological upgrading will advance in lower energy consumption and environmental pollution while increasing material utilization[46, 47]. Improving total factor productivity is the fundamental way to achieve sustainable growth in the construction industry[48]. The integration of robotic and automated construction(RAAC) into the construction industry has the potential to enhance sustainability. Increase productivity and safety, save resources[49]. RAAC has been repeatedly identified as a potential solution to low productivity levels in the construction industry as early as the late 20th century[50]. In the development of RAAC, industrial robot arms were proven as a universal manufacturing medium[51]. The high degrees-of-freedom, relatively modest cost, high precision, velocity, and robustness, and universal design proven by other industries, combined with the high flexibility offered by the proliferation of computer-aided design software, have inspired a multifaceted exploration of the materialization potential of RAAC technology for advanced building forms[52], leading to a proliferation of RAAC-based innovation-driven research efforts[53]. In addition to exploring new possibilities for new building forms[54], these studies show that RAAC, combined with new digital design methods, can be crucial in guiding the efficient application of materials and optimizing structural performance[55]. Despite the fact that robotics has gradually opened up new areas of application in on-site construction [53, 56-58]. Practical applications for RAAC are still limited[59, 60]. One reason for this is that after the bubble economy burst in the late 1990s, the investment in new construction technologies dropped significantly, limiting the development of RAAC[61, 62]. The high cost and lack of sound economics and rationality are significant barriers to adopting construction robots[63].

1.2.3 The factors affecting RAAC implementation

Modern construction companies need to innovate to promote increased productivity in the construction industry [64]. According to [65]. While construction companies believe that RAAC is expected to contribute to increased productivity, sustainability and safety, significant risks are associated with adoption, including commercial and technical risks. The high innovation costs and adoption risks discourage construction companies from proactively innovating[40]. Instead of being driven by market mechanisms alone, RAAC's development needs to be combined with government incentives[66]. Incentives are the driving force behind RAAC's development[67]. [68] believe that financial compensation from the government can reduce the economic burden on construction companies and encourage them to adopt innovative decisions. Green Building Action Plan, a policy document issued by the General Office of the State Council of China in 2013, states that China will vigorously develop green buildings and promote construction in a government-led and market-driven manner, with RAAC being the critical technology to achieve this target. However, the choices of construction companies are dynamic, and if the incentives are insufficient to compensate for the additional cost of innovation and the adoption of RAAC technology does not generate sufficient profits, construction companies will gravitate towards traditional construction methods[69]. Excessive incentives would put the government under great financial pressure, making the policy unsustainable[70].

Lack of expertise is also considered an essential factor is hindering the development of RAAC technology[71]. Therefore, the education of technical personnel in universities is crucial. Design, construction, and operation methods in the construction industry need to be systematically altered in response to the needs of industrial upgrading[72]. The technical inventory of construction professionals is challenged. Architecture education needs to evolve to encourage adaptation to the new demands of the construction industry[73]. However, only 10% of architecture universities in

China provide RAAC-related courses, and half of them are unable to provide the necessary equipment[74]. According to[75], Although Chinese universities have made some academic contributions to the development of RAAC, the lack of an overall teaching framework has prevented the education of professionals to a satisfactory level.

COVID-19, first reported in December 2019, was officially declared an epidemic by the World Health Organization(WHO) on March 11, 2020[76]. The pandemic brings new challenges and opportunities to the construction industry. Most industries, including the construction industry, have been badly hit and brought to a halt, resulting in the closure of many construction sites and related businesses[77]. To control the spread of COVID-19, the World Bank[78] and WHO[79] have recommended implementation procedures. Includes telecommuting, maintaining social distance, and staggering shifts to reduce the number of people working simultaneously. But these rules are challenging for the construction industry, which emphasizes on-site, labor-intensive work. But it also brings new opportunities for technological transformation in the construction industry. The adoption of ARC technology can enhance the construction industry's compliance with COVID-19. While the construction industry has been slow to adopt RAAC technology[80], ref [81] argues that COVID-19 can be considered a force majeure for developing the construction industry. The government might choose more substantial incentives for RAAC technology development. Construction companies may invest in research and development(R&D) to meet regulatory requirements.

1.2.4 Future outlook of RAAC

To improve those situation, German macroeconomist Börsch-Supan proposes a solution to increase productivity and economic wealth primarily by complementing human capital with capital intensity, non-linear advances in machine technology and productivity, known as Industry 4.0[82]. Under this concept, strategies from general manufacturing require ultra-flexible and highly automated manufacturing systems (also considered the fourth industrial revolution) - highly autonomous, flexible and distributed but still networked automated and robotic systems that work together to produce personalized and complex products in near real-time with sustained and continuous productivity - thus guaranteeing higher productivity The construction industry, which has been stagnant for decades, needs to change. Innovation in the construction industry has been extremely slow to develop. One of the main reasons for this situation is the multifaceted nature of the products involved and their complexity, the long life cycle, the diversity of dimensions and materiality, and the fixed-site nature of construction. The future RAAC can successfully address the problems and deficiencies of the construction industry. the superposition of the S-curve[83] can be used to describe the relationship between the stagnation and technological limits of a technology and the initiation, development and growth of new strategies and technologies that start less than existing technologies but increase over time in importance, performance and adoption rates.

Ref[41] believes that in the future, robotics will be ubiquitous. By observing the progress of robotics, it is predicted that robotics will undergo a similar development to that of personal computers in the nineties. Experts and planners, such as Bill Gates, have declared the era of robotics and reckon that robotics has become an inherent element of our daily lives. The Korean government recently announced strong support for the development of robotics with the goal of establishing at least one robotic system in every home. This means that in the future all occupations and areas of life will receive the spread of robotics, and in most cases these areas will be closely related to construction activities, so this diagram also depicts the potential application areas of RAAC in the future.

1.3 Research background of Human-robot interaction timber construction

The demand for new architectural forms and the end users' aspiration for personalization is growing in both China and Japan. Compared to other industries, the construction industry is not very productive, has Inefficient use of materials, and low levels of automation in design and construction[44]. Simultaneously, the production model of the construction industry is obsolete. The construction industry is regarded as still in the Industrial 1.0 era. The scarcity of skilled labor and the increasing scarcity of natural resources are challenging that the construction industry must confront today. Integration of robotics and automated construction into the construction industry has the potential to enhance sustainability. Improving productivity and safety, economizing resources, and diminishing reliance on skilled workers[49].

1.3.1 Environmental impact of the current construction industry

The construction industry is the highest demand for raw materials, and in 2015 the world consumed 47.5 gigatons of raw materials in such a sector solely[84]. Wood constitutes a very significant portion and has played an essential part in Chinese and Japanese architectural history. Wood can moderate climate variations by storing carbon and providing alternatives to materials associated with manufacturing processes with greater carbon intensity[85]. According to ref[86], increasing the use of wood in construction, civil engineering, furniture materials, and energy production would effectively mitigate the global environmental footprint. Mainly, replacing non-renewable resources such as concrete and steel with wood products in architectural construction can significantly cut environmental impact. According to ref[87], buildings represent more than 40% of global energy use and 33% of global greenhouse gas emissions. Approximately 85.4% of carbon emissions are generated during the operational life-cycle and 12.6% during construction(Figure 1-5). Compared to other industrial products, buildings have a prolonged lifetime. Actions taken at the initial stages of design and construction may influence carbon emissions in the long-term throughout the building life-cycle. Although embodied carbon only accounts for 10-20% of a building's life-cycle carbon emissions, the reduction potential cannot be ignored[88]. Embodied carbon is the carbon emission from direct or indirect processes associated with a product or service during the production cycle, including material acquisition, manufacturing, and transportation until the product passes through the factory gates[89]. The use of building materials with less embodied carbon in construction allows for lower carbon emission levels requirements[90]. Oka et al. conducted a quantitative experiment on building carbon emissions in Japan and concluded that wood-framed buildings have less carbon embodied than concrete and steel structures. Scholars have reached similar conclusions in New Zealand, North America, Australia, and Europe[91-94]. At the same time, the current construction method has low utilization of materials and generates a lot of unnecessary waste and carbon emissions in the construction process. New theories and methods need to be introduced from the acquisition of raw materials to construction production.

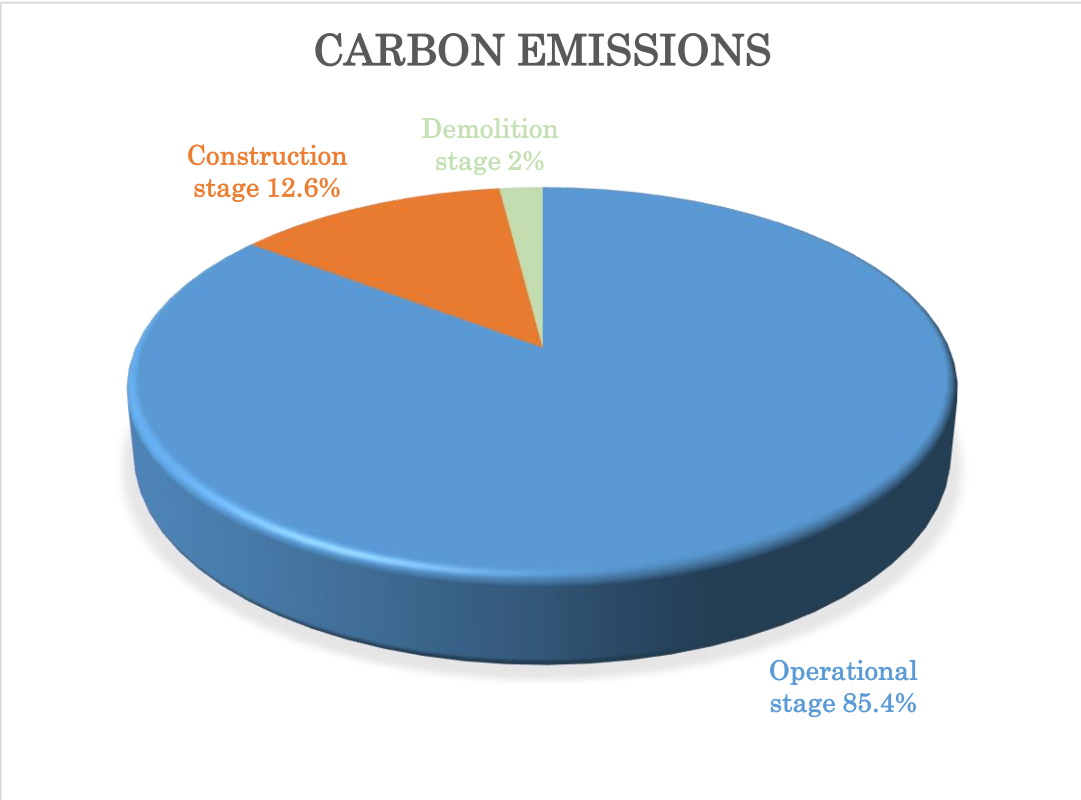

Fig. 1-5 Percentage of carbon emissions over the building life cycle[87]

1.3.2 Automation and robotics for the construction industry

The level of automation(LoA) in manufacture increases from an utterly manual build to the introduction of tools to optimize the build process, which allows for repetition until full automation is achieved. Peter Burggräf et al. [95]. Define LoA as seven levels; the details are shown in Table 1-1. Integrating robotics into the construction industry to promote construction efficiency was proposed in the late 20th century[96]. Thomas Bock[41] maintains that traditional construction methods have reached their limits. While the technology for automation in construction is still innovative or nascent, it is likely to mature and gain adoption on a larger scale as efforts continue to be invested in research and development. Construction automation and robotics involve applying automated construction processes that span the whole project life cycle—preliminary design, on-site and off-site implementation, maintenance and operational control, and final demolition. Construction automation and robotics have demonstrated adequate potential, so many research institutes and universities have set up various pilot projects and experimented more or less with automation and robotics in the construction industry[97]. The selection of the proper technology implementation is essential[96]. Warszawski[98] first proposed using robots in construction and different robot configurations to solve different construction tasks. Skibniewsk[99] proposes a decision support system that allows the application of advanced robotics in construction sites. The University of Southern California[100] has developed a mechanical structure that uses 3D printing technology for large-scale construction. The 'In situ Fabricator' developed by ETH Zurich[101] and the 'semi-automated mason' technology developed by construction Robotics[102] are used in mobile robots for on-site construction. Overall, the application of construction automation and robotics is still in its infancy and is an emerging area worthy of research.

Table 1-1 LoA of the construction industry

Level	Equipment	Description	Working method
1	None	Totally manual	Manual
2	Static hand tool	Using static tools	Manual
3	Flexible hand tool	Using flexible tools	Manual
4	Automated hand tool	Automated tool-assisted	HRI
5	Static automation system	Static automation assisted	HRI
6	Flexible automation system	Flexible automation tool-assisted	Automatic
7	Fully automated system	Totally automatic	Automatic

1.3.3 Towards the flexibility of robotic timber construction

Considering full-scale applications, Robotic Timber Construction(RTC) research is still in its infancy and presents a full range of challenges to the construction industry[103]. Several attempts have been made to develop RTC systems in building construction, such as ref[103] and ref[104].

However, these cases attempted to achieve the complete automation of RTC(LoA level 7), some trade-offs were applied to the construction process. In order to automate the nailing process, pneumatic nails were chosen as the joining tool, which was not strong enough to allow the choice of thicker and more solid timber as the construction material, which is not in line with the actual market situation and leads to experiments that remain in the laboratory stage. Furthermore, the construction conditions for full automation are harsh, and it is hard to achieve a laboratory environment in the actual construction process. Two other studies demonstrating the potential of RTC technology in large building projects are located on the sequential roof of the ITA building at ETH Zurich[105] and the BUGA Wood Pavilion at Hans Jakob Wagner et al. [53]. These two projects show the great potential of RTC's efficient construction systems, except that they both employ unique and expensive robotic devices and use large teams of technical professionals. While these research efforts demonstrate the future of wood construction, the high costs and extremely high technical requirements preclude replication in a hyper-competitive, bottom-margin construction industry[106]. Providing a more efficient, cost-effective, and flexible solution for applicability becomes imperative. Otherwise, these highly promising studies may become irrelevant to the general public[107].

1.3.4 Human-robot interaction

Traditional manual construction and fully automated robotic construction each have their advantages and disadvantages[108]. Moreover, in a market condition where the technology and industry scale of the construction industry is as yet unable to meet the scale of full automation (LoA 7), human-robot interaction(HRI) is a more adaptable working model that can combine the advantages of both and be flexibly integrated into the market[109], as shown in Table 1-2. In order to implement a flexible and efficient construction system, the study should concentrate on HRI rather than merely increasing the level of automation[110]. While construction will be more automated in the future with iterations of technology, humans will continue to fill an integral role[95]. HRI will be an approach that combines the advantages of working together. The digital technology and efficiency of robots can support the flexibility of human workers, and the improvisation of human workers can solve unexpected events that robots are unable to solve. This paper concentrates on the application of human-robot interaction timber construction(HRITC). It also proposes a construction process that optimizes HRI to minimize the experience required of workers in the construction process, enabling inexperienced generalists to collaborate with robots to perform high-precision construction work with high quality based on simple safety training. It can be referred to as a fundamental framework for further consideration of developments and future trends in building automation.

Table 1-2 Comparison of the advantages and disadvantages of traditional manual construction and each level of automation(Red: Unacceptable; Blue: Acceptable)

LoA	1--3	4--6	7
Equipment	Hand tool	HRI automated system	Automated system
Working method	Full manual	Using static tools	Full automation
Economical	Low	Controllable	High
Efficiency	Low	Controllable	High
Flexibility	High	High	Low
Construction complexity	Low	High	High
Precision	Low	High	High
Site condition requirements	Low	Moderate	High
Wastage	High	Low	Low

1.3.5 The objective of HRITC

The HRITC construction method proposed in this paper aims to provide a new idea to the existing RTC research by combining the advantages of manual construction and automated robotic construction. The more costly and flexibility-demanding aspects are handed over to the manual process, and the laborious and precision-demanding aspects are handed over to the robot. The efficiency of robots and innovative digital technologies can support the flexibility of human workers, resulting in an efficient and flexible construction framework. Technology improvements such as these make possible new automated configurations involving human workers, and lower costs and low requirements for equipment sites make possible the diffusion and larger-scale application of the technology.

We note that a shorter conference version of this paper appeared at[57]. Our original conference paper did not discuss and address all of the issues. This manuscript discusses and addresses these issues and analyzes additional data during construction and overall image reconstruction.

1.4 Research structure and logical framework

1.4.1 Research purpose and core content

Against the backdrop of low productivity in the construction industry and the growing aging in both China and Japan, it is imperative to achieve a digital transformation of the construction industry. This paper examines the feasibility of digital transformation in the construction industry from both design and construction directions. For the design direction, this paper proposes a PISAD design process that allows designers to invite users to participate in the design process. The real-time visualization of challenging design solutions aims to reduce design time and cost, and achieve economy and sustainability of small-scale customization. For construction, this paper proposes a human-robot collaborative building workflow that allows inexperienced laymen to efficiently and quickly complete complex wooden structures with robot collaboration. Also in this paper, two evolutionary game models are developed to investigate the factors influencing the implementation of robotic and automated construction in two contexts: highway university involvement and COVID-19 influence, respectively. Policy support is provided for the digital transformation of the construction industry. Research logic of the article show in Figure 1-6

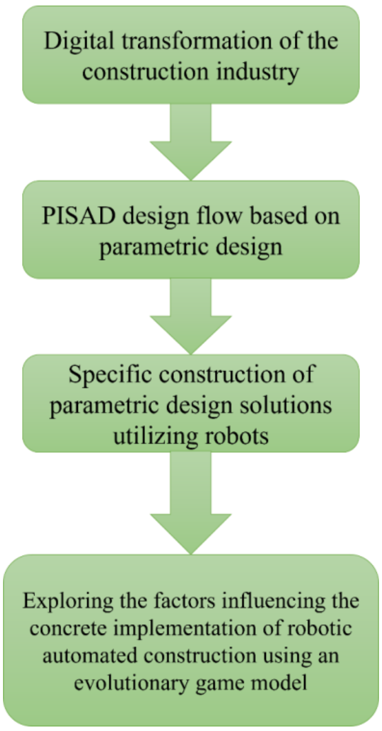

Fig 1-6 Research logic of the article

1.4.2 Chapter content overview and related instructions

The chapter names and basic structure of this paper are shown in Fig 1-7. Besides, the brief introduction of chapters schematic is shown in Fig 1-8.

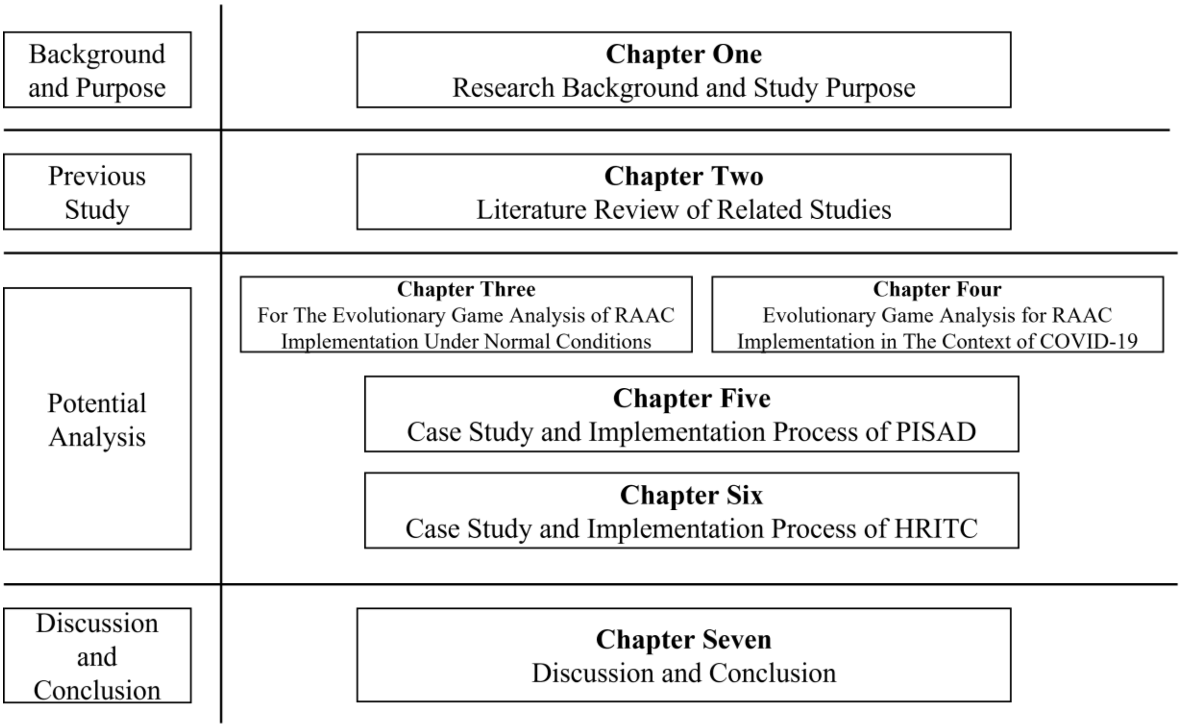

Fig 1-7 Chapter name and basic structure

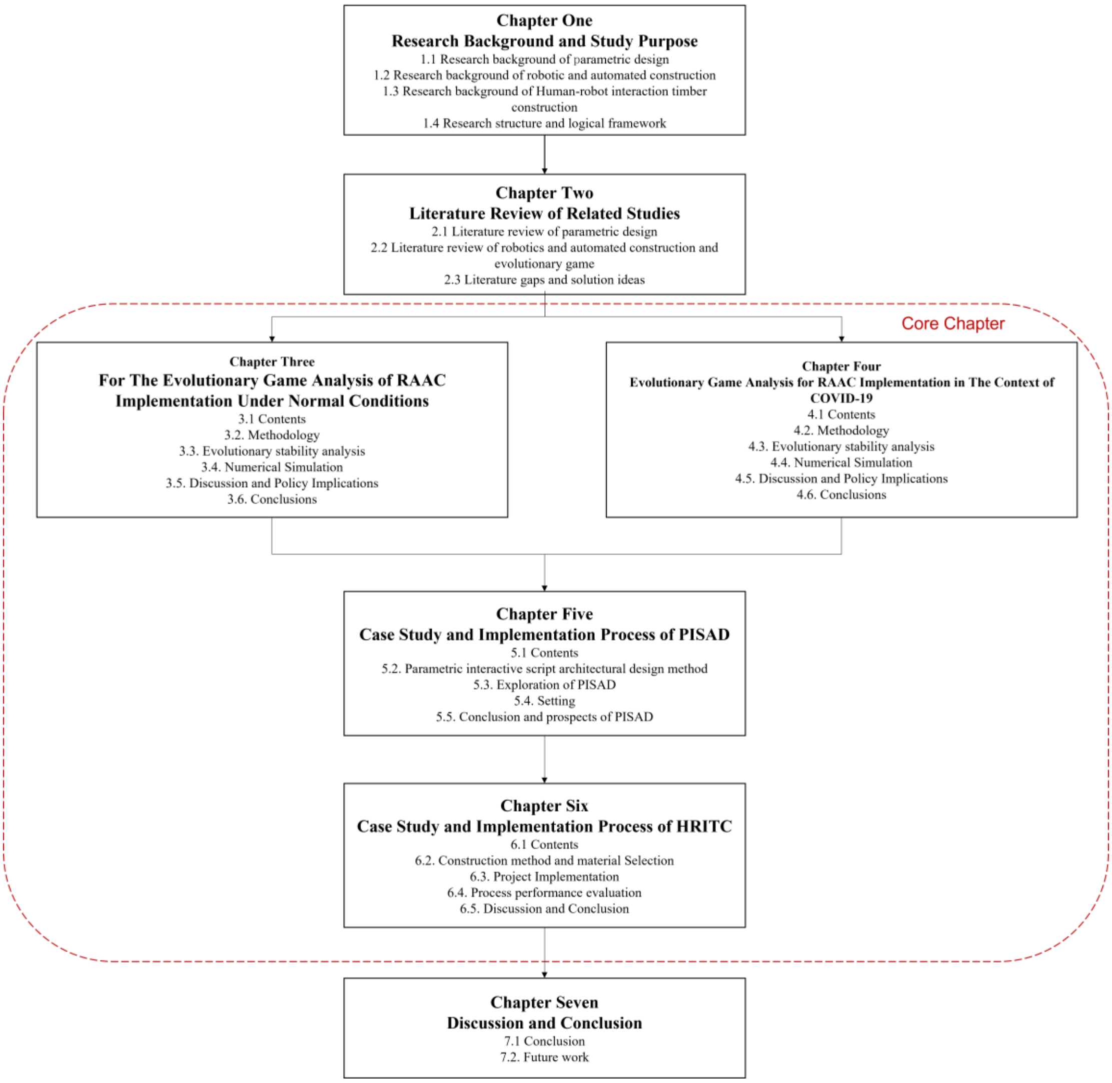

Fig 1-8 Brief chapter introduction

In Chapter 1, RESEARCH BACKGROUND AND PURPOSE OF THE STUDY.

Chapter 1 presents the research background of parametric design and robotic automated construction, including the current status and bottlenecks of integrated technology development. and the significance of digital transformation in the construction industry. Then, the development and current status of robotic automated construction in the world and China are presented. It is pointed out that the combination of parametric design and robotic construction is crucial to achieve digital transformation in the construction industry. Finally, the purpose of the study and the logical framework are presented to help reviewers understand the content of this paper.

In Chapter 2, LITERATURE REVIEW OF PARAMETRIC DESIGN AND ROBOTIC AUTOMATED CONSTRUCTION.

This chapter provides a review of the relevant studies in this paper. It includes the development and current status of parametric design, the current development of robotic automated construction and the development of digital-related technologies in the construction industry. In addition, the significance and scope of use of the evolutionary game model is explained. Based on the previous studies, this paper helps to combine them to understand and explore the influencing factors that affect the application of robotic automated construction and contribute to its development and implementation.

In Chapter 3, FOR THE EVOLUTIONARY GAME ANALYSIS OF RAAC IMPLEMENTATION UNDER NORMAL CONDITIONS.

This chapter begins with an analysis of the current problems in the construction industry, namely low productivity and poor sustainability, while noting that both China and Japan are facing the challenges of low population growth and increasing aging. While there have been many studies that point to robotics and automated construction as the key to breaking the ice, there has been little practical application. This paper analyzes the interests of the government, construction companies, and public universities by analyzing the relationship between them. A three-way evolutionary game model is developed to analyze the evolutionary trends of decision making under different conditions and explore the influencing factors that affect the actual adoption of RAAC. It provides a reference for the decision making of stakeholders.

In Chapter 4, EVOLUTIONARY GAME ANALYSIS FOR RAAC IMPLEMENTATION IN THE CONTEXT OF COVID-19.

This section builds on the previous chapter by introducing COVID-19 as an influencing factor. In the face of the COVID-19 pandemic, the global construction industry received an unprecedented shock, with the epidemic leading to labor shortages, expenditures on epidemic prevention costs and changes in the labor environment, leaving a large number of construction companies facing bankruptcy. However, the pandemic also brought new opportunities. On one hand, the high cost of pandemic prevention made construction companies desperately in need of new construction models, and on the other hand, it also broke the traditional concept of construction mode change. This chapter analyzes the interests of the government and construction companies in the context of COVID-19 and develops an evolutionary game model. The evolutionary trends under different conditions are analyzed to explore the key parameters affecting the evolution. Theoretical references are provided for the decision-making choices of the government and construction companies.

In Chapter 5, CASE STUDY AND IMPLEMENTATION PROCESS OF PISAD.

This section presents a rapid interaction design process based on parametric design that allows designers to invite users to participate in design decisions. The feasibility of the flow is verified through an example. The aim is to address the challenge of insufficient design cost and design time faced by small design projects, but users have individual customization needs.

In Chapter 6, CASE STUDY AND IMPLEMENTATION PROCESS OF HRITC.

This chapter goes through a practical construction case. A building process for collaborative human-robot construction of complex wood structures is presented, allowing inexperienced laymen to build complex wood structures simply, efficiently, and accurately with the assistance of robots. It allows for the actual construction of parametrically designed 3d models. The purpose of this chapter is to first resolve the paradox that parametric design solutions are too complex and difficult to achieve with manual construction. The second is to verify the potential of robotic and automated construction to improve the efficiency, productivity and sustainability of the construction process. Finally, the problems of high cost of full automation, too much technical difficulty and too many restrictions on construction sites are solved by human-machine collaboration.

In Chapter 7, CONCLUSION AND FUTURE WORK.

Conclusion and future work of the chapters are concluded.

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Chapter 2

LITERATURE REVIEW OF RELATED STUDIES

CHAPTER TWO: LITERATURE REVIEW OF RELATED STUDIES

2.1 Literature review of parametric design

2.1.1. Design flow over time

The design process is the cornerstone of many professions, such as engineering, industry, vehicles, mechanics or computer science, which are all ahead of the construction industry in the digitalization process[1, 2] and from which the construction industry can gain much experience. Therefore it is important to study design process models that emerge from various design-related disciplines[3]. These include Simon's problem-solution and Schön's seminal theory of See-Transform-See[4, 5]. The definition of design itself has evolved over time, depending on the specific considerations of each era. In short, design is considered as a solution to a complex and ill-defined problem, a creative process, a conceptual outcome resulting from the synthesis of knowledge expressions or the construction of representations[6-10]. Dubberly et al. summarize the design process in various disciplines (including but not limited to architecture, industrial design, mechanical engineering, and vehicle design), listing twenty-four linear models; thirty-two linear models containing iterative loops; three tree models; seven spiral models; eight circular models; and twelve different models, each representing a design process[11]. Some researchers have identified a common core of design activities from one domain to another, including, for example, iterative phases for building multiple design process models[12]. Several researchers have studied the effect of various individual parameters on design results[13-15]. Blessing summarizes the theoretical representation of the design process into four different categories, namely, four types of models: linear, cyclic, Archimedean spiral, and convergent conical spiral. These models reflect the evolution of multiple successive representations of the design process. The evolution from a basic linear scheme to a more complex multi-step iterative model[16].

2.1.2. The evolution of architectural design models, from simulation to parametric design

Tom Markus and Tom Maver were among the first to produce drawings dedicated to the architectural design process[17, 18]. However, the distinction between the architectural design process and the engineering process has remained much debated for decades. In particular, Cross and Roozenburg have modeled and compared the design processes of engineering and architecture[19].

Cross et al. wrote a book to illuminate the way designers think and work in various fields, including observations of the architectural design process[20]. Specific models such as Ostwald's System-enabler model and Chokhachian and Atun's transparent layered system model integrate more specifically the particularities of architectural design[21, 22]. Among these particularities, one can emphasize the diversity of restrictions related to the positioning characteristics of the design result, the lack of prescribed methods, the diversity of the nature of the representation, the need to represent the third dimension, or the central role of the part[23]. The researchers quickly observed that the design tools used to support this process were rarely integrated into the theoretical model in the early stages, despite having proven their importance[24, 25]. Parametric design and its increasing impact on design and production practices therefore requires a re-examination of design theory, workflow, and model representation. Parametric design itself needs an updated conceptual framework and theoretical foundation.

Hillyard and Braid were the first to propose parametric design tools derived from computer-aided design systems in 1978[26]. Allows the designer to change these constraints within specified geometric constraints and a given range. On this basis, a more mature parametric tool was proposed, which is considered as the main reference for the origin of parametric design tools[27]. Although this design approach defines the design form by changing parameters, at its core, it defines the design logic by defining the relationships between parameters[28]. Well-defined, logical relationships can solve the challenge of modifying designer-built models to implement the designer's ideas in an interactive way and with 3d visualization[29]. Oxman presents a model of digital design thinking that clearly demonstrates the fact that the tools used in the design process have a profound impact on the design process itself[30].

Parametric design tools allow variable input data, establish mathematical logic relationships and generate additional data, including geometric relationships and composite (light, ventilation, temperature and humidity, etc.) information[31]. With advances in computing power and increasing data availability, it is now possible to use parametric systems to deal with complex architectural phenomena at multiple scalar and multidimensional levels. In contrast to traditional design methods, parametric urban design uses rule sets as the basis for 3D building model configurations[32]. Allows for a wide range of alternatives by changing the parameters of the logical relationships[33]. With the traditional design approach, designers can only find solutions within a limited scope[34]. In addition, all procedures, activities and relationships for parametric design are clearly defined, allowing the designer to modify the rule-based model at any stage of the design process, allowing the design process to remain efficient, open and flexible[35]. Parametric design translates rule-based logic into geometric forms derived from the so-called "shape syntax"[36, 37]. Unlike traditional design patterns, parametric thinking requires prioritizing design parameters over solutions and developing interdependent rule sets to facilitate the generative design process[33]. This means that it is difficult for existing practitioners to change the existing practical paradigm, and many researchers have tried to use these parametric design tools for education[38-40].

2.1.3. Features of Parametric Design

In parametric modeling tools, models are generated and visualized through two types of interfaces. First, the representation is presented in the geometric form of the model, following the more traditional 3D object manipulation. Then, it is accompanied by a programming interface that uses modeler-specific algorithms and allows the model to be recomputed when modifying the elements of either representation[41]. Using parametric modeling tools, designers need to algorithmically model the conceptual structure, using the parameters as representations to guide its change and match it to the corresponding 3D models[42, 43]. During the design phase, the designer constructs a description of the algorithm for the intended design, including the logic and dependencies between input parameters, and the associated geometric operations[41, 44]. The 3D model is then created by executing the algorithm. Thus, the generation of the algorithm precedes the generation of the shape[45]. This significant change in the iterative design of near-virtual artifacts is closely related to the fundamental cognitive shift from modeling the "object" of the design to modeling the "logic" of its design[46]. Through this design workflow, which allows designers to perform this "multiple instantiation" exploration, designers are able to start with a single initial parameter model and generate different spaces and configurations by editing the parameters. When the value of one parameter changes, a logical chain of modified parameters is propagated, allowing the other parameters to automatically adapt to obtain different design results[47, 48].

2.1.4. Literature gap of parametric design

In recent years, although parametric design practices have been or are being implemented in large buildings[49-51]. However, these studies rarely quantify the actual state of practice (maturity, cost and scale of adoption). Most studies are conducted in experimental settings or in large projects, which do not reflect the situation of most architects. One survey showed that 71% of architecture firms are small organizations[52] without adequate design costs and design scale. While large construction companies may have internalized their own R&D teams and are able to develop and adapt their own parametric modeling software[53, 54]. But small and medium-sized construction companies know very little about it. Research into design models that are more in line with small firms would be more conducive to addressing the challenges facing the architectural design industry.

2.2 Literature review of robotics and automated construction and evolutionary game

2.2.1. Robotics and automated construction: developments and challenges

RAAC was first discussed in the 1970s and attempted in the 1980s[55, 56], leading to extensive research and development work. Ref[57] presents a technical decision for the implementation of RAAC at the construction site. Ref[58] proposed an integrated robot arm system that can be mounted on a scaffold. [59] shows a robotic system for performing concrete spraying tasks. [60] demonstrates an automatic arm system that allows inexperienced non-specialists to collaborate with a robotic arm to assemble wood structures rapidly. Some architects and researchers also focus on additive manufacturing technologies, known as 3D printing[61]. [62] presented a robot technology that has been related to contour crafting technology. Another example of additive construction using stationary robots is the project DEMOCRITE from XtreeE and ENSA Paris-Malaquais[63]. The project aims to build higher-performance complex concrete elements. However, despite the variety of research on RAAC, practical applications of construction robots are still limited[64].

Ref[65] believes that the four underlying reasons for RAAC technology's slow adoption and implementation are inadequate development, inappropriate building design, management mismatch, and lack of economics. Economic challenges, high initial costs, low return on investment, business models, and contracts stifle collaboration; construction companies are reluctant to adopt ARC technology[61, 66]. At the same time, the construction industry is a very mature industry with a long history, and practitioners have negative feelings about the transition[67]. Fragmentation of the construction industry[68], fierce competition[69], and conflicts of interest in the supply chain[70] have also affected the adoption and development of RAAC technology.

2.2.2. Robotics and automated construction in the construction industry

This paragraph briefly describes the different RAAC systems currently used in the construction industry. The classification method is based on the work of literature[66]. However, please note that these systems are differentiated, there is no precise definition within the industry, and the boundaries between categories continue to blur as technology develops and innovates. The categories presented here are intended to facilitate understanding the complexity and diversity of the RAAC technical environment. The types of RAAC can be divided into three major categories[61]:

1) **Architectural prefabrication of RAAC.** This system is originated from the successful industrial industrialization of Japanese automobile manufacturing industry utilizing robots[71]. This category includes the manufacture of sizeable, prefabricated building elements. This method takes inspiration from the experience of other manufacturing industries that have applied RAAC to automate the industrialization of prefabricated building components using an automated approach. Various building materials (concrete, wood, steel, stone, etc.) and low-level components are transformed into high-level building components through a highly mechanized, automated, and robot-supported chain[72]. This category also contains additive manufacturing technologies(3D printing technologies)[73]. Perkins I et al. [74] review many cases involving the application of 3D printing technology to the construction industry, discussing its application prospects, challenges, and advantages. Although limited by technology and material costs, additive manufacturing technology is still in the experimental stage[75]; it has progressed and can now be used to print large-scale components[76, 77].

2) **On-site automation.** This type aims to achieve construction site automation—a controlled, automated environment established at a RAAC field factory[78]. Using single-task construction robots (usually industrial robotic arms) as automation tools, it can perform single repetitive tasks, or multiple machines can collaborate on complex assignments[79].

This method is popular with research institutes and architectural universities because of its flexibility, allowing it to combine with other traditional construction methods. Wagner, H.J., et al.[60, 80, 81] proposes combining on-site automated systems with traditional timber frame construction, showing future robotic timber frame construction possibilities. Reichenbach S et al.[82] reviews the current practice in integrating on-site automation and concrete production. Goessens S et al. [83] presents the feasibility of using industrial robotic arms to build masonry structures. Moreover, some Japanese, Korean and German scholars focus on on-site automation for building demolition[84].

3) **Remotely operated equipment and exoskeletons.** This category addresses extreme and hazardous environmental problems that traditional construction methods cannot address. It includes ground, air, sea, and even space robots[85] that can be remotely operated or require command. These robots have been developed for sampling studies in extreme environments, exploring and monitoring hazardous areas, navigating and collecting data at construction sites, and have automated excavation and transportation[86-89]. This category also includes augmentation devices arch construction workers wear that can enhance workers' abilities, mitigate the effects of the environment on workers, help them lift heavy objects, and reduce fatigue to improve recognized productivity[90].

2.2.3. Robotics and automated construction in wooden construction

In recent years, the field of architectural education and research has turned its attention to the integration of robotic architecture with traditional wood. The AA School of Architecture at ETH Zurich and the ICD at the University of Stuttgart, among others, have achieved remarkable results in this field. For example, the designers of the Gantenbein Vineyard[91]. Designed by Dr. Nebosja Mojsilovic and Markus Baumann of ETH Zurich. The robotic production method they developed at ETH Zurich enabled them to lay each of the 20,000 bricks precisely at the desired angle and at the exact specified intervals, according to programmed parameters. This allowed the design and construction of each wall with ideal light transmission and air permeability, while creating a pattern that covered the entire building facade. Depending on the angle they are set at, each brick reflects light in a different way, resulting in different levels of brightness. Like pixels on a computer screen, they add up to a unique image, thus conveying the identity of the vineyard. However, in contrast to a two-dimensional screen, there is a dramatic play between plasticity, depth and color, depending on the position of the viewer and the angle of the sun.

And the "Lumen Pavilion" at Virginia Tech was designed by Allison Ransom, Mathew Vibberts, Florence Graham, Megan Sunderman, Christian Truitt, Zachary Bacon, Travis Rookstool, Casey Reeve, Osamu Osawa The designers cut a number of circular holes in the building's facade and set up a number of circular shades of the same size. By using robots to change the angle of each sunshade, it also provides good shading and good visibility[92]. Hans JakobWagner et al[81]. have designed a mobile robotic construction platform that can be quickly integrated on a per-project basis into the existing manufacturing environment of a typical woodworker. This allows the use of emerging synergies between traditional processes and specialized automation technologies. The quasi-industrial prefabrication of BUGA WOOD segmented wood shells was achieved with multi-disciplinary collaboration.

2.2.4. COVID-19 adjustments to the construction industry

The COVID-19 epidemic has had a massive impact on most industries, including the construction industry, resulting in the closure of many construction sites. At the time of revision of this manuscript (March 5, 2022), there were more than 444,103,410 confirmed cases of COVID-19 and more than 6,010,125 deaths worldwide[93]. The uncertainty about COVID-19 vaccine efficacy introduces concerns[94, 95]. In response to the pandemic, most industries worldwide, including the construction industry, have implemented strict work restrictions such as telecommuting, complete lockdowns, and controlled social distances[96, 97]. However, these measures are difficult to be strictly enforced on construction sites. Most construction activities are still carried out manually on-site, limiting the ability to work remotely and maintain social distance[98]. Even if the companies involved approve the application of COVID-19 measures, workers will intentionally or unintentionally ignore these measures and regulations[99]. COVID-19 imposes considerable additional economic costs on construction projects, and the companies involved need to spend extra equipment costs and labor costs to ensure compliance. Productivity will be significantly reduced compared to normal operations[100]. The construction industry must devise and implement effective strategies to counter these challenges[97].

2.2.5. Evolutionary game theory

Evolutionary game theory(EGT) is an integrated approach that combines traditional game theory and dynamic evolution[101, 102]. It was initiated in the late 1970s and gradually applied in various fields[103, 104]. In the assumptions of traditional game theory, policymakers are required to maintain a strong memory, absolute rationality, and excellent analytical skills[105]. However, such stringent conditions are challenging to meet in practice, resulting in limited methods [106]. Unlike traditional game theory, EGT does not require stakeholders to be entirely rational and informed[107]. EGT assumes that participants have finite rationality and will continue to learn and iteratively alter their strategies in the game to maximize their benefits[108]. This matches the essential characteristics of most inter-game players[109] and allows EGT to be widely used to analyze cooperation and strategic choice problems[110].

Many studies have emphasized the importance of government action[111]. Ref[112] constructs an evolutionary model of low carbon strategies under complex networks from the perspective of the government-firm game and emphasizes the function of government incentives in the adoption of common carbon strategies by companies. Ref[113] provides a tripartite evolutionary game model between service platforms, government, and consumers and proposes a governance mechanism for regulating discriminatory pricing in-service platforms. Ref[114] analyzed the impact of government measures on public-private partnerships for green transformation and pointed out that joint policy incentives are the best measures to promote public-private partnerships' green retrofits. Ref[115] uses an evolutionary game model to analyze whether manufacturers should take more social responsibility.

2.2.6. Literature gaps of robotics and automated construction

Based on the above literature, the existing literature gaps were identified. First, most studies on RAAC indicate that the development of RAAC technologies is a fundamental solution to the low productivity and inefficient application of materials in the construction industry, and is the key to sustainable transformation of the construction industry. At the same time RAAC technology can transform parametric design from pie-in-the-sky imagination to easily realized construction examples. However, the existing literature has paid little attention to the human-machine collaborative construction process, and few studies have examined the influencing factors affecting RAAC adoption.

To address these gaps, the following work was done in this paper. First, we conducted a specific experiment using a human-robot collaborative robotic construction process to complete a wood-frame building generated efficiently and precisely from a parametric design using inexperienced laymen with the assistance of robots. Then, we analyzed the interests of the construction company, the government, and the public university under normal conditions, constructed a three-way evolutionary game model, analyzed the evolutionary game evolutionary trends under different conditions, and identified key parameters that affect the adoption of RAAC technology. Next, using the evolutionary game model to analyze the development of RAAC, we analyzed the development of RAAC technology by the government and construction companies by formulating hypotheses and identifying the parameters of their respective interests. The payoff matrix is constructed, dynamic replication equations are established, asymptotic stability under different conditions is analyzed, and the effect of COVID-19 is introduced. The model is then numerically simulated to determine the impact of key parameters. Policy insights are provided for the government and construction companies to facilitate both parties to overcome the challenges posed by COVID-19 and to promote the development of RAAC technology.

2.3 Literature gaps and solution ideas

From the above literature review, we identified literature gaps in the explicit memory and developed a corresponding experimental protocolas shown in Figure 2-10. The aim is to fill the literature gaps and provide theoretical support for subsequent studies.

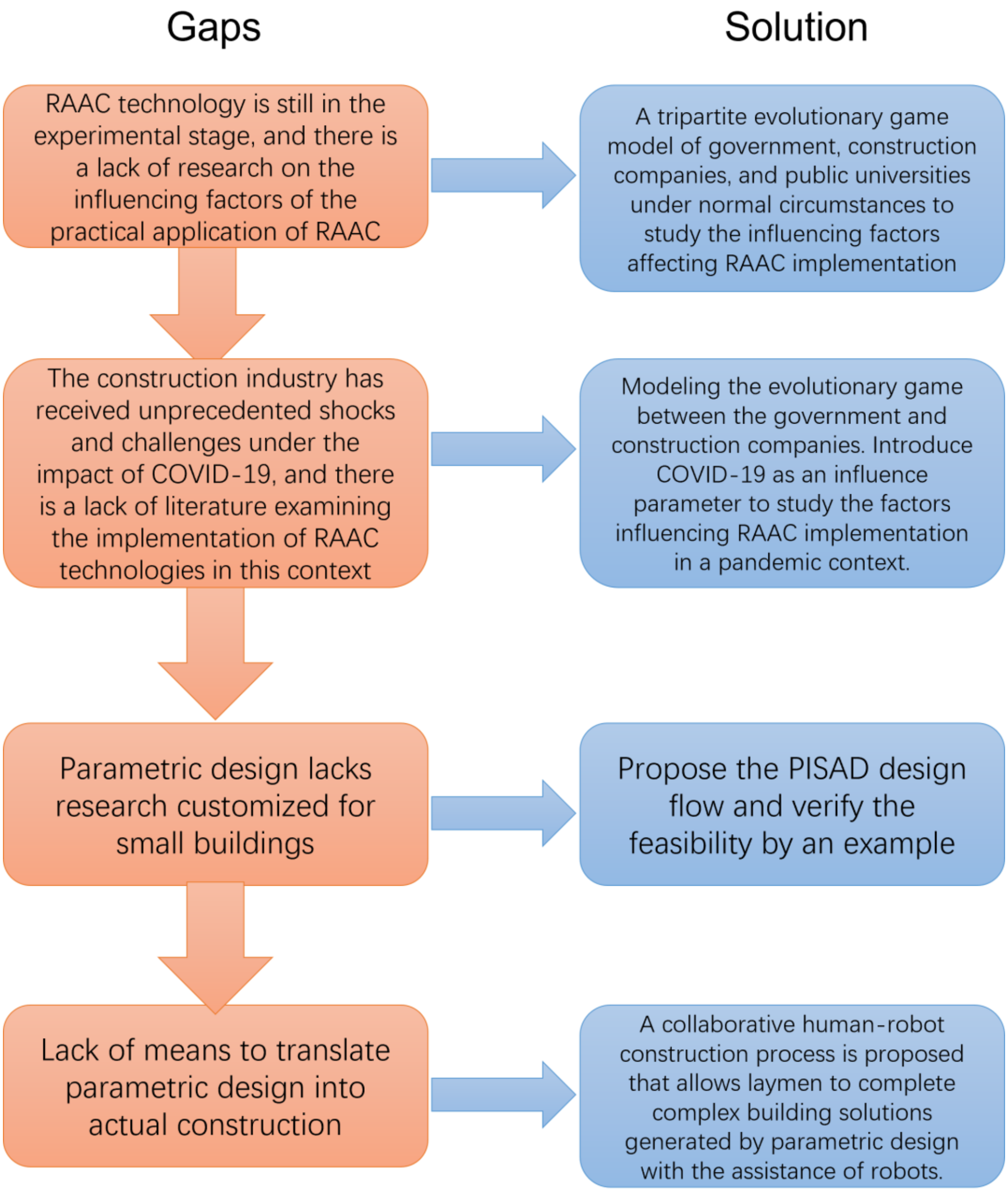

Figure 2-10 Literature gaps and solution ideas

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Chapter 3

FOR THE EVOLUTIONARY GAME ANALYSIS OF RAAC IMPLEMENTATION UNDER NORMAL CONDITIONS

CHAPTER THREE: FOR THE EVOLUTIONARY GAME ANALYSIS OF RAAC IMPLEMENTATION UNDER NORMAL CONDITIONS

3.1 Contents

Traditional construction methods have reached their limits, and the current construction industry is facing many challenges such as low productivity, low material application rates, and poor environmental benefits. Robotic and automated construction(RAAC) technologies are a significant departure from traditional construction methods and are considered to be an effective way to improve productivity, environmental efficiency, and sustainability in the construction industry. However, the high cost of research and development and the lack of investment in research and development in the construction field have made Chinese construction companies reluctant to innovate. Only a few public universities in China are equipped to cultivate relevant talents. This chapter constructs an evolutionary game model between the government, construction companies, and public universities around the choice of RAAC innovation, discussing the tripartite evolutionary stable strategies(ESS). Establishing a compound incentive policy of financial and reputational rewards can accelerate the realization of ESS between the government and construction companies. Increasing the percentage of RAAC-related academic achievements and employment rates of RAAC talent in academic evaluations can accelerate the achievement of ESS between the government and public universities. This study provides a reference for policymakers to develop RAAC innovation strategies, stakeholders such as governments, construction companies, and public universities should consider and work together to promote the development and application of RAAC technologies to improve productivity and environmental sustainability in the construction industry.

In this context, it is significant to explore the ESS of the Chinese government, public universities and construction companies after a long evolutionary game and to identify the key influences of the ESS. This will help the government gain insight into developing appropriate incentives, better coordinating planning with public universities, and better balancing the allocation of government, construction companies, universities, and innovation costs. This chapter focuses on the following three questions by building a three-party evolutionary game (TEG) model:

(i) How to balance the benefits and costs of the Chinese government, public universities and construction companies in the TEG model and construct a benefit matrix?

(ii) (ii) What are the ESSs involved for the three parties and what are the conditions for their realization?

(iii) (iii) How do the key parameters affect the evolutionary outcomes and trajectories? The purpose of this section is to contribute to existing research by applying for the first time an evolutionary game model to tripartite decision making in RAAC development.

The analysis of the asymptotic stability of the three parties under different conditions provides a strong theoretical guide to promote the development of RAAC in China.

3.2. Methodology

3.2.1. Description of the gamer

This chapter aims to study the behavior of construction companies in adopting RAAC technology driven by government policies. The government and construction companies are the two leading players in the game. Meanwhile, whether public universities increase the training of RAAC technology talents directly affects the innovation cost of construction companies; therefore, public universities are identified as another player influencing the decision choice.

Government: The government can promote the development of RAAC technology by developing programs, regulations, and incentives[1]. RAAC has been proven to increase productivity and promote sustainability in the construction industry[2, 3]. The government aims to motivate construction companies to adopt RAAC through incentive policies. However, excessive subsidies will cause substantial financial pressure, and the government should consider the strength of the incentive policy.

Construction Company: The ultimate pursuit of construction companies is financial gain[4]. However, RAAC is considered the key to increasing productivity and sustainability in the construction industry. However, higher R&D costs and investment risks have discouraged most construction companies from innovating. Construction companies doubt whether they can get sufficient compensation from government incentives and recruit relevant expertise from universities.

Public Universities: For Chinese public universities, subject assessment scores(SAS) are an essential indicator. According to ref[5], the quality of talent training is the crucial factor affecting SAS. Among them, the quality of graduates depends on the employment situation and the evaluation of employers. Public universities need to weigh the ability of government fiscal policies to compensate them for the additional cost of training RAAC talent and the need of construction companies for RAAC talent.

3.2.2. Basic assumptions

We have the following hypotheses by analyzing the evolutionary game relationship between multiple stakeholders.

Assumption I

An essential assumption of evolutionary games is that each player is finitely rational[6]. In the early stage of the game, it is difficult for the players to choose the perfect strategy. However, they can learn from each other, imitate and exchange, and use it to adjust their strategies to pursue the maximum benefit[7].

Assumption II

The government has two strategies: incentive or no incentive. The probability of the government choosing the incentive is $x(x \in [0,1])$ the probability of choosing no incentive is $1-x$. Construction companies also have two strategies: innovate or do not innovate. The probability that the construction company chooses to innovate is $y(y \in [0,1])$ the probability of choosing not to innovate is $1-y$. Public universities have two strategies as well: To cultivate RAAC talents or not to cultivate. The probability of the public universities choosing to cultivate is $z(z \in [0,1])$ the probability of choosing not to cultivate is $1-z$.

Assumption III

Players can only choose one strategy at one time; other companies do not influence construction companies' strategic choices; other universities do not influence public universities' strategic choices

Based on the above assumptions, the relevant symbols were further defined as shown in (Table 3-1)

Table 3-1 Meaning of parameters

Parameters	Meanings	Domain
$\mathcal{B}_1$	The tax revenue of the government when construction companies choose not to Innovate	$\mathcal{B}_1 \geq 0$
$\mathcal{B}_2$	Extra benefits by the entire construction industry chain when construction companies innovate with RAAC when the government does not incentivize	$\mathcal{B}_2 \geq 0$
$\mathcal{B}_3$	Extra benefits by the entire construction industry chain when construction companies innovate with RAAC when the government incentives	$\mathcal{B}_3 \geq 0$
$\mathcal{B}_4$	Government fines for poor environmental performance due to non-innovation by construction companies	$\mathcal{B}_4 \geq 0$
$\mathcal{B}_5$	The cost of improved environmental benefits of traditional construction methods	$\mathcal{B}_5 \geq 0$
$\mathcal{C}_1$	Economic benefits for construction companies when they do not innovate	$\mathcal{C}_1 \geq 0$
$\mathcal{C}_2$	Economic benefits increment for construction companies when they innovate	$\mathcal{C}_2 \geq 0$

$\mathcal{C}_3$	Reputation and brand value of construction companies for RAAC Innovation	$\mathcal{C}_3 \geq 0$
$\mathcal{C}_4$	Cost of RAAC innovation for construction companies	$\mathcal{C}_4 \geq 0$
$\mathcal{C}_5$	Subsidies that construction companies gain from the government for RAAC innovation	$\mathcal{C}_5 \geq 0$
$\mathcal{C}_6$	Innovation cost savings from acquiring RAAC talent from universities	$\mathcal{C}_6 \geq 0$
$\mathcal{P}_1$	Subsidies that public universities gain from the government for RAAC talent cultivation	$\mathcal{P}_1 \geq 0$
$\mathcal{P}_2$	Academic evaluation benefits of public universities for RAAC talent cultivation	$\mathcal{P}_2 \geq 0$
$\mathcal{P}_3$	Academic evaluation penalties of public universities for RAAC talent cultivation	$\mathcal{P}_3 \geq 0$
$\mathcal{P}_4$	Cost of RAAC talent cultivation for public universities	$\mathcal{P}_4 \geq 0$
x	Probability of the government choosing to incentivize	$0 \leq x \leq 1$
$1 - x$	Probability of the government choosing not to incentivize	$0 \leq x \leq 1$
y	Probability of the construction company choosing to innovate	$0 \leq y \leq 1$
$1 - y$	Probability of the construction company choosing not to innovate	$0 \leq y \leq 1$
z	Probability of the public universities choosing to cultivate	$0 \leq z \leq 1$
$1 - z$	Probability of the public universities choosing not to cultivate	$0 \leq z \leq 1$

3.2.3. Establishment of payoff model

The payoff matrix of Government, construction companies, and public universities is shown in Table 3-2.

Table 3-2 Payoff matrix

Stakeholders				**Construction companies**	
				Innovate(y)	Not to innovate(1-y)
Government	Incentive(x)	**Public universities**	Cultivate(z)	$\mathcal{B}_1+\mathcal{B}_3-\mathcal{C}_5-\mathcal{P}_1$ $\mathcal{C}_1+\mathcal{C}_2+\mathcal{C}_3+\mathcal{C}_5+\mathcal{C}_6-\mathcal{C}_4$ $\mathcal{P}_1+\mathcal{P}_2-\mathcal{P}_4$	$\mathcal{B}_1+\mathcal{B}_4-\mathcal{B}_5-\mathcal{P}_1$ $\mathcal{C}_1-\mathcal{B}_4$ $\mathcal{P}_1+\mathcal{P}_2-\mathcal{P}_4$
			Not to cultivate(1-z)	$\mathcal{B}_1+\mathcal{B}_3-\mathcal{C}_5$ $\mathcal{C}_1+\mathcal{C}_2+\mathcal{C}_3+\mathcal{C}_5-\mathcal{C}_4$ $-\mathcal{P}_3$	$\mathcal{B}_1+\mathcal{B}_4-\mathcal{B}_5$ $\mathcal{C}_1-\mathcal{B}_4$ $-\mathcal{P}_3$
Government	No incentive(1-x)	**Public universities**	Cultivate(z)	$\mathcal{B}_1+\mathcal{B}_2$ $\mathcal{C}_1+\mathcal{C}_2+\mathcal{C}_3+\mathcal{C}_6-\mathcal{C}_4$ $\mathcal{P}_2-\mathcal{P}_4$	$\mathcal{B}_1-\mathcal{B}_5$ $\mathcal{C}_1$ $\mathcal{P}_2-\mathcal{P}_4$
			Not to cultivate(1-z)	$\mathcal{B}_1+\mathcal{B}_2$ $\mathcal{C}_1+\mathcal{C}_2+\mathcal{C}_3-\mathcal{C}_4$ 0	$\mathcal{B}_1-\mathcal{B}_5$ $\mathcal{C}_1$ 0

Assume that the expected utility of the government incentive strategy is $\mathcal{H}_{11}$, the expected utility of the government disincentive strategy is $\mathcal{H}_{12}$, and the average expected utility is $\bar{\mathcal{H}}_1$. Then:

$$\mathcal{H}_{11} = yz(\mathcal{B}_1+\mathcal{B}_3-\mathcal{C}_5-\mathcal{P}_1)+(1-y)z(\mathcal{B}_1+\mathcal{B}_4-\mathcal{B}_5-\mathcal{P}_1)+y(1-z)(\mathcal{B}_1+\mathcal{B}_3-\mathcal{C}_5)+(1-y)(1-z)(\mathcal{B}_1+\mathcal{B}_4-\mathcal{B}_5) = \mathcal{B}_1+\mathcal{B}_4-\mathcal{B}_5-z\mathcal{P}_1+y(\mathcal{B}_3-\mathcal{B}_4+\mathcal{B}_5-\mathcal{C}_5) \quad (1)$$

$$\mathcal{H}_{12} = yz(\mathcal{B}_1+\mathcal{B}_2)+(1-y)z(\mathcal{B}_1-\mathcal{B}_5)+y(1-z)(\mathcal{B}_1+\mathcal{B}_2)+(1-y)(1-z)(\mathcal{B}_1-\mathcal{B}_5) = \mathcal{B}_1-\mathcal{B}_5+y(\mathcal{B}_2+\mathcal{B}_5) \quad (2)$$

$$\bar{\mathcal{H}}_1 = x\mathcal{H}_{11}+(1-x)(\mathcal{H}_{11}-\mathcal{H}_{12}) \quad (3)$$

The replicated dynamic equation[8] of government $G(x)$ is:

$$G(x) = \frac{dx}{dt} = x(\mathcal{H}_{11} - \bar{\mathcal{H}}_1) = x(1-x)(\mathcal{H}_{11} - \mathcal{H}_{12}) = x(1-x)[\mathcal{B}_4 - z\mathcal{P}_1 + y(\mathcal{B}_3 - \mathcal{B}_4 - \mathcal{B}_2 - \mathcal{C}_5)] \tag{4}$$

Assume that the expected utility of the construction companies innovation strategy is $\mathcal{H}_{21}$, the expected utility of the construction companies do not innovate is $\mathcal{H}_{22}$, and the average expected utility is $\bar{\mathcal{H}}_2$. Then:

$$\mathcal{H}_{21} = xz(\mathcal{C}_1 + \mathcal{C}_2 + \mathcal{C}_3 + \mathcal{C}_5 + \mathcal{C}_6 - \mathcal{C}_4) + (1-x)z(\mathcal{C}_1 + \mathcal{C}_2 + \mathcal{C}_3 + \mathcal{C}_6 - \mathcal{C}_4) + x(1-z)(\mathcal{C}_1 + \mathcal{C}_2 + \mathcal{C}_3 + \mathcal{C}_5 - \mathcal{C}_4) + (1-x)(1-z)(\mathcal{C}_1 + \mathcal{C}_2 + \mathcal{C}_3 - \mathcal{C}_4) = \mathcal{C}_1 + \mathcal{C}_2 + \mathcal{C}_3 - \mathcal{C}_4 + z\mathcal{C}_6 + x\mathcal{C}_5 \tag{5}$$

$$\mathcal{H}_{22} = xz(\mathcal{C}_1 - \mathcal{B}_4) + (1-x)z(\mathcal{C}_1) + x(1-z)(\mathcal{C}_1 - \mathcal{B}_4) + (1-x)(1-z)(\mathcal{C}_1) = \mathcal{C}_1 - x\mathcal{B}_4 \tag{6}$$

$$\bar{\mathcal{H}}_2 = y\mathcal{H}_{21} + (1-y)(\mathcal{H}_{21} - \mathcal{H}_{22}) \tag{7}$$

The replicated dynamic equation of construction companies $D(y)$ is:

$$D(y) = \frac{dy}{dt} = y(\mathcal{H}_{21} - \bar{\mathcal{H}}_2) = y(1-y)(\mathcal{H}_{21} - \mathcal{H}_{22}) = y(1-y)[x(\mathcal{C}_5 + \mathcal{B}_4) + z\mathcal{C}_6 + \mathcal{C}_2 + \mathcal{C}_3 - \mathcal{C}_4] \tag{8}$$

Assume that the expected utility of the strategies for cultivating RAAC talent at public universities is $\mathcal{H}_{31}$, the expected utility of the strategies for not cultivating RAAC talent at public universities is $\mathcal{H}_{32}$. And the average expected utility is $\bar{\mathcal{H}}_3$. Then:

$$\mathcal{H}_{31} = xy(\mathcal{P}_1 + \mathcal{P}_2 - \mathcal{P}_4) + (1-x)y(\mathcal{P}_2 - \mathcal{P}_4) + x(1-y)(\mathcal{P}_1 + \mathcal{P}_2 - \mathcal{P}_4) + (1-x)(1-y)(\mathcal{P}_2 - \mathcal{P}_4) = x\mathcal{P}_1 + \mathcal{P}_2 - \mathcal{P}_4 \tag{9}$$

$$\mathcal{H}_{32} = xy(-\mathcal{P}_3) + x(1-y)(-\mathcal{P}_3) = -x\mathcal{P}_3$$

(10)

$$\bar{\mathcal{H}}_3 = z\mathcal{H}_{31} + (1-z)(\mathcal{H}_{31} - \mathcal{H}_{32})$$

(11)

The replicated dynamic equation of public universities $E(z)$ is:

$$E(z) = \frac{dz}{dt} = z(\mathcal{H}_{31} - \bar{\mathcal{H}}_3) = z(1-z)(\mathcal{H}_{31} - \mathcal{H}_{32}) = z(1-z)[x(\mathcal{P}_1 + \mathcal{P}_3) + \mathcal{P}_2 - \mathcal{P}_4]$$

(12)

In order to further discuss the evolutionary stable points of the TEG, the simultaneous equations are as follows:

$$\begin{cases} G(x) = \frac{dx}{dt} = x(\mathcal{H}_{11} - \bar{\mathcal{H}}_1)x(1-x)(\mathcal{H}_{11} - \mathcal{H}_{12}) = x(1-x)[\mathcal{B}_4 - z\mathcal{P}_1 + y(\mathcal{B}_3 - \mathcal{B}_4 - \mathcal{B}_2 - \mathcal{C}_5)] = 0 \\ D(y) = \frac{dy}{dt} = y(\mathcal{H}_{21} - \bar{\mathcal{H}}_2)y(1-y)(\mathcal{H}_{21} - \mathcal{H}_{22}) = y(1-y)[x(\mathcal{C}_5 + \mathcal{B}_4) + z\mathcal{C}_6 + \mathcal{C}_2 + \mathcal{C}_3 - \mathcal{C}_4] = 0 \\ E(z) = \frac{dz}{dt} = z(\mathcal{H}_{31} - \bar{\mathcal{H}}_3)z(1-z)(\mathcal{H}_{31} - \mathcal{H}_{32}) = z(1-z)[x(\mathcal{P}_1 + \mathcal{P}_3) + \mathcal{P}_2 - \mathcal{P}_4] = 0 \end{cases}$$

(13)

From the above simultaneous equations, the evolutionary stability points of the government, construction companies, and public universities can be obtained: $S_1(0,0,0)$, $S_2(0,0,1)$, $S_3(0,1,0)$, $S_4(1,0,0)$, $S_5(0,1,1)$, $S_6(1,0,1)$, $S_7(1,1,0)$, $S_8(1,1,1)$ and $S_s(x^*, y^*, z^*)$, when $S_s(x^*, y^*, z^*)$ satisfies the following simultaneous equations:

$$\begin{aligned} \mathcal{B}_4 - z\mathcal{P}_1 + y(\mathcal{B}_3 - \mathcal{B}_4 - \mathcal{B}_2 - \mathcal{C}_5) = 0 \\ x(\mathcal{C}_5 + \mathcal{B}_4) + z\mathcal{C}_6 + \mathcal{C}_2 + \mathcal{C}_3 - \mathcal{C}_4 = 0 \\ x(\mathcal{P}_1 + \mathcal{P}_3) + \mathcal{P}_2 - \mathcal{P}_4 = 0 \end{aligned}$$

(14)

3.3. Evolutionary stability analysis

3.3.1. Asymptotic stability analysis

According to the above equation and referring to the stability principle of the replicated dynamic equation[9], the asymptotic stability of the three parties, the government, the construction company, and the public university, can be obtained as follows:

1) Asymptotic stability analysis of government:

Let $\frac{dx}{dt} = 0$, $x_1 = 0$, and $x_2 = 1$, $y^* = \frac{z\mathcal{P}_1 - \mathcal{B}_4}{\mathcal{B}_3 - \mathcal{B}_4 - \mathcal{B}_2 - \mathcal{C}_5}$.

When $y = y^*$, $G(x) = 0$. This means that the government will get the same benefits regardless of whether it chooses the incentive strategy or not. When $y > y^*$, the probability of construction companies choosing innovative strategies exceeds y^*. To satisfy $G(x) \geq 0$, $x_2 = 1$ is the evolutionary stable point, which indicates that the probability that the government will choose the incentive is increasing, and eventually, the government will choose the incentive strategy. When $y < y^*$, the probability of construction companies choosing innovative strategies are more diminutive than y^*. To protect $G(x) \geq 0$, $x_1 = 0$ is the evolutionary stable point. The probability that the government will choose to incentivize continues to decline and eventually choose not to incentivize.

Let $\frac{dx}{dt} = 0$, $x_1 = 0$, and $x_2 = 1$, $z^* = \frac{y(\mathcal{B}_3 - \mathcal{B}_4 - \mathcal{B}_2 - \mathcal{C}_5) + \mathcal{B}_4}{\mathcal{P}_1}$.

When $z = z^*$, $G(x) = 0$. This means that the government's strategy will not change over time. When $z > z^*$, the probability that public universities will choose the strategy to develop RAAC talent exceeds z^*. To safeguard $G(x) \geq 0$, $x_2 = 1$ is the evolutionary stable point, suggesting that the government's probability of choosing incentives improves; ultimately, the government will choose an incentive strategy. When $z < z^*$, the probability of construction companies choosing strategies for RAAC talent cultivation is less than z^*. To guarantee $G(x) \geq 0$, $x_1 = 0$ is the evolutionary stable point. The government's probability of choosing to incentivize continues to decline and eventually chooses not to incentivize.

2) Asymptotic stability analysis of construction companies:

Let $\frac{dy}{dt} = 0$, $y_1 = 0$, and $y_2 = 1$, $x^* = \frac{\mathcal{C}_4 - \mathcal{C}_2 - \mathcal{C}_3 - z\mathcal{C}_6}{\mathcal{C}_5 + \mathcal{B}_4}$

When $x = x^*$, $D(y) = 0$. This means that the benefits of RAAC innovation for construction companies are the same as the benefits of maintaining traditional construction methods. When $x > x^*$, the probability that the government choosing to incentivize exceeds x^*. To secure $D(y) \geq 0$, $y_2 = 1$ is the evolutionary stable point. It shows that the strategy of construction companies will change from non-innovation to innovation and eventually get a stable innovation strategy. When $x < x^*$, the probability that the government choosing to incentivize is less than x^*. To guarantee $D(y) \geq 0$, $y_1 = 0$ is the evolutionary stable point. The probability that an architectural firm will choose to innovate continues to decline and eventually choose not to innovate.

Let $\frac{dy}{dt} = 0$, $y_1 = 0$, and $y_2 = 1$, $z^* = \frac{\mathcal{C}_4 - \mathcal{C}_2 - \mathcal{C}_3 - x(\mathcal{C}_5 + \mathcal{B}_4)}{\mathcal{C}_6}$

When $z = z^*$, $D(y) = 0$. This means that the benefits of RAAC innovation for construction companies are the same as the benefits of maintaining traditional construction methods. When $z > z^*$, the probability that public universities will choose the strategy to develop RAAC talent exceeds z^*. To secure $D(y) \geq 0$, $y_2 = 1$ is the evolutionary stable point. This suggests that the strategy of construction companies will shift from non-innovation to innovation and eventually acquire a stable innovation strategy. When $z < z^*$, the probability of construction companies choosing strategies for RAAC talent cultivation is less than z^*. In order to ensure that $D(y) \geq 0$, $y_1 = 0$ is the evolutionary stable point. Construction companies will move from innovation to non-innovation and ultimately choose not to innovate.

3) Asymptotic stability analysis of public universities:

Let $\frac{dz}{dt} = 0$, $z_1 = 0$, and $z_2 = 1$, $x^* = \frac{\mathcal{P}_4 - \mathcal{P}_2}{\mathcal{P}_1 + \mathcal{P}_3}$

When $x = x^*$, $E(z) = 0$. The probability that a public university chooses to train RAAC talent does not change over time. When $x > x^*$, the probability that the government choosing to incentivize exceeds x^*. To secure $E(z) \geq 0$, $z_2 = 1$ is the evolutionary stable point. This indicates that the strategy of public universities is gradually tending to cultivate RAAC talents and eventually acquire a stable cultivation strategy. When $x < x^*$, the probability that the government choosing to incentivize is less than x^*. To guarantee $E(z) \geq 0$, $z_1 = 0$ is the evolutionary stable point. The probability that public universities choose to train RAAC talent continues to decline, and eventually choose not to cultivate.

3.3.2. The analysis of the trend of tripartite evolutionary game

In order to analyze the ESS of the RAAC innovation TEG, according to ref[10], it can be determined by the local stability analysis of the Jacobi matrix. A Jacobi matrix $\mathcal{J}(x, y, z)$ corresponding to the evolutionary game model in this chapter appears as follows:

$$\mathcal{J}(x, y, z) = \begin{pmatrix} \frac{\partial G(x)}{\partial x} & \frac{\partial G(x)}{\partial y} & \frac{\partial G(x)}{\partial z} \\ \frac{\partial D(y)}{\partial x} & \frac{\partial D(y)}{\partial y} & \frac{\partial D(y)}{\partial z} \\ \frac{\partial E(z)}{\partial x} & \frac{\partial E(z)}{\partial y} & \frac{\partial E(z)}{\partial z} \end{pmatrix} \tag{15}$$

Where $\frac{\partial G(x)}{\partial x} = [(1-2x)[\mathcal{B}_4 - z\mathcal{P}_1 + y(\mathcal{B}_3 - \mathcal{B}_4 - \mathcal{B}_2 - \mathcal{C}_5)]$, $\frac{\partial G(x)}{\partial y} = x(1-x)(\mathcal{B}_3 - \mathcal{B}_4 - \mathcal{B}_2 - \mathcal{C}_5)$, $\frac{\partial G(x)}{\partial z} = x(1-x)(-\mathcal{P}_1)$, $\frac{\partial D(y)}{\partial x} = y(1-y)(\mathcal{C}_5 + \mathcal{B}_4)$, $\frac{\partial D(y)}{\partial y} = (1 -$

$2\mathcal{y})[x(\mathcal{C}_5+\mathcal{B}_4)+z\mathcal{C}_6+\mathcal{C}_2+\mathcal{C}_3-\mathcal{C}_4]$, $\frac{\partial D(\mathcal{y})}{\partial z}=\mathcal{y}(1-\mathcal{y})\,\mathcal{C}_6$, $\frac{\partial E(z)}{\partial x}=z(1-z)(\mathcal{P}_1+\mathcal{P}_3)$, $\frac{\partial E(z)}{\partial \mathcal{y}}=0$, $\frac{\partial E(z)}{\partial z}=(1-2z)[x(\mathcal{P}_1+\mathcal{P}_3)+\mathcal{P}_2-\mathcal{P}_4]$.

The eigenvalues of the respective Jacobi matrices are obtained by banding the eight equilibrium points: $S_1(0,0,0)$, $S_2(0,0,1)$, $S_3(0,1,0)$, $S_4(1,0,0)$, $S_5(0,1,1)$, $S_6(1,0,1)$, $S_7(1,1,0)$, $S_8(1,1,1)$ into equation (15), as shown in Table 5-3. When all eigenvalues of the Jacobi matrix are negative simultaneously, the equilibrium point satisfies ESS[10, 11].

3.4. Numerical Simulation

3.4.1. The evolutionary trajectory of ESS

For analyzing the dynamic evolution process, the strategy evolution process of the tripartite in different scenarios can be simulated by changing the parameter settings. Based on replicator dynamic equations different stability conditions are brought into MATLAB R2021b to simulate the evolutionary trajectory of ESS mentioned. The MATLAB simulation program and equation analysis are shown in Figure 3-1,3-2,3-3.

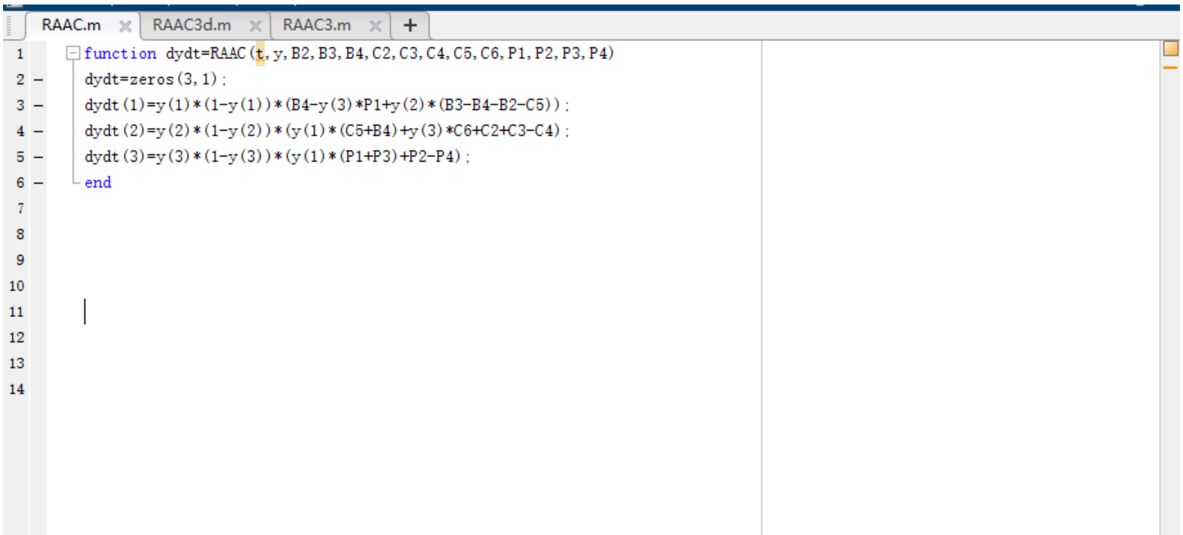

Figure 3-1 The dynamic equilibrium of evolutionary games

RAAC.m | RAAC3d.m | RAAC3.m

```
B2=30;B3=150;B4=20;C2=20;C3=15;C4=25;C5=15;C6=15;P1=10;P2=10;P3=50;P4=15;
for i=0.1:0.2:1
    for j=0.1:0.2:1
        for k=0.1:0.2:1
            [t,y]=ode45(@(t,y) RAAC(t,y,B2,B3,B4,C2,C3,C4,C5,C6,P1,P2,P3,P4),[0 100],[i j k]);
            figure(1)
            grid on
            plot3(y(:,1),y(:,2),y(:,3),'linewidth',1);
            set(gca,'XTick',[0:0.2:1],'YTick',[0:0.2:1],'ZTick',[0:0.2:1]);
            hold on
            axis([0 1 0 1 0 1])
            view([45 10])
        end
    end
end
```

Figure 3-1 Analytic production procedure for 3-dimensional evolutionary curves

RAAC.m | RAAC3d.m | RAAC3.m

```
B2=30;B3=40;B4=4;C2=8;C3=3;C4=20;C5=5;C6=5;P1=2;P2=3;P3=3;P4=10;
for i=0.5
    for C4=0:6:30
    [t,y]=ode45(@(t,y) RAAC(t,y,B2,B3,B4,C2,C3,C4,C5,C6,P1,P2,P3,P4),[0 100],[i 0.5 0.5]);
    figure(1)
    grid on
    plot(t,y(:,1),'lineWidth',2.2);
    hold on
    %plot(t,y(:,2),'color',[0.11765,0.56471,1],'lineWidth',2.2);
    %hold on
    %plot(t,y(:,3),'color',[0.66,0.84314,0.653],'lineWidth',2.2);
    %hold on
    xlim([0 1]),ylim([0 1]);
    xlabel('Time');ylabel('Probability','Rotation',90);
    legend({'P_2=0','P_2=3','P_2=6','P_2=9','P_2=12','P_2=15'})
    end
end
for j=0.5
    for C4=0:6:30
    [t,y]=ode45(@(t,y) RAAC(t,y,B2,B3,B4,C2,C3,C4,C5,C6,P1,P2,P3,P4),[0 100],[0.5 j 0.5]);
    figure(2)
    grid on
    %plot(t,y(:,1),'lineWidth',2.2);
    %hold on
    plot(t,y(:,2),'lineWidth',2.2);
    hold on
    %plot(t,y(:,3),'color',[0.66,0.84314,0.653],'lineWidth',2.2);
    %hold on
    xlim([0 1]),ylim([0 1]);
    xlabel('Time');ylabel('Probability','Rotation',90);
    legend({'C_4=0','C_4=6','C_4=6','C_4=9','C_4=12','C_4=15'})
    end
end
for k=0.5
    for C4=0:6:30
    [t,y]=ode45(@(t,y) RAAC(t,y,B2,B3,B4,C2,C3,C4,C5,C6,P1,P2,P3,P4),[0 100],[0.5 0.5 k]);
    figure(3)
    grid on
    %plot(t,y(:,1),'lineWidth',2.2);
    %hold on
    %plot(t,y(:,2),'lineWidth',2.2);
    %hold on
    plot(t,y(:,3),'lineWidth',2.2);
    hold on
    xlim([0 1]),ylim([0 1]);
    xlabel('Time');ylabel('Probability','Rotation',90);
    legend({'P_2=0','P_2=3','P_2=6','P_2=9','P_2=12','P_2=15'})
    end
end
```

Figure 3-3 Analytical production procedures for the influence of key parameters on evolutionary trends

1) Assumption i

$\mathcal{B}_2 = 30$, $\mathcal{B}_3 = 40$, $\mathcal{B}_4 = 6$, $\mathcal{C}_2 = 8$, $\mathcal{C}_3 = 4$, $\mathcal{C}_4 = 20$, $\mathcal{C}_5 = 4$, $\mathcal{C}_6 = 2$, $\mathcal{P}_1 = 10$, $\mathcal{P}_2 = 15$, $\mathcal{P}_3 = 10$, $\mathcal{P}_4 = 10$ the evolutionary trajectory of $S_2(0,0,1)$ is featured in Figure.3-4. When the initial probabilities of all three parties are 0.5, the evolutionary trajectory is displayed in Figure.3-5.

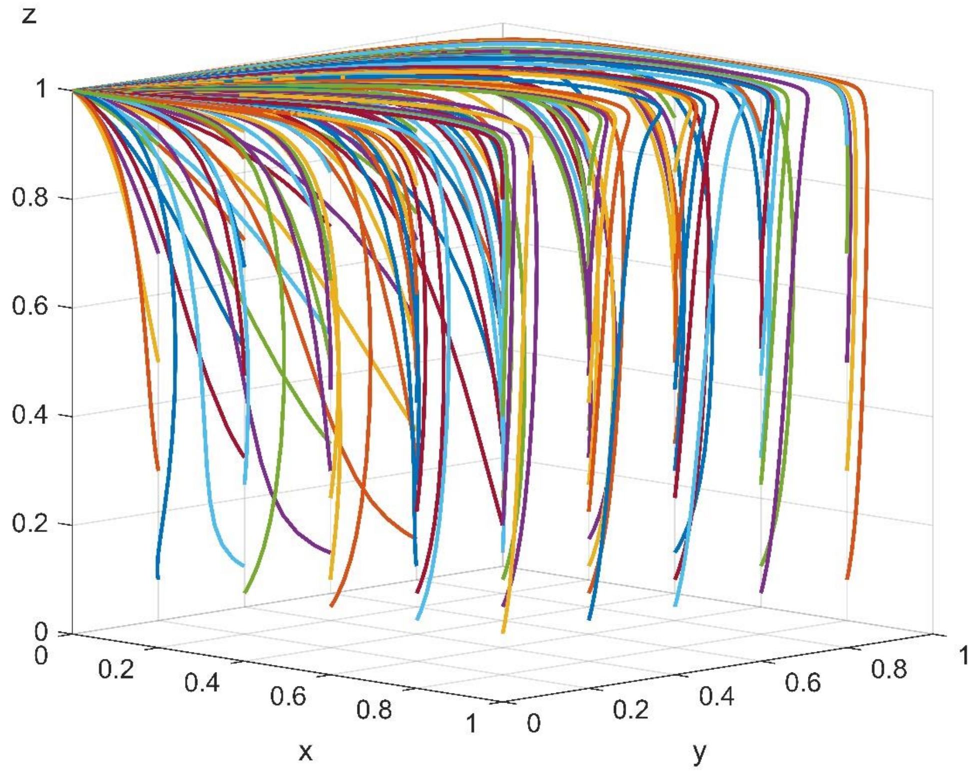

Figure 3-4 Three-dimension evolutionary trajectory of $S_2(0,0,1)$

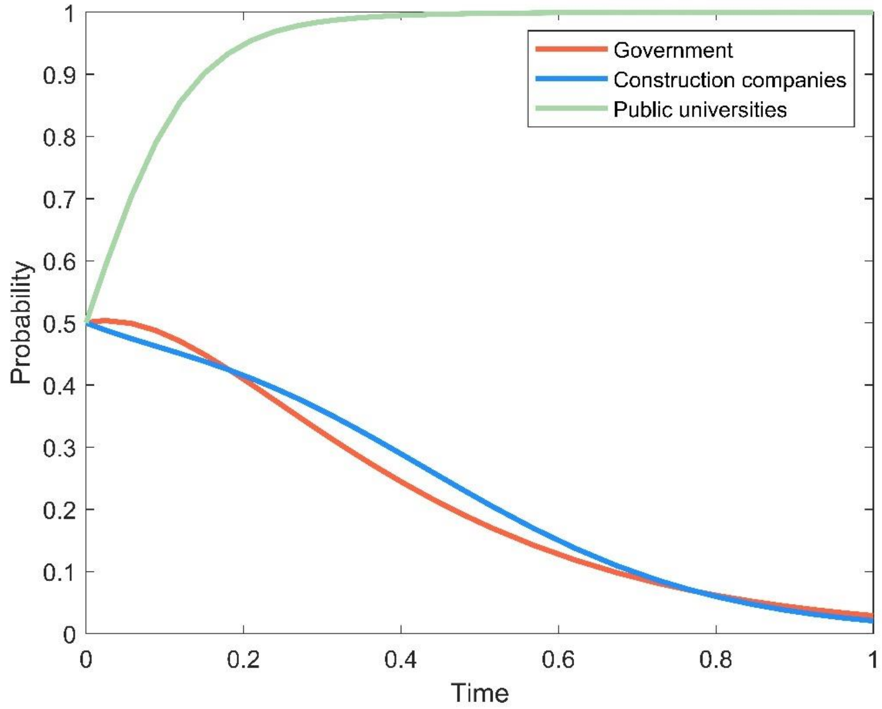

Figure 3-5 Two-dimension evolutionary trajectory of $S_2(0,0,1)$

2) Assumption ii

$\mathcal{B}_2 = 30$, $\mathcal{B}_3 = 40$, $\mathcal{B}_4 = 6$, $\mathcal{C}_2 = 8$, $\mathcal{C}_3 = 13$, $\mathcal{C}_4 = 20$, $\mathcal{C}_5 = 13$, $\mathcal{C}_6 = 2$, $\mathcal{P}_1 = 10$, $\mathcal{P}_2 = 5$, $\mathcal{P}_3 = 5$, $\mathcal{P}_4 = 10$ the evolutionary trajectory of $S_3(0,1,0)$ is featured in Figure.3-6. When the initial probabilities of all three parties are 0.5, the evolutionary trajectory is displayed in Figure.3-7.

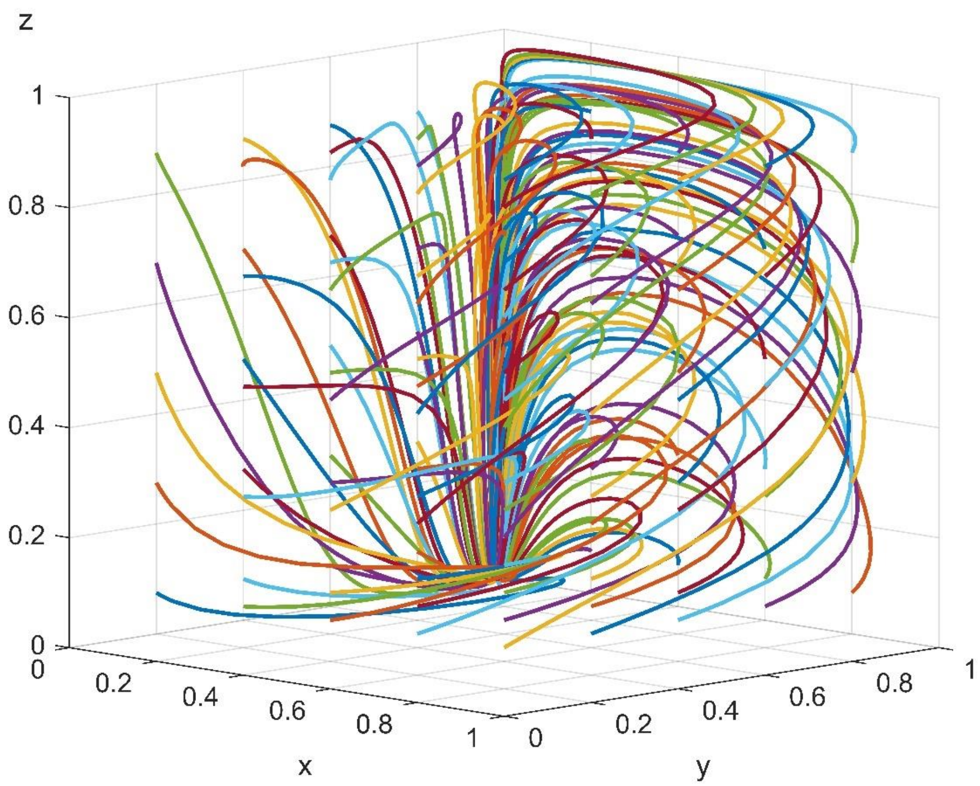

Figure 3-6 Three-dimension evolutionary trajectory of $S_3(0,1,0)$

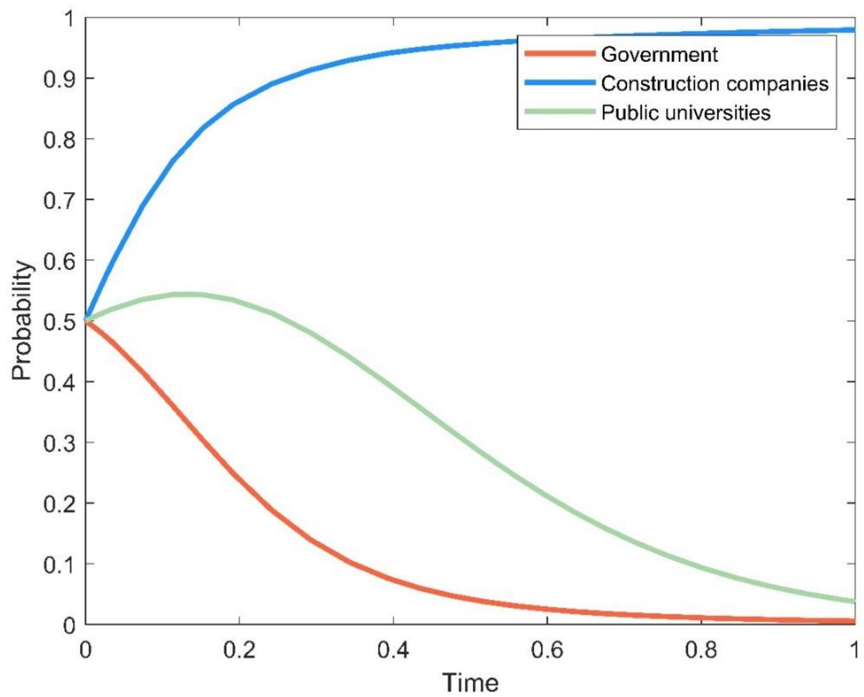

Figure 3-7 Two-dimension evolutionary trajectory of $S_3(0,1,0)$

3) Assumption iii

$\mathcal{B}_2 = 30$, $\mathcal{B}_3 = 40$, $\mathcal{B}_4 = 4$, $\mathcal{C}_2 = 8$, $\mathcal{C}_3 = 3$, $\mathcal{C}_4 = 20$, $\mathcal{C}_5 = 3$, $\mathcal{C}_6 = 2$, $\mathcal{P}_1 = 2$, $\mathcal{P}_2 = 3$, $\mathcal{P}_3 = 3$, $\mathcal{P}_4 = 10$ the evolutionary trajectory of $S_4(1,0,0)$ is featured in Figure.3-8. When the initial probabilities of all three parties are 0.5, the evolutionary trajectory is displayed in Figure.3-9.

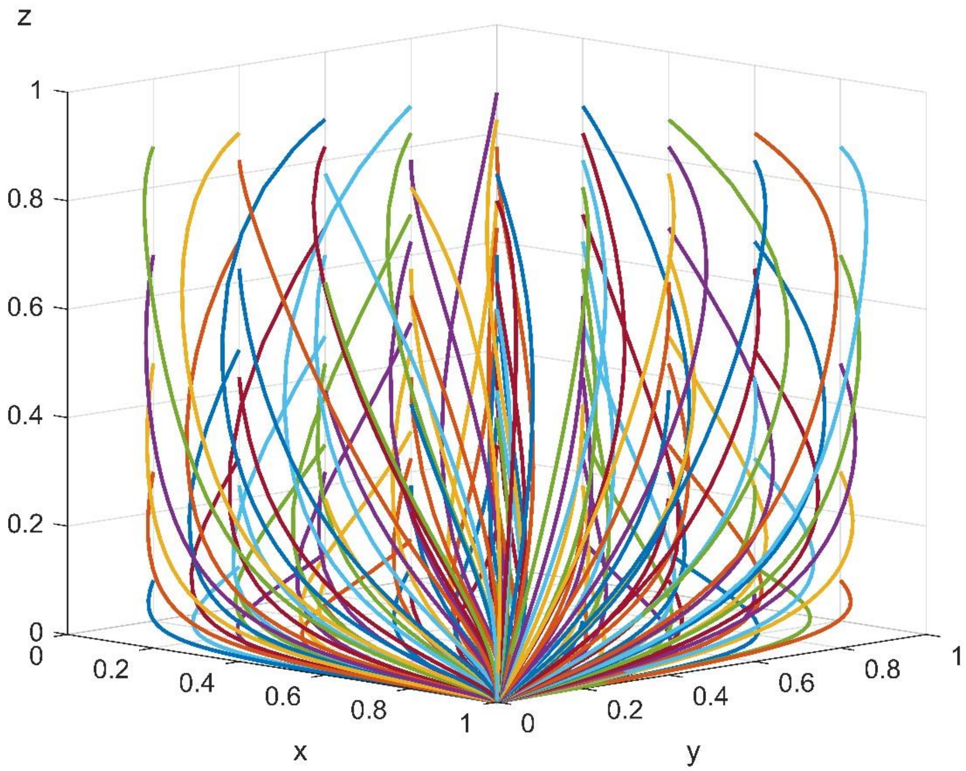

Figure 3-8 Three-dimension evolutionary trajectory of $S_4(1,0,0)$

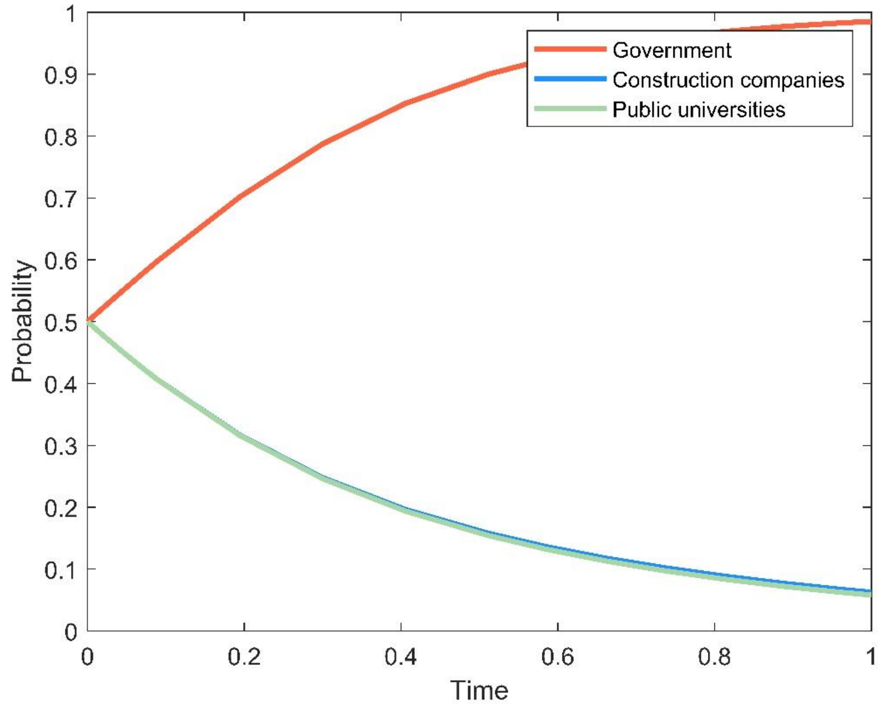

Figure 3-9 Two-dimension evolutionary trajectory of $S_4(1,0,0)$

4) Assumption iv

$\mathcal{B}_2 = 30$, $\mathcal{B}_3 = 40$, $\mathcal{B}_4 = 4$, $\mathcal{C}_2 = 8$, $\mathcal{C}_3 = 13$, $\mathcal{C}_4 = 20$, $\mathcal{C}_5 = 8$, $\mathcal{C}_6 = 2$, $\mathcal{P}_1 = 7$, $\mathcal{P}_2 = 13$, $\mathcal{P}_3 = 13$, $\mathcal{P}_4 = 10$ the evolutionary trajectory of $S_5(0,1,1)$ is featured in Figure.5-10. When the initial probabilities of all three parties are 0.5, the evolutionary trajectory is displayed in Figure.3-11.

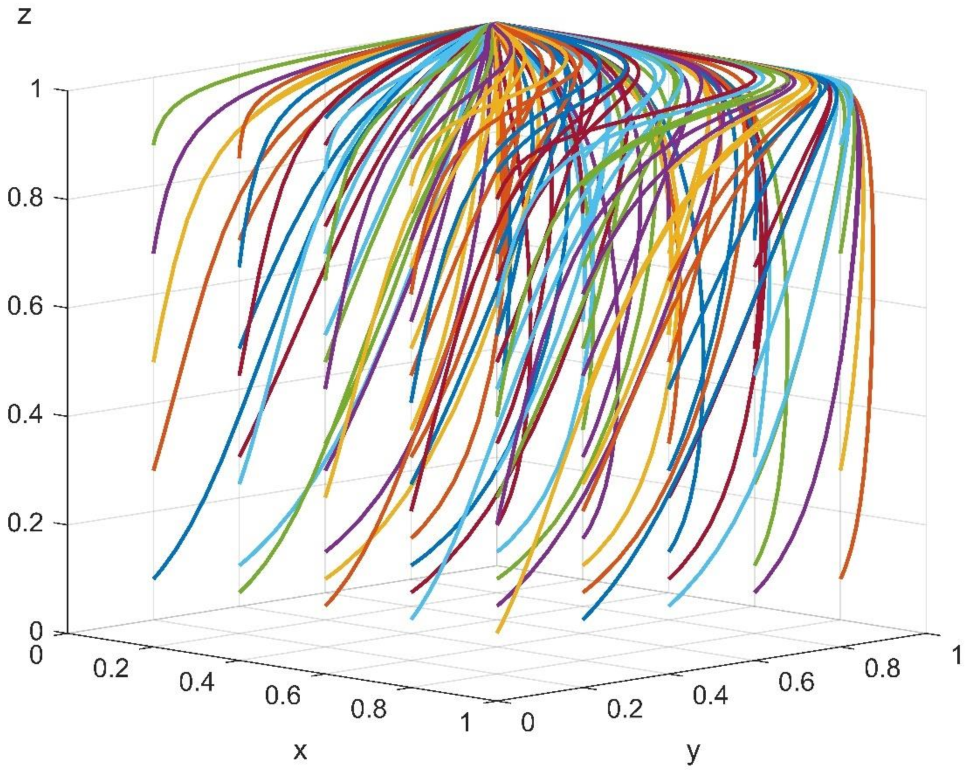

Figure 3-10 Three-dimension evolutionary trajectory of $S_5(0,1,1)$

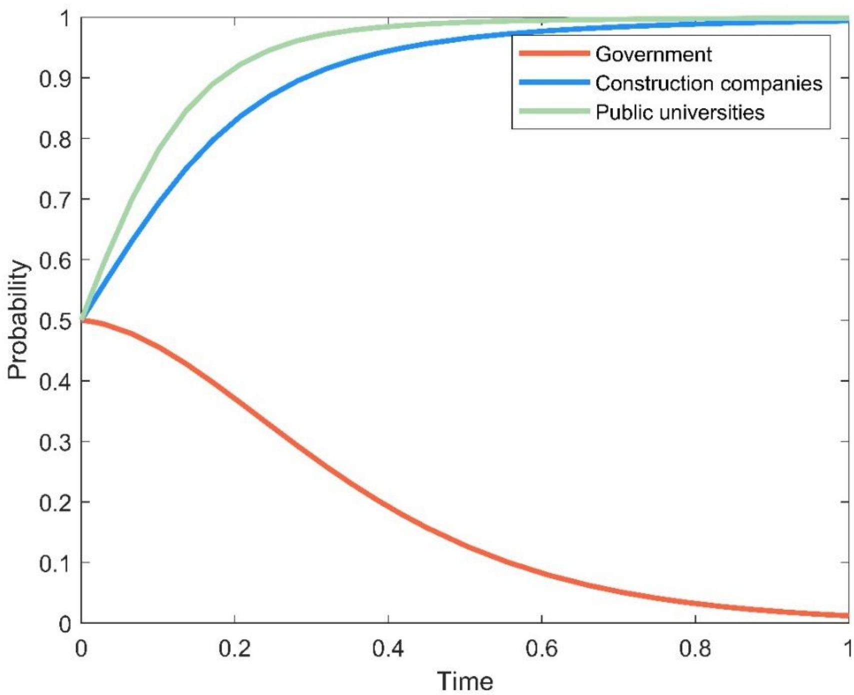

Figure 3-11 Two-dimension evolutionary trajectory of $S_5(0,1,1)$

5) Assumption v

$\mathcal{B}_2 = 30$, $\mathcal{B}_3 = 40$, $\mathcal{B}_4 = 5$, $\mathcal{C}_2 = 8$, $\mathcal{C}_3 = 1$, $\mathcal{C}_4 = 20$, $\mathcal{C}_5 = 2$, $\mathcal{C}_6 = 2$, $\mathcal{P}_1 = 3$, $\mathcal{P}_2 = 13$, $\mathcal{P}_3 = 13$, $\mathcal{P}_4 = 10$ the evolutionary trajectory of $S_6(1,0,1)$ is featured in Figure.3-12. When the initial probabilities of all three parties are 0.5, the evolutionary trajectory is displayed in Figure.3-13.

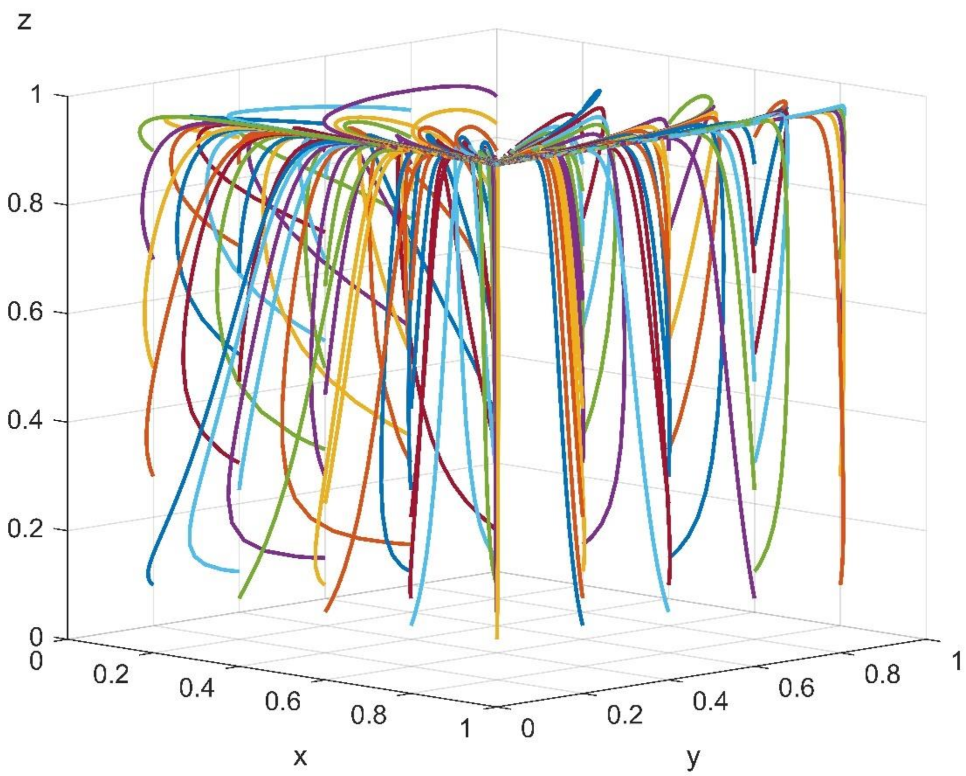

Figure 3-12 Three-dimension evolutionary trajectory of $S_6(1,0,1)$

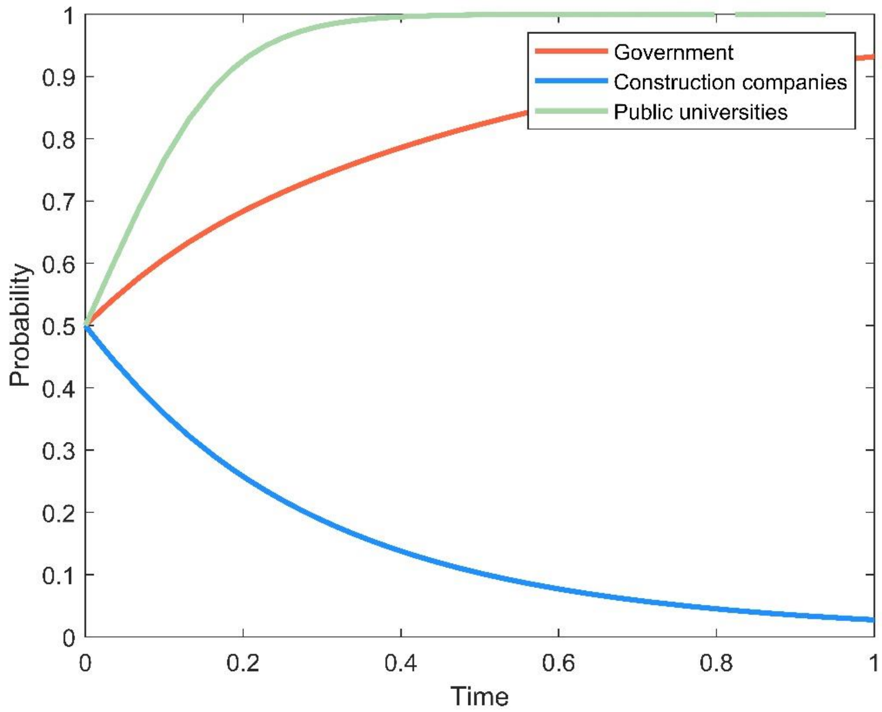

Figure 3-13 Two-dimension evolutionary trajectory of $S_6(1,0,1)$

6) Assumption vi

$\mathcal{B}_2 = 30$, $\mathcal{B}_3 = 40$, $\mathcal{B}_4 = 8$, $\mathcal{C}_2 = 8$, $\mathcal{C}_3 = 5$ $\mathcal{C}_4 = 20$, $\mathcal{C}_5 = 2$, $\mathcal{C}_6 = 2$, $\mathcal{P}_1 = 3$, $\mathcal{P}_2 = 2$, $\mathcal{P}_3 = 2$, $\mathcal{P}_4 = 10$ the evolutionary trajectory of $S_7(1,1,0)$ is featured in Figure.3-14. When the initial probabilities of all three parties are 0.5, the evolutionary trajectory is displayed in Figure.3-15.

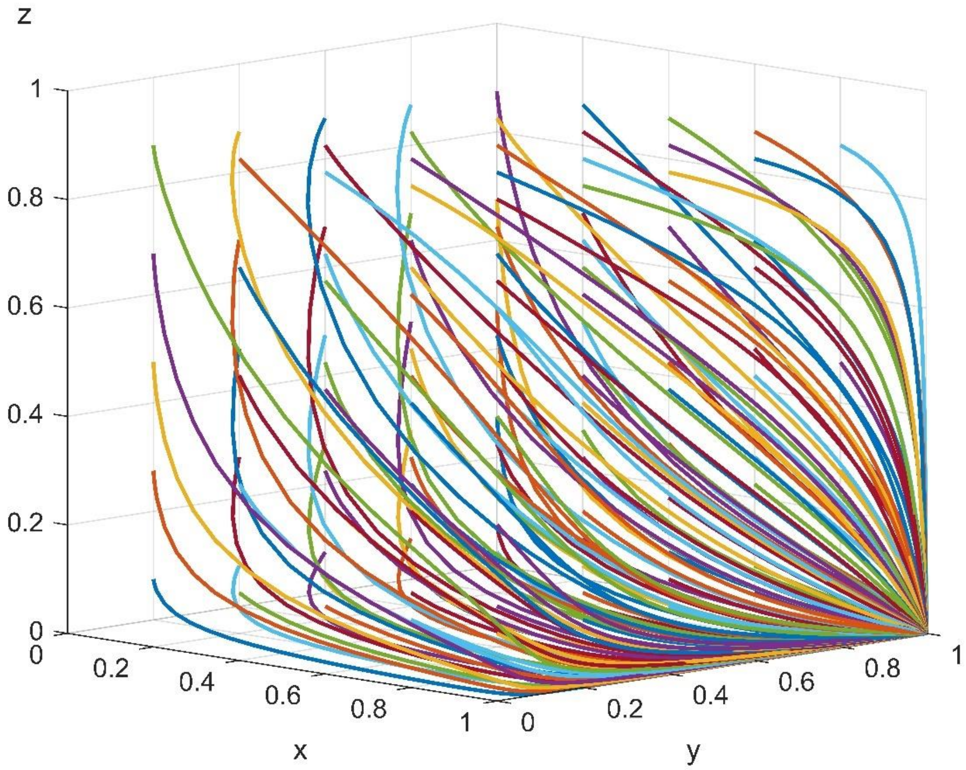

Figure 3-14 Three-dimension evolutionary trajectory of $S_7(1,1,0)$

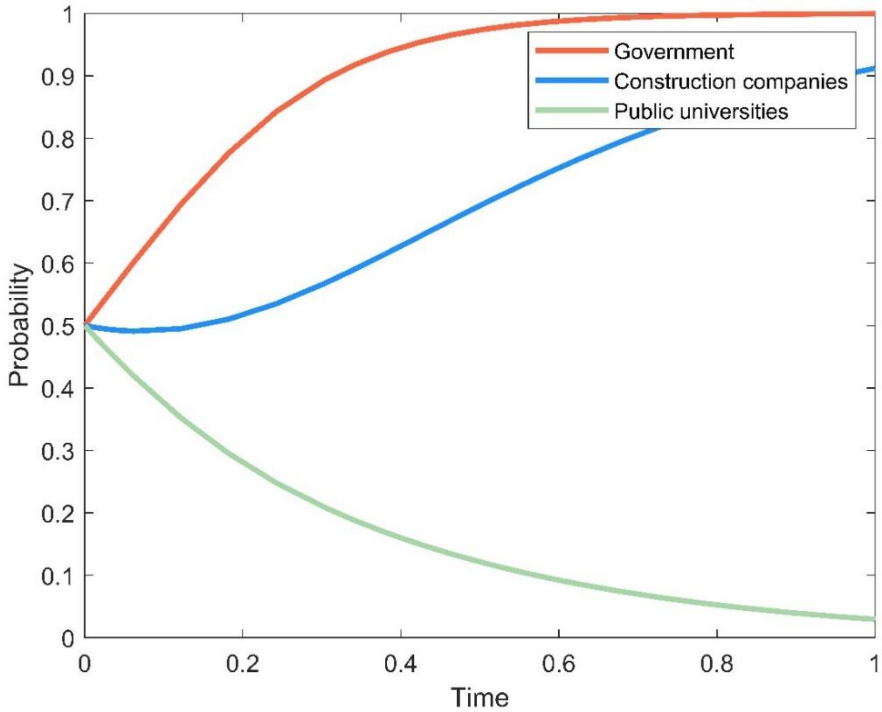

Figure 3-15 Two-dimension evolutionary trajectory of $S_7(1,1,0)$

7) Assumption vii

$\mathcal{B}_2 = 30, \mathcal{B}_3 = 40, \mathcal{B}_4 = 8, \mathcal{C}_2 = 8, \mathcal{C}_3 = 5\ \mathcal{C}_4 = 20, \mathcal{C}_5 = 2, \mathcal{C}_6 = 2, \mathcal{P}_1 = 3, \mathcal{P}_2 = 6, \mathcal{P}_3 = 6, \mathcal{P}_4 = 10$ the evolutionary trajectory of $S_8(1,1,1)$ is featured in Figure.3-16. When the initial probabilities of all three parties are 0.5, the evolutionary trajectory is displayed in Figure.3-17.

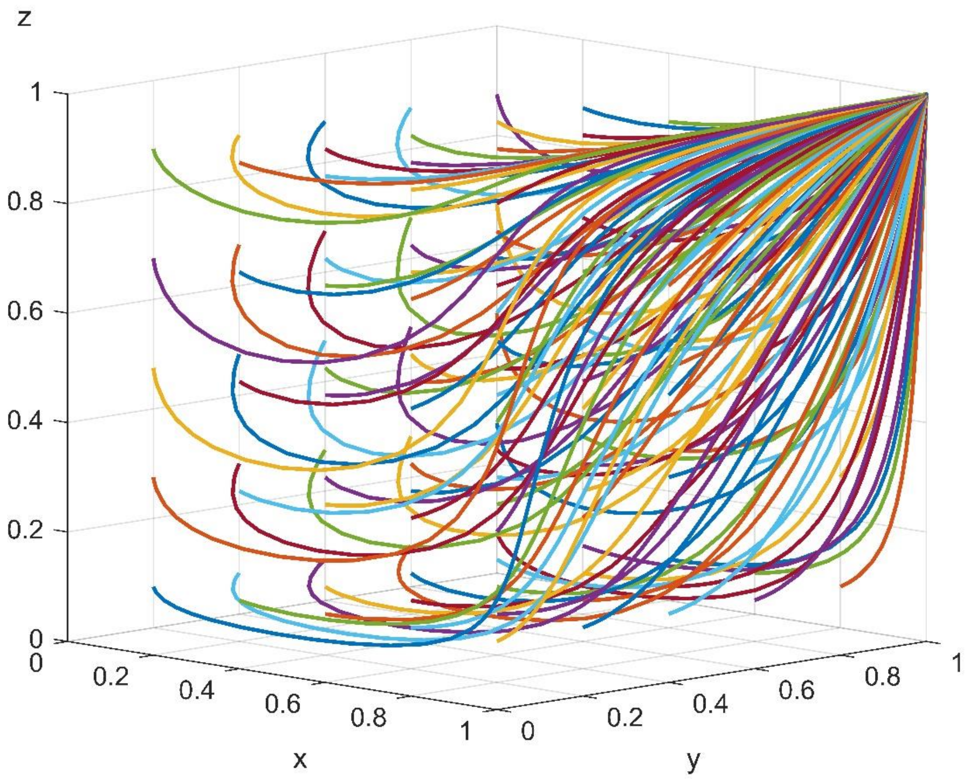

Figure 3-16 Three-dimension evolutionary trajectory of $S_8(1,1,1)$

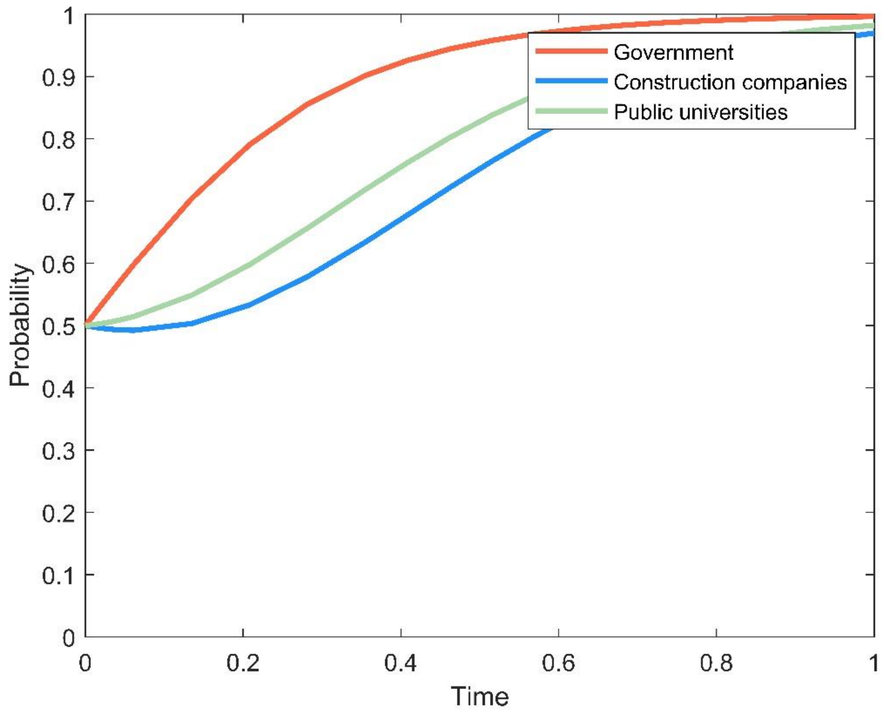

Figure 3-17 Two-dimension evolutionary trajectory of $S_8(1,1,1)$

3.4.2. Impact of incentive policy on evolutionary results and trajectories

To evaluate the impact of government incentives on the evolutionary outcomes and trajectories of the RAAC innovation tripartite ESS, numerical simulations were conducted in this chapter. Set the initial parameters as follows: $S_4(1,0,0)$: $\mathcal{B}_2 = 30$, $\mathcal{B}_3 = 40$, $\mathcal{B}_4 = 4$, $\mathcal{C}_2 = 8$, $\mathcal{C}_3 = 3$, $\mathcal{C}_4 = 20$, $\mathcal{C}_5 = 5$, $\mathcal{C}_6 = 5$, $\mathcal{P}_1 = 2$, $\mathcal{P}_2 = 3$, $\mathcal{P}_3 = 3$, $\mathcal{P}_4 = 10$ and $x = 0.5$, $y = 0.5$, $y = 0.5$

1) The effect of $\mathcal{C}_5$

Let $\mathcal{C}_5 = 0,10,20,30,40,50$ and keep other parameters constant, the evolutionary outcomes and trajectories of the RAAC innovation of government's ESS as shown in Figure.3-18. The construction companies' ESS as show in Figure.3-19. The public universities' ESS as show in Figure.3-20. This indicates that as the financial subsidies granted by the government to construction companies increase, the probability that the government is willing to maintain the incentives gradually decreases and eventually converges to zero. Excessive financial subsidies will exert pressure on the government's finances and will both reduce the government's willingness to provide incentives and accelerate the rate of evolution. For construction companies, government subsidies have a positive effect on their choice of RAAC innovation. When the government chooses to incentivize and increases the incentive amount, the probability of construction companies choosing to innovate increases, but as the subsidy amount increases, the probability of the government choosing not to incentivize increases, and the probability of construction companies choosing to innovate decreases and finally tends to zero. For public universities, C_5 does not affect their decision choice.

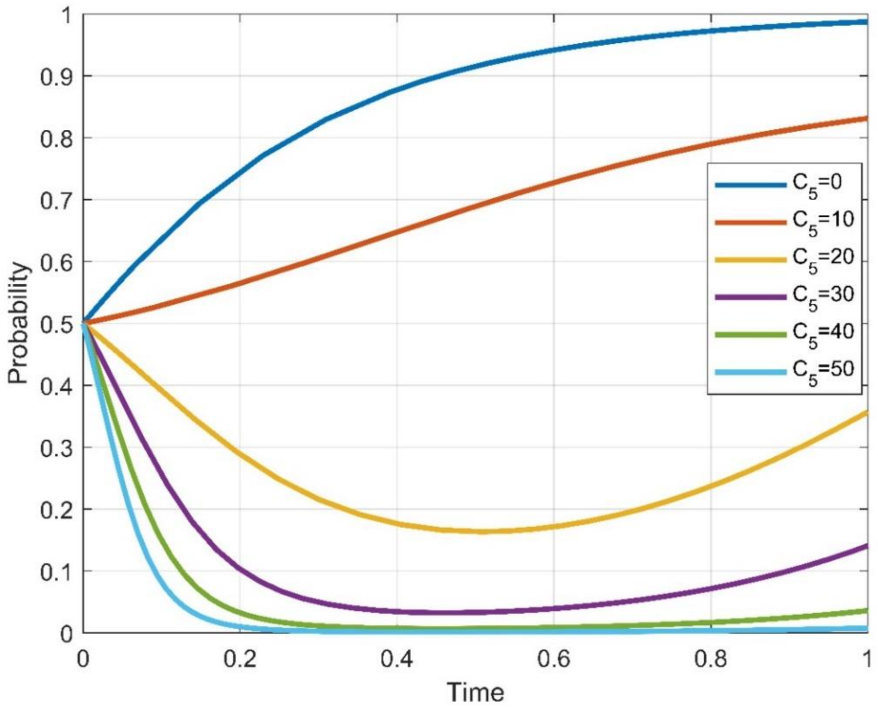

Figure 3-18 Impact of C_5 on evolutionary outcomes and trajectories of government.

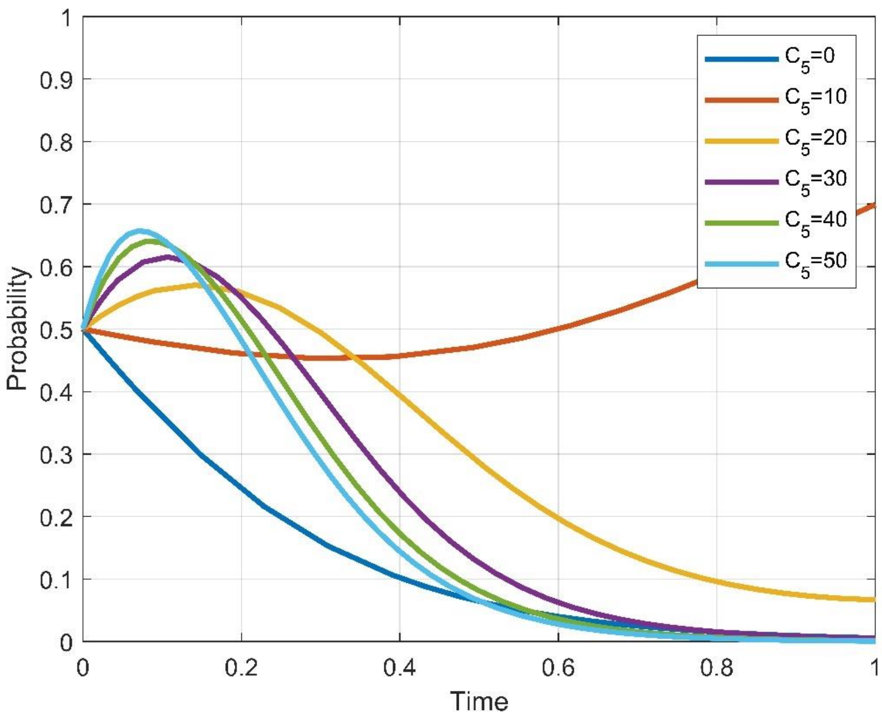

Figure 3-19 Impact of C_5 on evolutionary outcomes and trajectories of construction

companies.

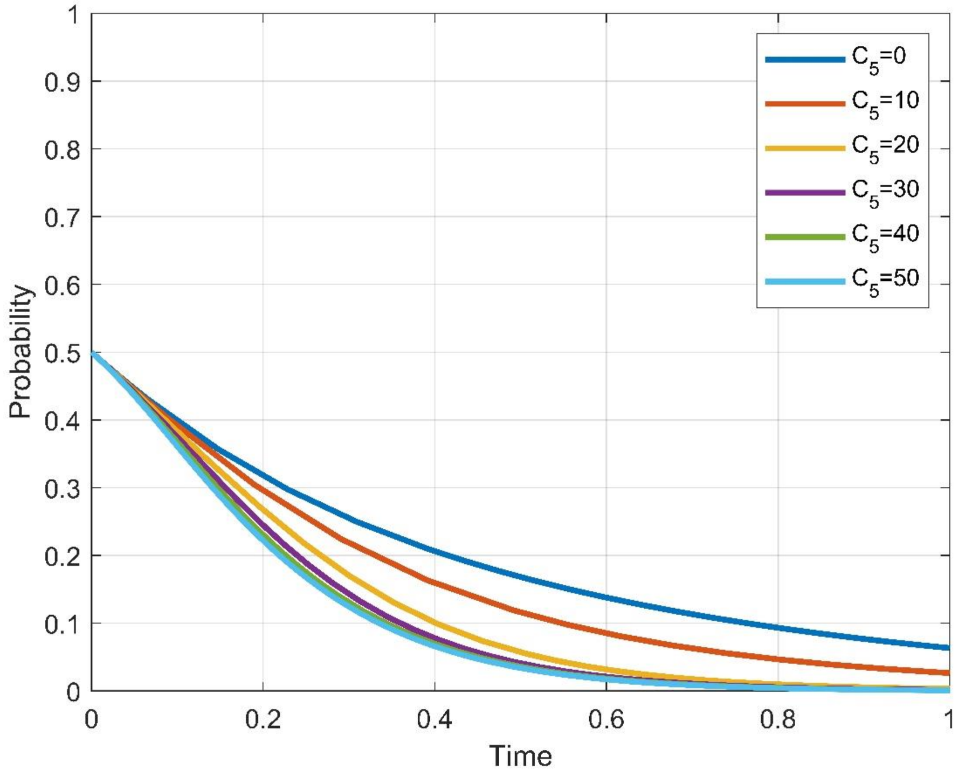

Figure 3-20 Impact of C_5 on evolutionary outcomes and trajectories of public universities.

2) The effect of C_3

Let $C_3 = 0,3,6,9,12,15$ and keep other parameters constant, the evolutionary outcomes and trajectories of the RAAC innovation of government's ESS as shown in Figure.3-21. The construction companies' ESS as show in Figure.3-22. The public universities' ESS as show in Figure.3-23. Reputation and brand value gained by construction companies with RAAC innovations have no impact on government and public university decision-making choices. But for construction companies, it can effectively increase the probability that they will choose to innovate and will accelerate the rate of evolution.

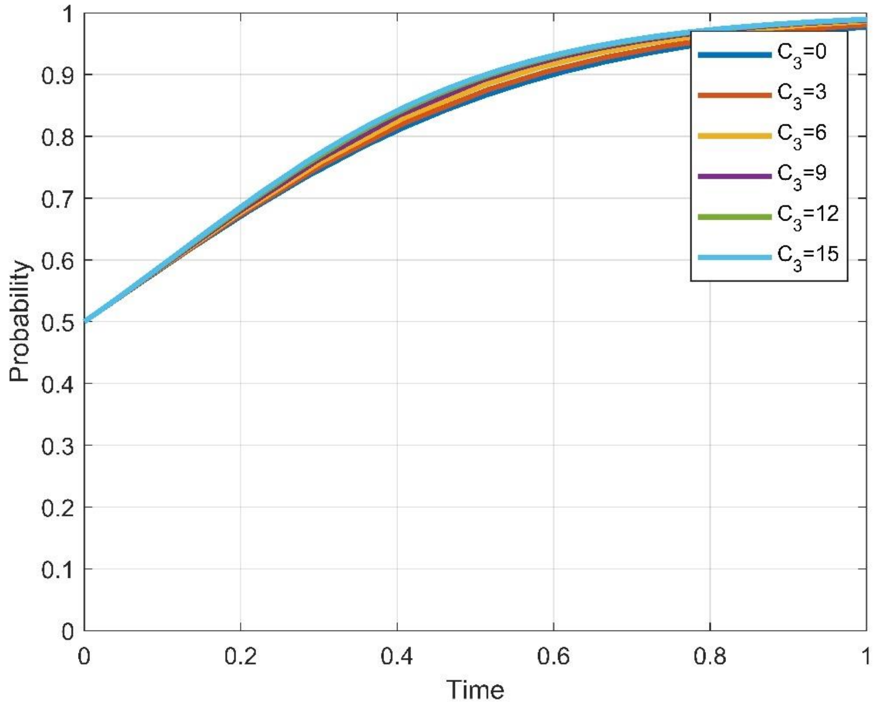

Figure 3-21 Impact of C_3 on evolutionary outcomes and trajectories of government.

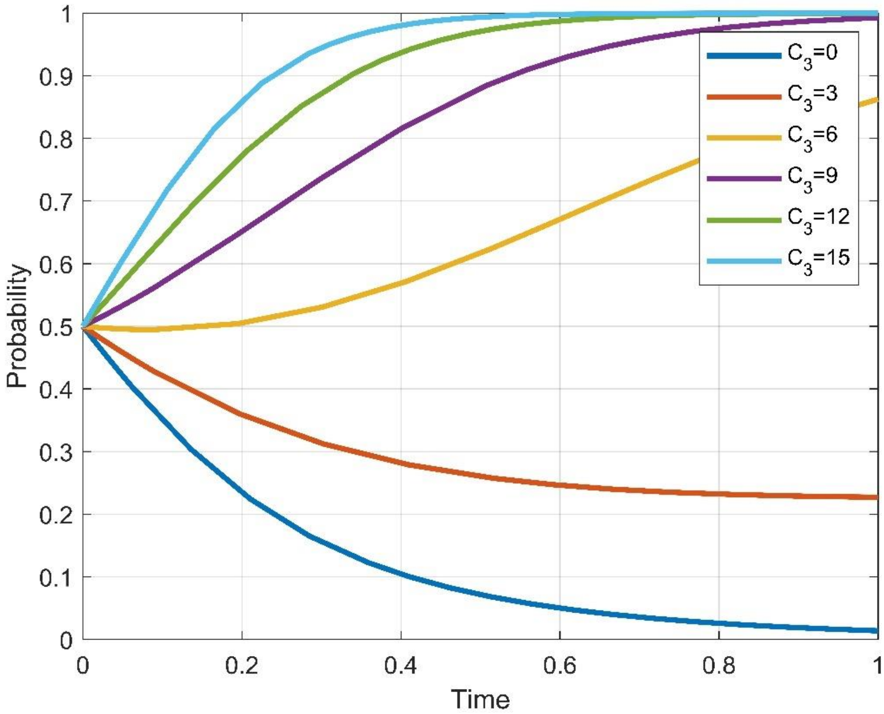

Figure 3-22 Impact of C_3 on evolutionary outcomes and trajectories of construction companies.

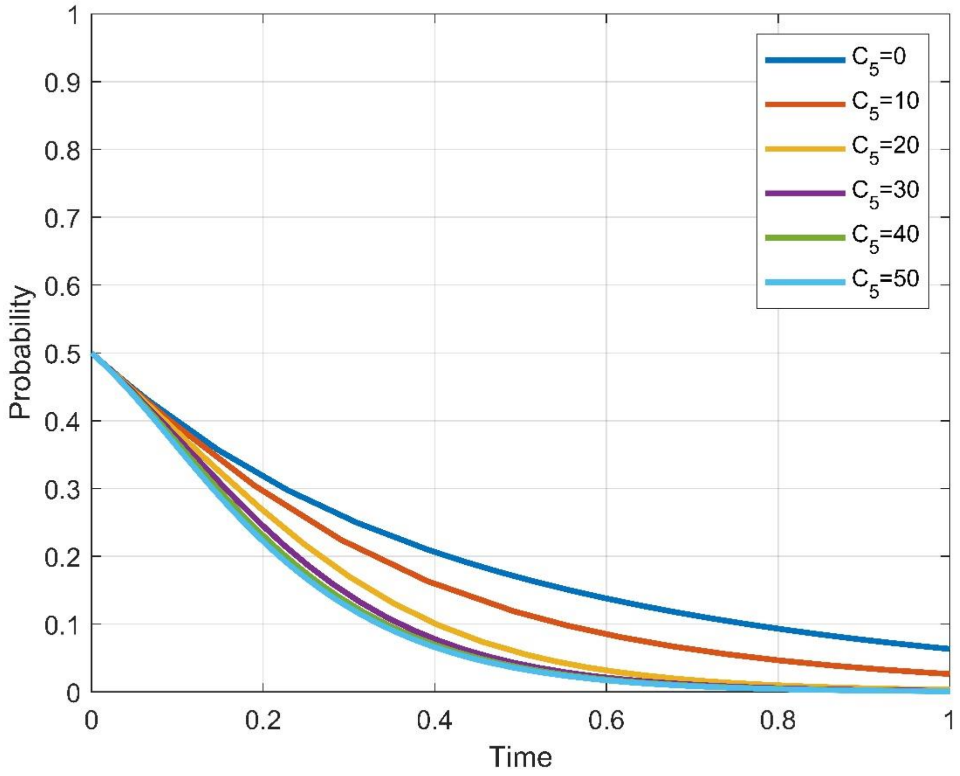

Figure 3-23 Impact of C_3 on evolutionary outcomes and trajectories of public universities.

3) The effect of $\mathcal{P}_1$

Let $\mathcal{P}_1 = 0,6,12,18,24,30$ and keep other parameters constant, the evolutionary outcomes and trajectories of the RAAC innovation of government's ESS as shown in Figure.3-24. The construction companies' ESS as show in Figure.3-25. The public universities' ESS as show in Figure.3-26. For the government, excessive subsidies will reduce the probability that the government chooses to incentivize and will accelerate the rate of evolution. For public universities, higher subsidies increase the probability of choosing RAAC talent development, but as the probability of government choice incentives decreases, the probability of public schools developing talent decreases until it approaches zero. For construction companies, A has a limited impact on their strategy choice, but only accelerates the rate of evolution.

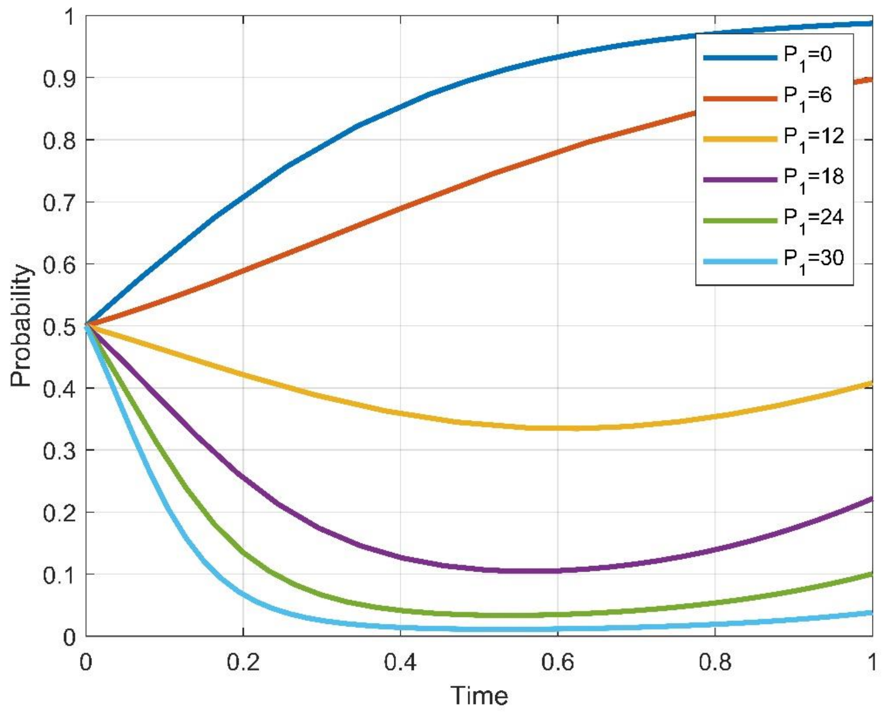

Figure 3-24 Impact of $\mathcal{P}_1$ on evolutionary outcomes and trajectories of government.

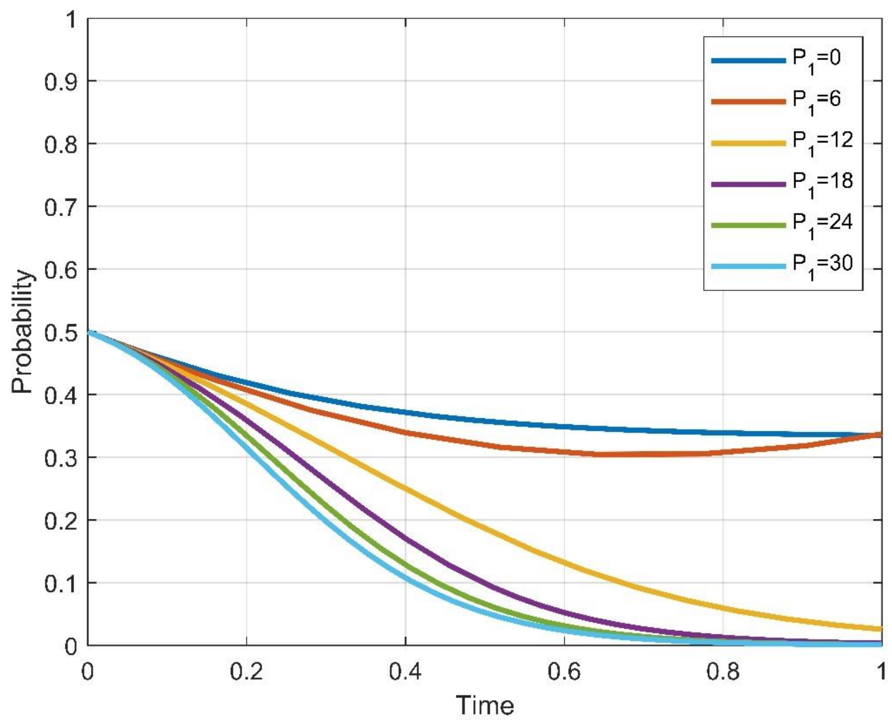

Figure 3-25 Impact of $\mathcal{P}_1$ on evolutionary outcomes and trajectories of construction companies.

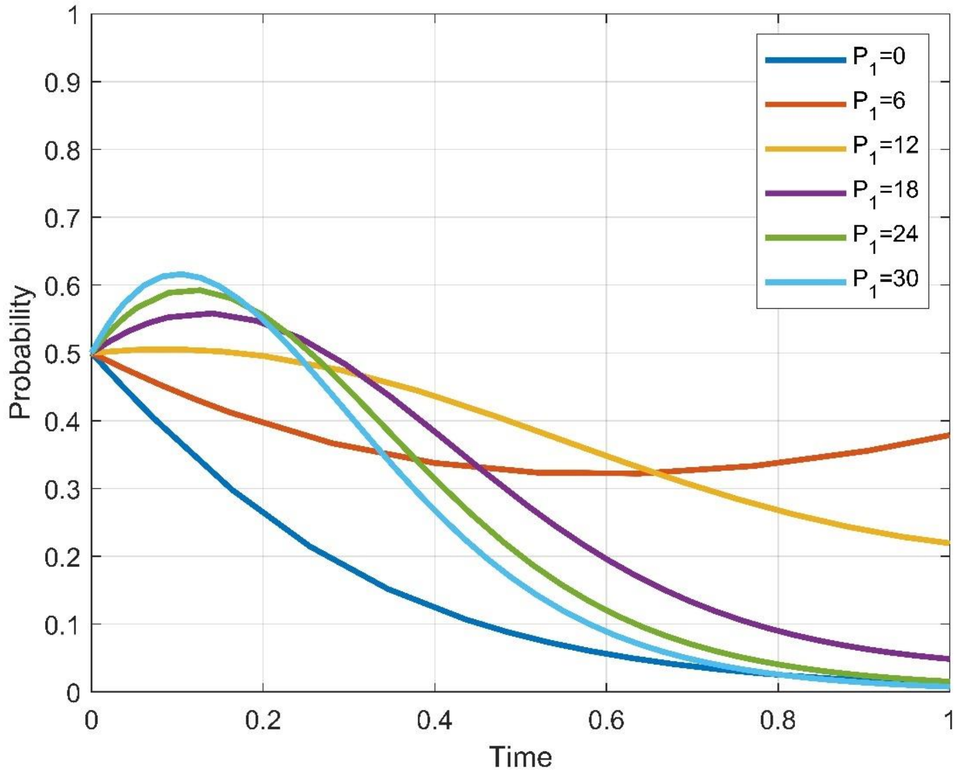

Figure 3-26 Impact of $\mathcal{P}_1$ on evolutionary outcomes and trajectories of public universities.

4) The effect of $\mathcal{P}_2$

Let $\mathcal{P}_2 = 0,2,4,6,8,10$ and keep other parameters constant, the evolutionary outcomes and trajectories of the RAAC innovation of government's ESS as shown in Figure.3-27. The construction companies' ESS as show in Figure.3-28. The public universities' ESS as show in Figure.3-29. The academic evaluation effectiveness has little impact on government policy choices. For public universities, academic evaluation benefits are the main concern. Increasing academic evaluation benefits will increase the probability that public universities will choose to train and will accelerate the rate of evolution. For construction companies, academic evaluation is not their main concern, but the willingness of universities to decide to cultivate talent can indirectly affect the cost of acquiring innovative talent for construction companies, so improving the academic evaluation benefit can also increase the probability of construction companies choosing RAAC innovations.

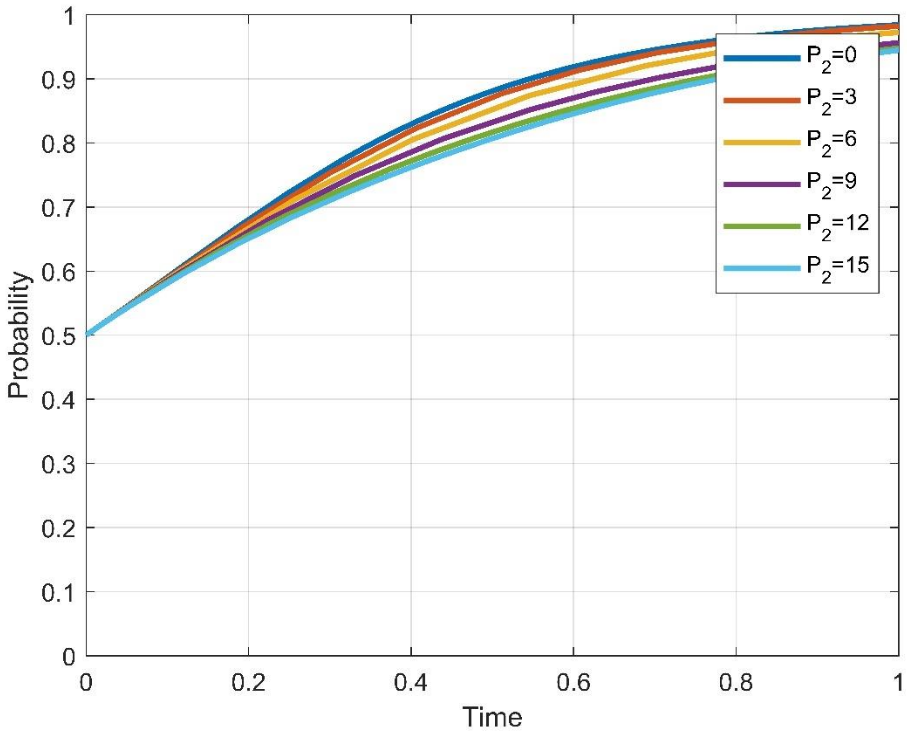

Figure 3-27 Impact of $\mathcal{P}_2$ on evolutionary outcomes and trajectories of government.

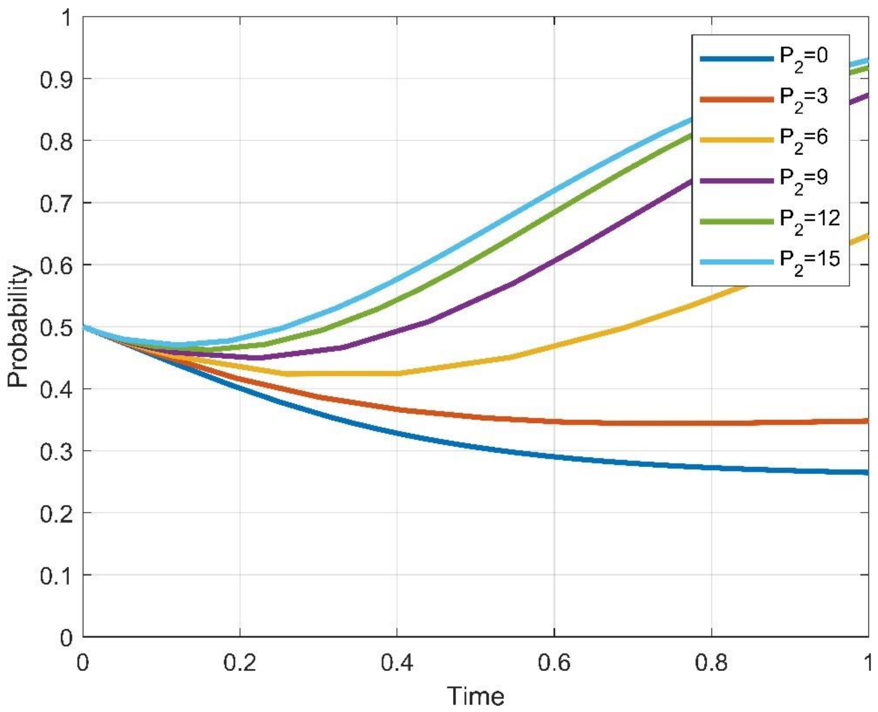

Figure 3-28 Impact of $\mathcal{P}_2$ on evolutionary outcomes and trajectories of construction companies.

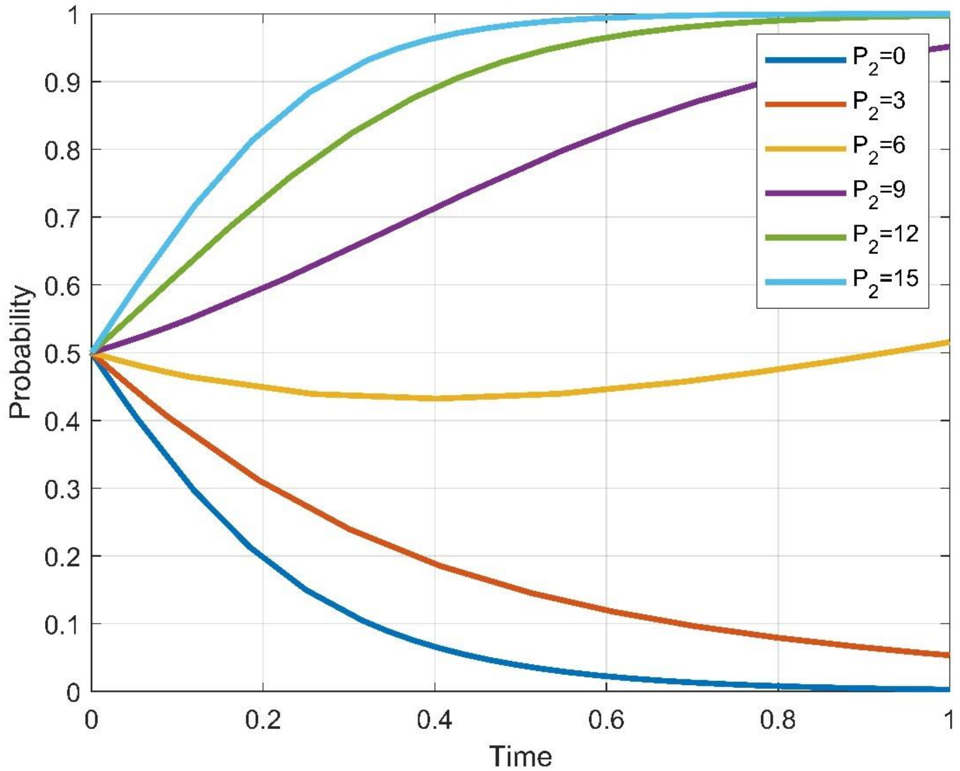

Figure 3-29 Impact of $\mathcal{P}_2$ on evolutionary outcomes and trajectories of public universities.

3.5. Discussion and Policy Implications

3.5.1. Comparison with Previous Studies and Working Hypotheses

RAAC innovation is critical to improving sustainability in the construction industry. Stakeholders' conflicting benefits and costs then directly influence their strategic choices, which in turn affect RAAC innovation. Consistent with the literature, the results of our analysis confirm that the high cost of innovation is one of the reasons why construction companies are reluctant to innovate[12, 13]. Inadequate financial support for the education sector is also a major impediment to RAAC R&D and talent development in public schools [14]. However, contrary to our hypothesis, simply raising financial incentives does not help much in achieving RAAC innovation, with the reason being that excessive fiscal spending leads to a decrease in the government's willingness to choose incentives. Improving the reputation that RAAC innovations bring to construction companies and the academic ratings given to public universities can effectively contribute to the implementation of RAAC innovations, which is consistent with our previous assumptions.

3.5.2. Policy implications

Our research results suggest that innovation costs, financial incentives, and prestige incentives are determinants of responsible stakeholder behavior. Therefore, this chapter offers the following policy insights:

1. Construction companies need to continuously improve their strength to meet the technical requirements of RAAC innovation, reduce the cost of innovation, and improve their risk degree capability. Public universities should establish a plan for RAAC talent training, gradually accumulate research technologies and talents in related directions, and reduce the cost of talent training.

2. Government can promote the development and implementation of RAAC technology by implementing policies that create compound incentives and developing a policy mix of financial and reputational incentives. On the one hand, the government needs to introduce a system to regulate industry standards, and on the other hand, the government needs to provide some financial support to help construction companies to relieve their worries about the high cost of RAAC innovations. At the same time, the government can increase the brand benefits of RAAC innovation for construction companies by organizing exhibitions and granting "progress awards" to active companies. For construction companies that refuse to innovate, the government needs to fine them for poor environmental performance resulting from their construction methods.

3. At present, China's construction companies are reluctant to innovate due to insufficient investment in R&D in the construction field[14]. The government needs to provide research funding support to public universities for the purchase of relevant equipment. In addition, RAAC-related academic achievements and the employment rate of RAAC talents should be taken into consideration in the academic evaluation.

3.6. Conclusions

The behavioral decisions of government, construction companies, and public universities affect the implementation of RAAC innovations, and their behavioral strategies are relatively understudied. This chapter analyzes the dynamic evolution of RAAC innovation strategy choices by modeling the TEG between the government, construction companies, and public universities. The following conclusions are drawn:

1. Through EGT analysis, the strategic decisions of government, construction companies, and public universities interact, and the ESS (Incentive, Innovative, Cultivation) can be achieved.

2. Financial incentives can motivate construction companies to innovate as well as universities to train talent. Still, once the financial incentive becomes too large, financial pressure

is put on the government, which thus chooses not to incentivize.

3. Improving reputational incentives for construction firms and academic evaluations of public universities can increase the probability that construction companies and universities respond to promoting RAAC innovation and accelerate the realization of the tripartite ESS.

4. High financial subsidies do not necessarily work well. Our research shows that higher financial subsidies tend to make the final decision of the tripartite non-innovative. In contrast, appropriately increasing reputational and academic evaluation rewards can effectively increase the likelihood that construction companies and public universities will choose RAAC innovations.

5. For the government, construction companies, and public universities to achieve the ultimate ESS, they need a reasonable set of compounding incentives. The government should set a reasonable financial cost and reputational reward for incentives. Construction companies need to accelerate technology upgrades and reduce the cost of innovation. Public universities need to accelerate the construction of experimental environments to prepare for the training of relevant technical talents.

The above research results provide a good reference for policymakers to develop strategies for RAAC innovation. However, some limitations of this study still exist: this study only considers the case where all three policymakers act as a single subject and does not consider the evolution between construction companies and other construction companies, and between public universities and other public universities. These complex evolutionary relationships still need to be studied in depth in the future.

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Chapter 4

EVOLUTIONARY GAME ANALYSIS FOR RAAC IMPLEMENTATION IN THE CONTEXT OF COVID-19

CHAPTER FOUR: EVOLUTIONARY GAME ANALYSIS FOR RAAC IMPLEMENTATION IN THE CONTEXT OF COVID-19

4.1 Contents

The construction industry is an integral part of the world economy, but low productivity and low environmental efficiency are the construction industry's current challenges. Increasing total factor productivity is considered the fundamental solution to improve the industry's sustainability. Automated robotic construction is one of the critical options. Then despite the incentives implemented in many countries, the practical application of the technology has been minimal. Since the end of 2019, COVID-19 has brought an enormous impact and force majeure to the construction industry. By building an evolutionary game model with the impact of COVID-19 as an influencing factor. To discuss the interactive effects of government and construction company behavior. It is possible to obtain the study results those the evolutionary stabilization strategies are achievable with government choice regulation and construction companies' adoption of automated construction robots. Establishing appropriate incentives and penalties can accelerate the development of government and construction companies. Focusing on the hazards of the epidemic and adhering to the prevention of the epidemic can help achieve industrial upgrading in the construction industry. The research results can be used to reference the government to formulate relevant policies and support stakeholders' strategy choices.

This chapter attempts to create an evolutionary game model to study the impact of government and construction companies' decision choices on the innovation and adoption of automated robotic construction(ARC) technology under the influence of COVID-19. Under the epidemic's effect, discuss government and construction companies' evolutionary stabilization strategies(ESS) following a long-term evolutionary game. And identify key parameters affecting ESS. The results of this study have important implications for construction companies in making utility-maximizing decisions and for governments in developing technically effective policies for ARC R&D under the impact of a pandemic.

4.2. Methodology

4.2.1. Interests analysis

This study aims to explore the evolutionary game process and results in the adoption and development of ARC technology under the influence of COVID-19, based on the interests of government and construction companies. Stakeholder needs information is provided as follows:

Government: The government can promote the development of ARC technology by creating programs, regulations, and incentives[1]. Under the impact of COVID-19, the government is facing a series of problems such as lower tax revenue[2] and increased unemployment[3]. However, it is also the government's responsibility to prevent the spread of the virus and protect the lives of practitioners. Government can establish policies to mitigate these issues and enhance the adoption of ARC technology[4].

Construction companies: Economic benefits are the ultimate claim of construction companies[5]. While ARC technology is key to improving sustainability in the construction industry, high R&D costs and intense competition prevent most construction companies from choosing to innovate. The impact of COVID-19 made it impossible for construction companies to operate normally, and many construction sites were forced to shut down. Construction companies need to pay higher equipment and labor costs than regular businesses to cope with the strict epidemic prevention measures. In the face of the increasingly severe form of the epidemic, construction companies need to innovate technologically to respond to the new policy and market environment. Construction companies are faced with the choice of whether to adopt ARC technology.

4.2.2. Basic assumptions

Based on the stakeholder's interest demands and the prospect theory proposed by [6], we made the following assumptions:

Assumption I: The stakeholders in this game, the government, and the construction companies are limitedly rational. They can hardly make perfect decisions, but they can keep learning, imitating, and communicating with each other in the decision-making process and adjusting their strategic choices to get the maximum benefit.

Assumption II: The government has two strategies: to regulate or not to regulate. The probability that the government chooses to regulate is x. The likelihood that the government decides not to regulate is $1 - x$. Construction companies have two strategies: to regulate or not to regulate. The probability that the government chooses to regulate is x. The probability that the government chooses not to regulate is $1 - x$.

Assumption III: To simplify the evolutionary model, assume that players can choose only one strategy simultaneously. Decisions between construction companies do not influence each other.

Assumption IV: COVID-19 has been mutating since its discovery, and now there are multiple variants with different degrees of harm[7]. Assuming that the hazard of the COVID-19 variant is $\mathcal{R}$. Let the menace of the original COVID-19 virus discovered in December 2019 $\mathcal{R}_0 = 1$.

Based on the above assumptions and the interests of players, the relevant parameters are defined as shown in Table 4-1:

Table 4-1 Meaning of parameters

Parameters	Meanings	Domain
$\mathcal{T}_1$	Government tax revenue is received when construction companies are adopting the traditional construction method and are operating normally	$\mathcal{T}_1 \geq 0$
$\mathcal{T}_2$	Government tax increment received when construction companies adopt ARC	$\mathcal{T}_2 \geq 0$
$\mathcal{T}_3$	Reduction in government tax revenue from construction under COVID-19	$\mathcal{T}_3 \geq 0$
$\mathcal{S}$	Dropping approval ratings due to government inaction	$\mathcal{S} \geq 0$
$\mathcal{F}$	Government fines for construction companies not adopting ARC technology	$\mathcal{F} \geq 0$
$\mathcal{M}$	Government subsidy for innovation paid to construction companies	$\mathcal{M} \geq 0$
$\mathcal{B}_1$	Revenue of a construction company when it adopts the traditional model and operates normally	$\mathcal{B}_1 \geq 0$
$\mathcal{B}_2$	Incremental revenue for construction companies when adopting ARC	$\mathcal{B}_2 \geq 0$
$\mathcal{B}_3$	Reputation and brand benefits for construction companies in adopting ARC	$\mathcal{B}_3 \geq 0$
$\mathcal{B}_4$	Reduction in revenue because of virus	$\mathcal{B}_4 \geq 0$
$\mathcal{C}_1$	The cost of prevention that construction companies must pay when using traditional methods	$\mathcal{C}_1 \geq 0$
$\mathcal{C}_2$	Savings in prevention costs for construction companies when adopting ARC	$\mathcal{C}_2 \geq 0$
$\mathcal{C}_3$	R&D costs for construction companies when adopting ARC	$\mathcal{C}_3 \geq 0$
$\mathcal{R}$	The extent of the hazard of virus variants	$\mathcal{R} \geq 0$

x	The probability that the government will choose to regulate	$0 \leq x \leq 0$
$1-x$	The probability that the government will choose not to regulate	$0 \leq x \leq 0$
y	The probability that the construction company will choose to adopt ARC	$0 \leq y \leq 0$
$1-y$	The probability that the construction company will choose not to adopt ARC	$0 \leq y \leq 0$

4.2.3. Evolutionary game model

Based on the parameters defined above, the revenue matrix for the government and the construction companies is shown in Table 4-2.

Table 4-2 Revenue Matrix

Players and strategy options		**Construction companies**	
		Adopting ARC technology (y)	**Adopting traditional technology ($1-y$)**
Government	**Regulation (x)**	$\mathcal{T}_1+\mathcal{T}_2-\mathcal{R}\mathcal{T}_3-\mathcal{M}$, $\mathcal{B}_1+\mathcal{B}_2+\mathcal{B}_3+\mathcal{M}-\mathcal{C}_3-\mathcal{R}(\mathcal{B}_4+\mathcal{C}_1-\mathcal{C}_2)$	$\mathcal{T}_1-\mathcal{R}\mathcal{T}_3+\mathcal{F}$, $\mathcal{B}_1-\mathcal{R}(\mathcal{B}_4+\mathcal{C}_1)-\mathcal{F}$
	Not to regulation ($1-x$)	$\mathcal{T}_1+\mathcal{T}_2-\mathcal{R}(\mathcal{T}_3+\mathcal{S})$, $\mathcal{B}_1+\mathcal{B}_2+\mathcal{B}_3-\mathcal{C}_3-\mathcal{R}(\mathcal{B}_4+\mathcal{C}_1-\mathcal{C}_2)$	$\mathcal{T}_1-\mathcal{R}(\mathcal{T}_3+\mathcal{S})$, $\mathcal{B}_1-\mathcal{R}(\mathcal{B}_4+\mathcal{C}_1)$

Assume that the expected benefits of the government's choice of regulation are G_{11}. The expected benefit of choosing not to regulate is G_{12}. The average expected benefit is $\bar{G}_1$, then:

$$G_{11}=y(\mathcal{T}_1+\mathcal{T}_2-\mathcal{R}\mathcal{T}_3-\mathcal{M})+(1-y)(\mathcal{T}_1-\mathcal{R}\mathcal{T}_3+\mathcal{F}) \quad (1)$$

$$G_{12}=y[\mathcal{T}_1+\mathcal{T}_2-\mathcal{R}(\mathcal{T}_3+\mathcal{S})]+(1-y)[\mathcal{T}_1-\mathcal{R}(\mathcal{T}_3+\mathcal{S})] \quad (2)$$

$$\bar{G}_1=xE_{11}+(1-x)E_{21} \quad (3)$$

The replication dynamics equation for the government V(x) is

$$\mathrm{V(x)} = \frac{dx}{dt} = x(G_{11} - \bar{G}_1) = x(1-x)(G_{11} - G_{12}) = x(1-x)[\mathcal{RS} + \mathcal{F} - y(\mathcal{M} + \mathcal{F})] \quad (4)$$

Equivalently assume that the expected benefit of the construction companies choosing to adopt ARC technology is G_{21}. The expected benefit of choosing not to adopt is G_{22}. The average expected benefit is $\bar{G}_2$, then:

$$G_{21} = x[\mathcal{B}_1 + \mathcal{B}_2 + \mathcal{B}_3 + \mathcal{M} - \mathcal{C}_3 - \mathcal{R}(\mathcal{B}_4 + \mathcal{C}_1 - \mathcal{C}_2)] + (1-x)[\mathcal{B}_1 + \mathcal{B}_2 + \mathcal{B}_3 - \mathcal{C}_3 - \mathcal{R}(\mathcal{B}_4 + \mathcal{C}_1 - \mathcal{C}_2)] \quad (5)$$

$$G_{22} = x[\mathcal{B}_1 - \mathcal{R}(\mathcal{B}_4 + \mathcal{C}_1) - \mathcal{F}] + (1-x)[\mathcal{B}_1 - \mathcal{R}(\mathcal{B}_4 + \mathcal{C}_1)] \quad (6)$$

$$\bar{G}_2 = yG_{21} + (1-y)G_{22} \quad (7)$$

The replication dynamics equation for the construction companies $\mathrm{U(y)}$ is

$$\mathrm{U(y)} = \frac{dy}{dt} = y(G_{21} - \bar{G}_2) = y(1-y)(G_{21} - G_{22}) = y(1-y)[x(\mathcal{M} + \mathcal{F}) + \mathcal{B}_2 + \mathcal{B}_3 - \mathcal{C}_3 + \mathcal{R}\mathcal{C}_2] \quad (8)$$

The joint cubic equation is as follows to allow discussion of the evolutionary stability point of the model.

$$\begin{cases} \mathrm{V(x)} = x(1-x)[\mathcal{RS} + \mathcal{F} - y(\mathcal{M} + \mathcal{F})] = 0 \\ \mathrm{U(y)} = y(1-y)[x(\mathcal{M} + \mathcal{F}) + \mathcal{B}_2 + \mathcal{B}_3 - \mathcal{C}_3 + \mathcal{R}\mathcal{C}_2] = 0 \end{cases} \quad (9)$$

The evolutionary stability point can be obtained from the above equation: $E_1(0,0)$; $E_2(1,0)$; $E_3(0,1)$; $E_4(1,1)$ and $E_5(x^*, y^*)$, where $E_5(x^*, y^*)$ satisfies the following equation. Then $x^* = \frac{\mathcal{C}_3 - \mathcal{R}\mathcal{C}_2 - \mathcal{B}_2 - \mathcal{B}_3}{\mathcal{M} + \mathcal{F}}$, $y^* = \frac{\mathcal{RS} + \mathcal{F}}{\mathcal{M} + \mathcal{F}}$.

$$\begin{cases} \mathcal{RS} + \mathcal{F} - y(\mathcal{M} + \mathcal{F}) = 0 \\ x(\mathcal{M} + \mathcal{F}) + \mathcal{B}_2 + \mathcal{B}_3 - \mathcal{C}_3 + \mathcal{R}\mathcal{C}_2 = 0 \end{cases}$$

4.3. Evolutionary stability analysis

4.3.1. Asymptotic stability analysis

For the government, according to the stability theorem of the replication dynamics equation, x is the evolutionary stability point when $\mathrm{V(x)} = 0$ and $\mathrm{V'(x)} < 0$ are satisfied.

$$\mathrm{V}'(x) = (1-2x)[\mathcal{RS} + \mathcal{F} - y(\mathcal{M} + \mathcal{F})] \quad (10)$$

Let $\mathrm{V(x)} = 0$, then $x = 0$ or $x = 1$. When $y^* = \frac{\mathcal{RS} + \mathcal{F}}{\mathcal{M} + \mathcal{F}}$. $\mathrm{V(x)} = 0$ always be satisfied. In this case, the government's strategy will not change over time. When $0 < y^* < \frac{\mathcal{RS}+\mathcal{F}}{\mathcal{M}+\mathcal{F}}$, $\mathcal{RS} + \mathcal{F} - y(\mathcal{M} + \mathcal{F}) > 0$ holds. Substituting $x = 0$ and $x = 1$ into $\mathrm{V}'(\mathrm{x})$, $\mathrm{V}'(\mathrm{x}) > 0$, $\mathrm{V}'(\mathrm{x}) < 0$ are obtained. So $x = 1$ is an evolutionary stable point. When the probability that construction companies choose to adopt ARC technology is less than a particular value, the probability that the government will decide to regulate will become higher and higher, and eventually choose to regulate. When $\frac{\mathcal{RS}+\mathcal{F}}{\mathcal{M}+\mathcal{F}} < y^* < 1$, $\mathcal{RS} + \mathcal{F} - y(\mathcal{M} + \mathcal{F}) < 0$ holds. Substituting $x = 0$ and $x = 1$ into $\mathrm{V}'(\mathrm{x})$, $\mathrm{V}'(\mathrm{x}) < 0$, $\mathrm{V}'(\mathrm{x}) > 0$ are obtained. This suggests that when the probability of construction companies choosing to adopt ARC technology is more significant than a value, the government's probability of regulating continues to decline.

For the construction companies, y is the evolutionary stability point when $\mathrm{U(y)} = 0$ and $\mathrm{U}'(\mathrm{y}) < 0$ are satisfied.

$$\mathrm{U}'(y) = (1 - 2y)[x(\mathcal{M} + \mathcal{F}) + \mathcal{B}_2 + \mathcal{B}_3 - \mathcal{C}_3 + \mathcal{RC}_2] \tag{11}$$

Let $\mathrm{U(y)} = 0$, then $y = 0$ or $y = 1$. When $x^* = \frac{\mathcal{C}_3-\mathcal{RC}_2-\mathcal{B}_2-\mathcal{B}_3}{\mathcal{M}+\mathcal{F}}$, $\mathrm{U(y)} = 0$ always be satisfied. At this point, the construction company's strategic choices will not alter over time. When $0 < x^* < \frac{\mathcal{C}_3-\mathcal{RC}_2-\mathcal{B}_2-\mathcal{B}_3}{\mathcal{M}+\mathcal{F}}$, $x(\mathcal{M} + \mathcal{F}) + \mathcal{B}_2 + \mathcal{B}_3 - \mathcal{C}_3 + \mathcal{RC}_2 < 0$ holds. Substituting $y = 0$ and $y = 1$ into $\mathrm{U}'(\mathrm{y})$, $\mathrm{U}'(\mathrm{y}) < 0$, $\mathrm{U}'(\mathrm{y}) > 0$ are obtained. This indicates that when the probability of government choosing regulation falls below a value, construction companies' probability of innovation decreases gradually. When $\frac{\mathcal{C}_3-\mathcal{RC}_2-\mathcal{B}_2-\mathcal{B}_3}{\mathcal{M}+\mathcal{F}} < x^* < 1$, $x(\mathcal{M} + \mathcal{F}) + \mathcal{B}_2 + \mathcal{B}_3 - \mathcal{C}_3 + \mathcal{RC}_2 > 0$ holds. Substituting $y = 0$ and $y = 1$ into $\mathrm{U}'(\mathrm{y})$, $\mathrm{U}'(\mathrm{y}) > 0$, $\mathrm{U}'(\mathrm{y}) < 0$ are obtained. This shows that when the probability of government choosing regulation is higher than a value, construction companies' probability of innovation gradually increases.

4.3.2. Stability analysis of the evolutionary game

According to ref[8], The ESS of the evolutionary game model can be determined by analyzing the local stability of the Jacobi matrix. The corresponding Jacobi matrix of the evolutionary model of this chapter can be obtained based on the above equation as follows:

$$\mathcal{J}(x,y) = \begin{pmatrix} \frac{\partial V(x)}{\partial x} & \frac{\partial V(x)}{\partial y} \\ \frac{\partial U(y)}{\partial x} & \frac{\partial U(y)}{\partial y} \end{pmatrix} = \begin{pmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{pmatrix} \tag{12}$$

Where

$J_{11} = (1-2x)[\mathcal{RS} + \mathcal{F} - y(\mathcal{M} + \mathcal{F})]$

$J_{12} = x(1-x)(\mathcal{M} + \mathcal{F})$

$J_{21} = y(1-y)(\mathcal{M} + \mathcal{F})$

$J_{22} = (1-2y)[x(\mathcal{M} + \mathcal{F}) + \mathcal{B}_2 + \mathcal{B}_3 - \mathcal{C}_3 + \mathcal{RC}_2]$

The equilibrium point has ESS when and only when all the eigenvalues of the Jacobi matrix are negative[8, 9]. In asymmetric evolutionary games, just the stability of the pure strategy equilibrium can be considered[5], so only $E_1(0{,}0)$; $E_2(0{,}1)$; $E_3(1{,}0)$; $E_4(1{,}1)$ needs to be discussed. The eigenvalues of the four equilibrium points are shown in Table 4-3:

Table 4-3 Eigenvalues of the Jacobian matrix

Stabilization point	Eigenvalue 1	Eigenvalue 2	Stable situation	Conditions
(0,0)	$\mathcal{RS} + \mathcal{F}$	$\mathcal{B}_2 + \mathcal{B}_3 + \mathcal{RC}_2 - \mathcal{C}_3$	No ESS	/
(0,1)	$\mathcal{RS} - \mathcal{M}$	$\mathcal{C}_3 - \mathcal{B}_2 - \mathcal{B}_3 - \mathcal{RC}_2$	ESS	$\mathcal{M} > \mathcal{RS}$, $\mathcal{C}_3 < \mathcal{B}_2 + \mathcal{B}_3 + \mathcal{RC}_2$
(1,0)	$-\mathcal{RS} - \mathcal{F}$	$\mathcal{M} + \mathcal{F} + \mathcal{B}_2 + \mathcal{B}_3 + \mathcal{RC}_2 - \mathcal{C}_3$	ESS	$\mathcal{C}_3 > \mathcal{M} + \mathcal{F} + \mathcal{B}_2 + \mathcal{B}_3 + \mathcal{RC}_2$
(1,1)	$\mathcal{M} - \mathcal{RS}$	$\mathcal{C}_3 - \mathcal{B}_2 - \mathcal{B}_3 - \mathcal{RC}_2 - \mathcal{M} - \mathcal{F}$	ESS	$\mathcal{M} < \mathcal{RS}$, $\mathcal{C}_3 < \mathcal{M} + \mathcal{F} + \mathcal{B}_2 + \mathcal{B}_3 + \mathcal{RC}_2$

1) When $\mathcal{M} > \mathcal{RS}$, $\mathcal{C}_3 < \mathcal{B}_2 + \mathcal{B}_3 + \mathcal{RC}_2$ holds. The eigenvalues of the Jacobi matrix corresponding to $E_2(0{,}1)$ are all negative. Thus $E_2(0{,}1)$ is an ESS. This implies that when government financial subsidies to companies are too high and the financial pressure is greater than the loss of support caused by the pandemic, the probability that the government will choose to regulate decreases. Meanwhile, when the additional cost caused by the epidemic is greater than the cost of innovation, firms will actively choose to adopt ARC technology. At this point (no regulation, adoption) is stable.

2) When $\mathcal{C}_3 > \mathcal{M} + \mathcal{F} + \mathcal{B}_2 + \mathcal{B}_3 + \mathcal{RC}_2$ is established. The eigenvalues of the Jacobi matrix corresponding to $E_3(1{,}0)$ are all negative. Therefore $E_3(1{,}0)$ is an ESS. This means that when the cost of adopting ARC technology is too high, exceeding the sum of government fines and government incentives, and the additional fees to be paid to combat the pandemic,

companies will choose to stay with the traditional approach. At this point, the government will take regulation with the view that companies will change their strategies.

3) When $\mathcal{M} < \mathcal{RS}$, $\mathcal{C}_3 < \mathcal{M} + \mathcal{F} + \mathcal{B}_2 + \mathcal{B}_3 + \mathcal{RC}_2$ is valid. The eigenvalues of the Jacobi matrix corresponding to $E_3(1,1)$ are all negative. $E_4(1,1)$ is an ESS is also a 'Pareto optimal solution.' This means that when the decline in support caused by meeting the epidemic is greater than the government's expenditure on financial subsidies to companies, the sum of economic benefits to construction companies from the adoption of ARC technology, the brand benefits, the savings in epidemic prevention expenditure and the rewards and penalties given by the government is greater than the cost of innovation. (Regulation, Adoption) is stable.

4.4. Numerical Simulation

4.4.1. The evolutionary trajectory of ESS

The numerical simulation allows us to obtain the overall situation of the evolutionary game. We brought the replicated dynamic equations into MATLAB R2021b and simulated the evolutionary trajectory of the 3 ESSs. The MATLAB simulation program and equation analysis are shown in Figure 4-1, Figure 4-2, Figure 4-3, Figure 4-4. The initial values of parameters are set based on logical relationships by analyzing the parties of the game. Generally, the final convergence of the curve is only influenced by the logical connection, while the values of the initial parameters only affect the fluctuations of the curve[10]. The initial values corresponding to the three ESSs are set in Table 4-4. The evolutionary trends of the three ESS points are shown in Figure 4-5, Figure 4-7, Figure 4-9 and. The evolutionary trend of the three ESS points with an initial probability of 0.5 is shown in Figure 4-6, Figure 4-8, Figure 4-10. The x-axis represents the probability that the government chooses to regulate, and the y-axis represents the probability that the construction company elects to adopt ARC technology. From those figures, the evolutionary trend of stakeholders eventually converges to the corresponding stable point, whatever the initial probability, given the constant logical relationship.

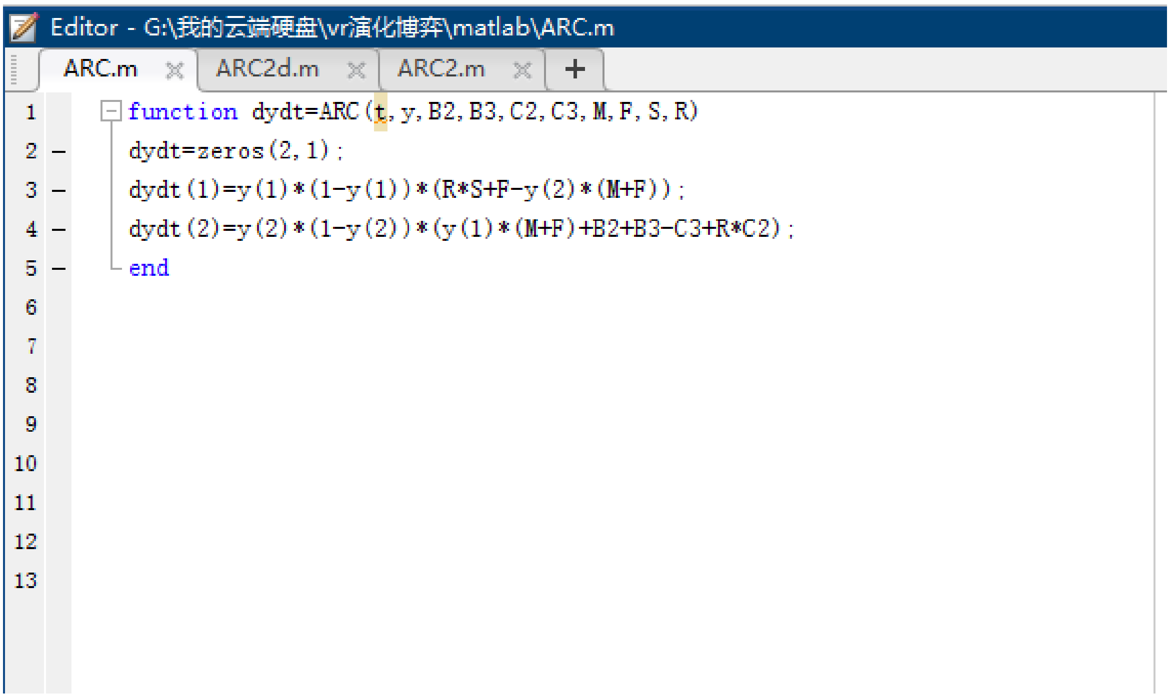

Figure 4-1 The dynamic equilibrium of evolutionary games

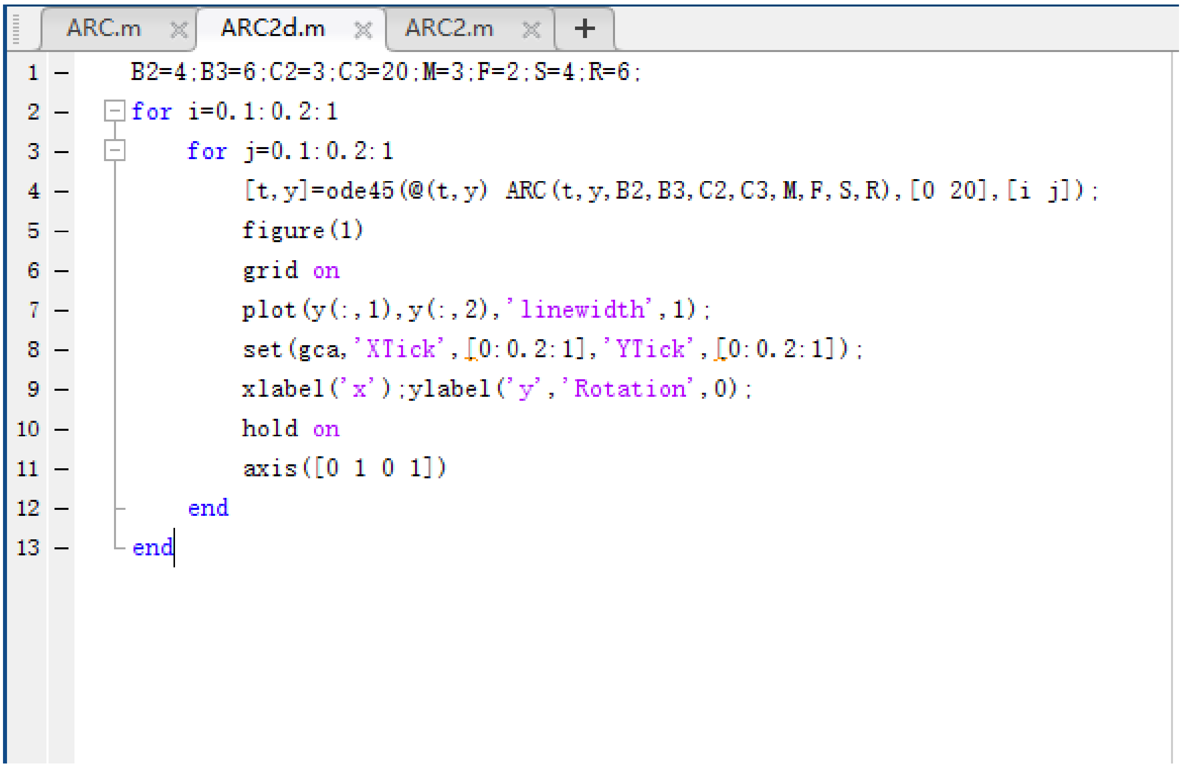

Figure 4-1 Analytic production procedure for evolutionary curves

ARC.m ARC2d.m ARC2.m

```
B2=4;B3=6;C2=5;C3=20;M=3;F=2;S=4;R=1;
for i=0.5
    %for R=0:0.5:5
    for M=0:2:10
    %for F=0:2.5:15
    [t,y]=ode45(@(t,y) ARC(t,y,B2,B3,C2,C3,M,F,S,R),[0 20],[i j]);
    figure(1)
    grid on
    plot(t,y(:,1),'lineWidth',2.2);
    hold on
    %plot(t,y(:,2),'color',[0.11765,0.56471,1],'lineWidth',2.2);
    %hold on
    %plot(t,y(:,3),'color',[0.66,0.84314,0.653],'lineWidth',2.2);
    %hold on
    xlim([0 10]),ylim([0 1]);
    xlabel('Time');ylabel('Probability','Rotation',90);
    legend({'M=0','M=2','M=4','M=6','M=8','M=10'})
    %legend({'F=0','F=2.5','F=5','F=7.5','F=10','F=12.5','F=15'})
    %legend({'R=0','R=0.5','R=1.0','R=1.5','R=2','R=2.5','R=3.0','R=3.5','R=4.0','R=4.5','R=5.0'})
    end
end
for j=0.5
    %for R=0:0.5:5
    for M=0:2:10
    %for F=0:2.5:15
    [t,y]=ode45(@(t,y) ARC(t,y,B2,B3,C2,C3,M,F,S,R),[0 20],[i j]);
    figure(2)
    grid on
    %plot(t,y(:,1),'lineWidth',2.2);
    %hold on
    plot(t,y(:,2),'lineWidth',2.2);
    hold on
    %plot(t,y(:,3),'color',[0.66,0.84314,0.653],'lineWidth',2.2);
    %hold on
    xlim([0 10]),ylim([0 1]);
    xlabel('Time');ylabel('Probability','Rotation',90);
    legend({'M=0','M=2','M=4','M=6','M=8','M=10'})
    %legend({'F=0','F=2.5','F=5','F=7.5','F=10','F=12.5','F=15'})
    %legend({'R=0','R=0.5','R=1.0','R=1.5','R=2','R=2.5','R=3.0','R=3.5','R=4.0','R=4.5','R=5.0'})
    end
```

Figure 4-3 Analytical production procedures for the influence of key parameters on evolutionary trends

```
B2=4;B3=6;C2=3;C3=5;M=3;F=2;S=4;R=0.2;
for i=0.5
    %for R=0:0.5:5
    %for M=0:2:10
    %for F=0:2.5:15
    [t,y]=ode45(@(t,y) ARC(t,y,B2,B3,C2,C3,M,F,S,R),[0 20],[i 0.5]);
    figure(1)
    grid on
    plot(t,y(:,1),'lineWidth',2.2);
    hold on
    plot(t,y(:,2),'color',[0.958,0.063,0.056],'lineWidth',2.2);
    hold on
    %plot(t,y(:,3),'color',[0.66,0.84314,0.653],'lineWidth',2.2);
    %hold on
    xlim([0 10]),ylim([0 1]);
    xlabel('Time');ylabel('Probability','Rotation',90);
    legend({'Government','Construction companies'})
    %legend({'F=0','F=2.5','F=5','F=7.5','F=10','F=12.5','F=15'})
    %legend({'R=0','R=0.5','R=1.0','R=1.5','R=2','R=2.5','R=3.0','R=3.5','R=4.0','R=4.5','R=5.0'})
    end
```

Figure 4-4 The evolutionary trend procedure of the two sides of the game when the initial probability is 0.5

Table 4-4 Initial values of $E_2(0,1)$; $E_3(1,0)$; $E_4(1,1)$

	$\mathcal{B}_2$	$\mathcal{B}_3$	$\mathcal{C}_2$	$\mathcal{C}_3$	$\mathcal{M}$	$\mathcal{F}$	$\mathcal{S}$	$\mathcal{R}$
$E_2(0,1)$	4	6	3	5	3	2	4	0.2
$E_3(1,0)$	4	6	3	20	3	2	4	1
$E_4(1,1)$	4	6	3	20	3	2	4	6

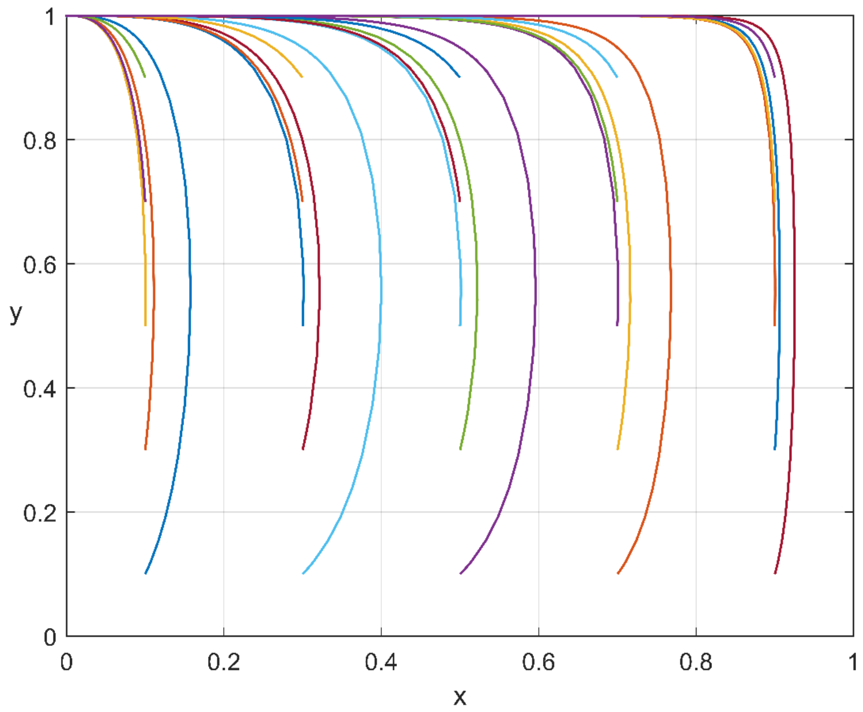

Figure 4-5 The evolutionary trajectory of $E_2(0,1)$.

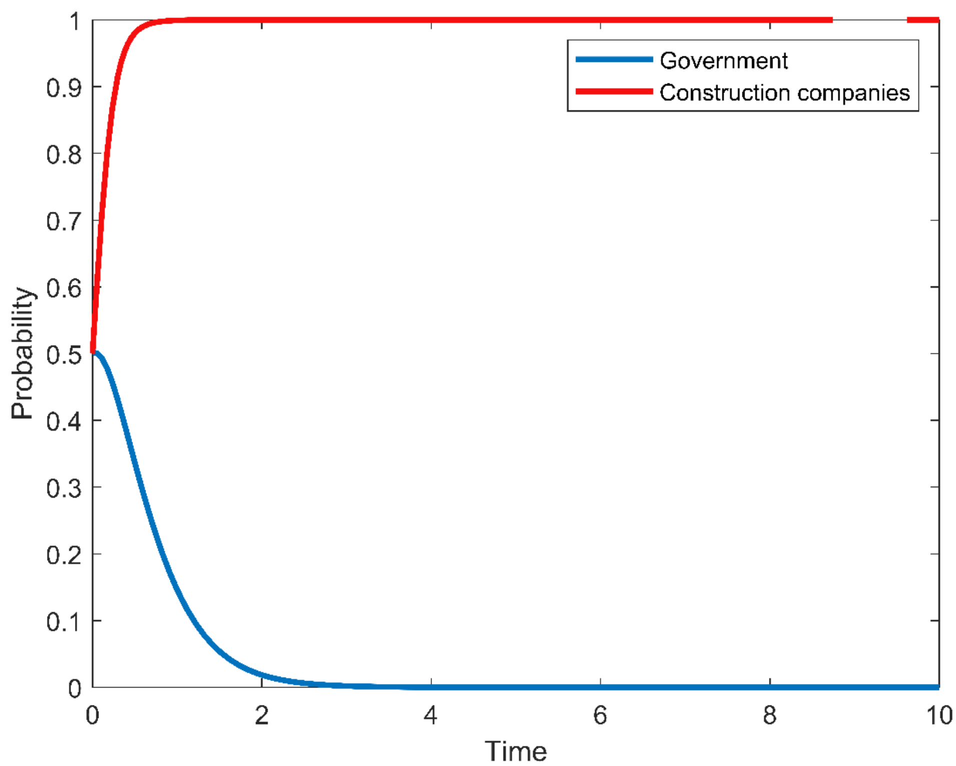

Figure 4-6 The evolutionary trajectory of $E_2(0,1)$, when the initial probability is 0.5.

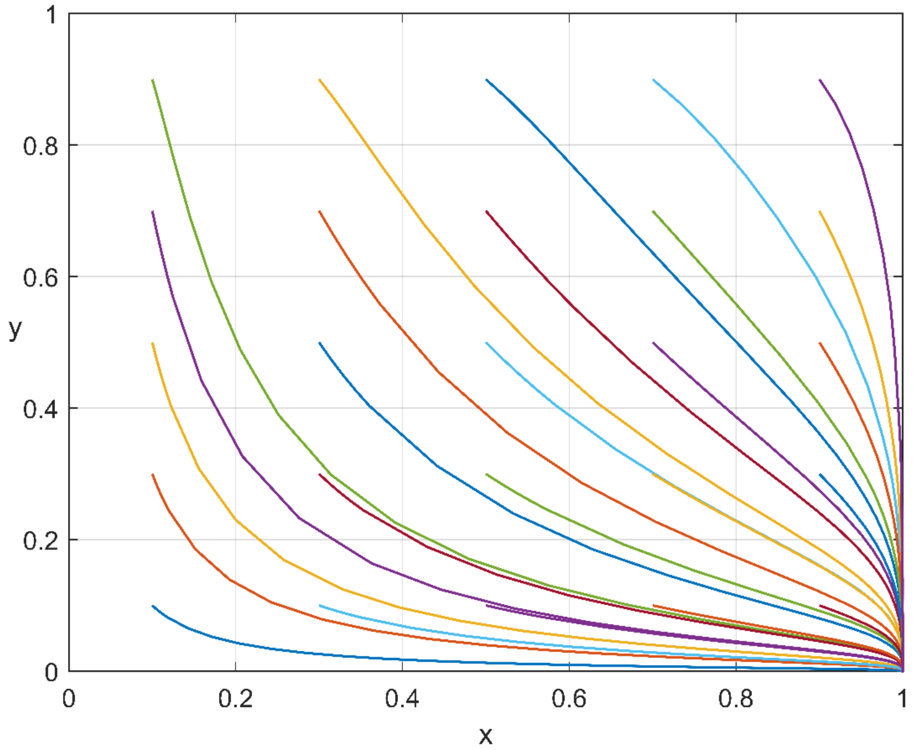

Figure 4-7 The evolutionary trajectory of $E_3(1,0)$.

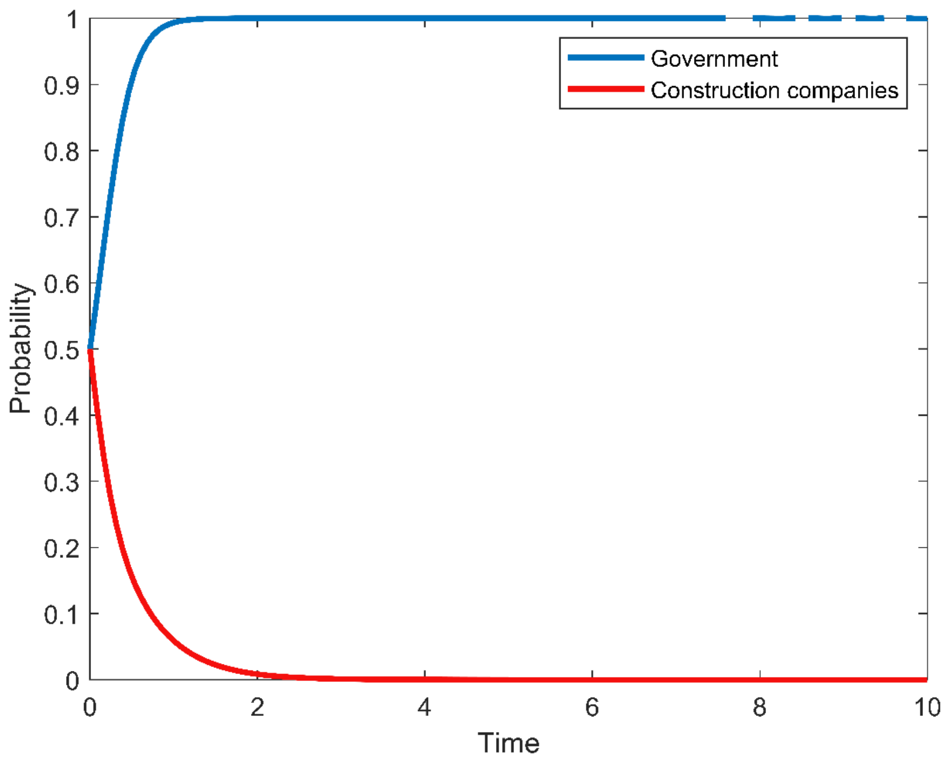

Figure 4-8 The evolutionary trajectory of $E_3(1,0)$, when the initial probability is 0.5.

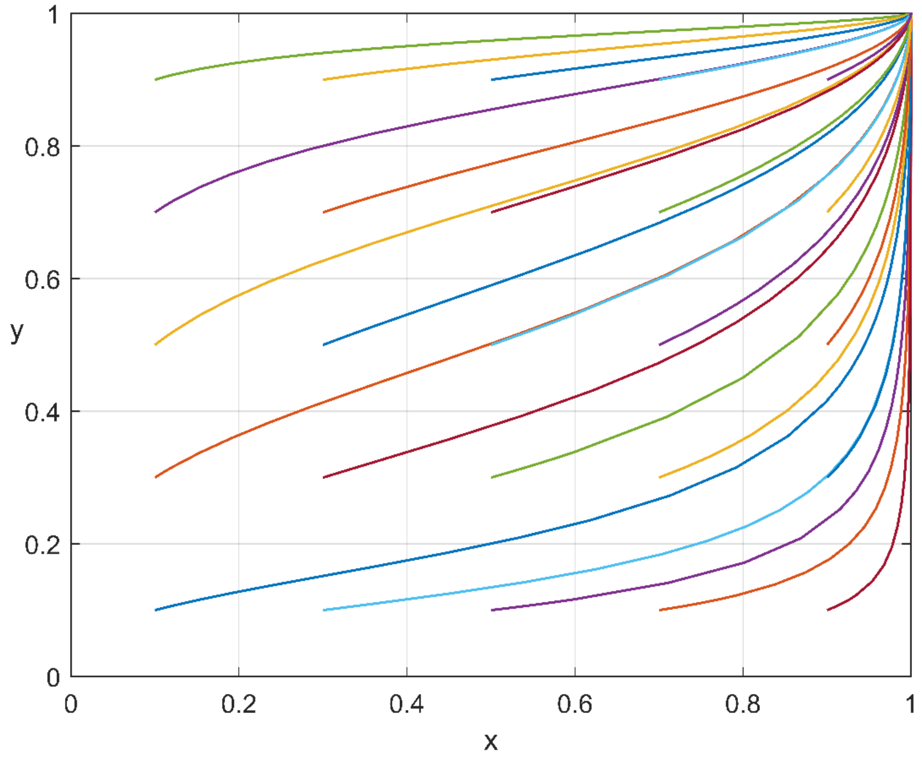

Figure 4-9 The evolutionary trajectory of $E_4(1,1)$.

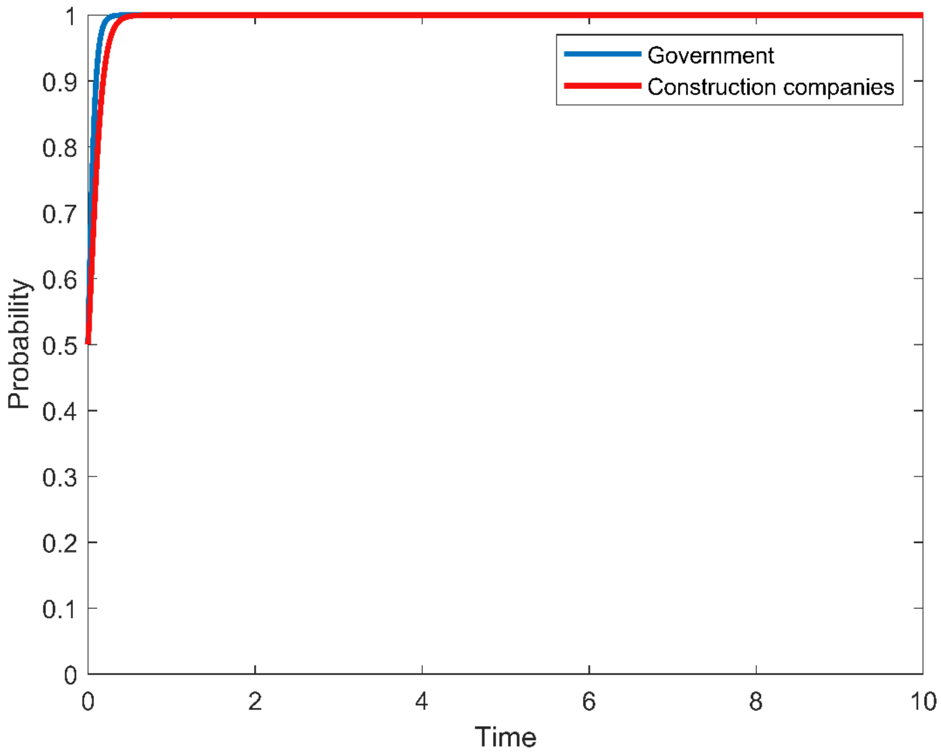

Figure 4-10 The evolutionary trajectory of $E_4(1,1)$, when the initial probability is 0.5.

4.4.2. Influence of critical parameters

Based on the above evolutionary results, $E_3(1,0)$, which is closest to the actual situation, is selected as the initial condition the government chooses to regulate. Still, construction companies are reluctant to adopt ARC technology because of the high cost of innovation. Holding other parameters constant, the effects of $\mathcal{M}$, $\mathcal{F}$, and $\mathcal{R}$ on the strategic evolution of the two sides of the game are explored separately.

1) Keeping other parameters constant, take $\mathcal{M}$ =0,4,8,12,16,20, the initial probability for all players is 0.5. We can obtain the evolutionary paths of the government and the construction company separately. With an increasing focus on the adoption of ARC technology by construction companies to improve the sustainability of the construction industry and its ability to combat the pandemic. The government has started implementing a subsidy policy for construction companies to adopt ARC. As shown in Figure 4-11 and Figure 4-12, the probability that the government chooses to regulate will converge to 1 when the value of $\mathcal{M}$ is below a certain value, which indicates that the government will actively regulate when the economic subsidy spending is not too high. Meanwhile, the probability of construction companies choosing to adopt ARC technology will gradually increase and eventually adopt ARC technology. However, after the value of M is greater than the critical value, the choices of the government and construction companies start to become unstable and fluctuate between certain values. This suggests that high government subsidies for the adoption of ARC technology are not sustainable.

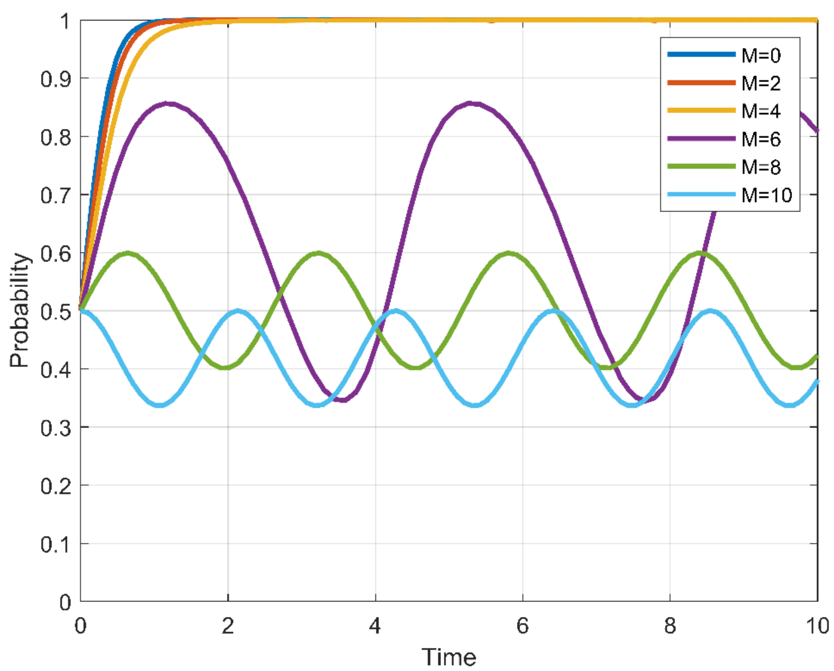

Figure 4-11 The impact of $\mathcal{M}$ on the evolutionary path of government.

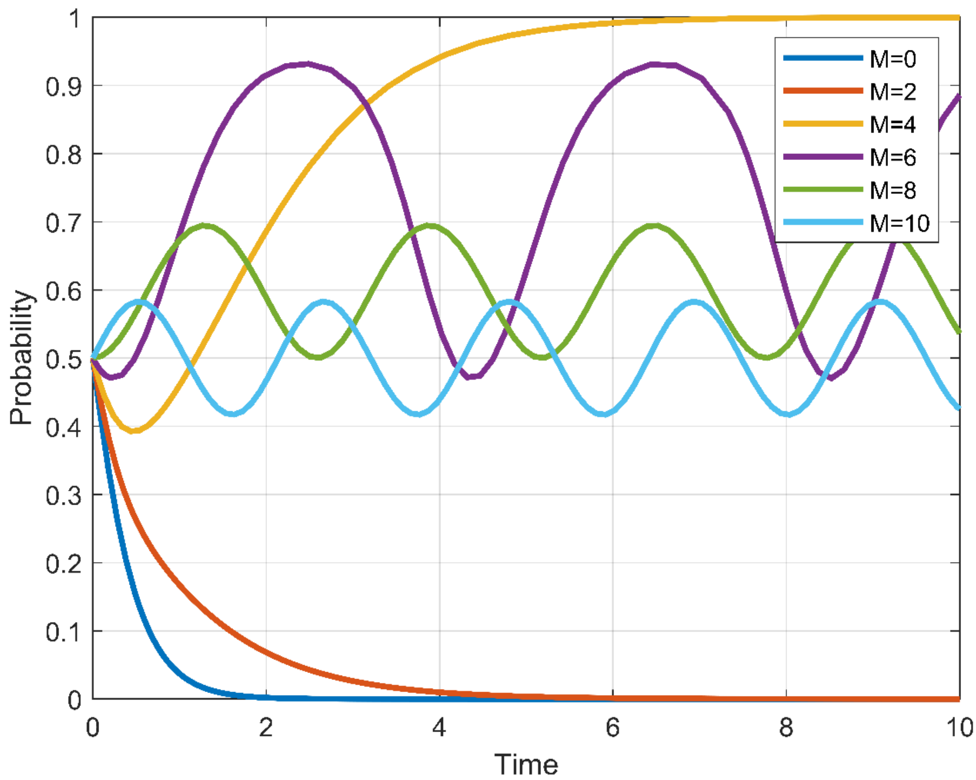

Figure 4-12 The impact of $\mathcal{M}$ on the evolutionary path of construction companies.

2) Keeping other parameters constant, let $\mathcal{F}$ =0,4,8,12,16,20, the initial probability for all players is 0.5. The impact of $\mathcal{F}$ on the evolutionary path of government and construction companies is shown in Figure 4-13 and Figure 4-14. Construction companies are susceptible to the strength of fines. As fines continue to increase, the probability that construction companies will choose to adopt ARC technology increases, and the rate of evolution increases. For the government, the intensity of fines does not influence government decisions, but as fines increase, the rate of evolution of the government's choice of regulation will decrease.

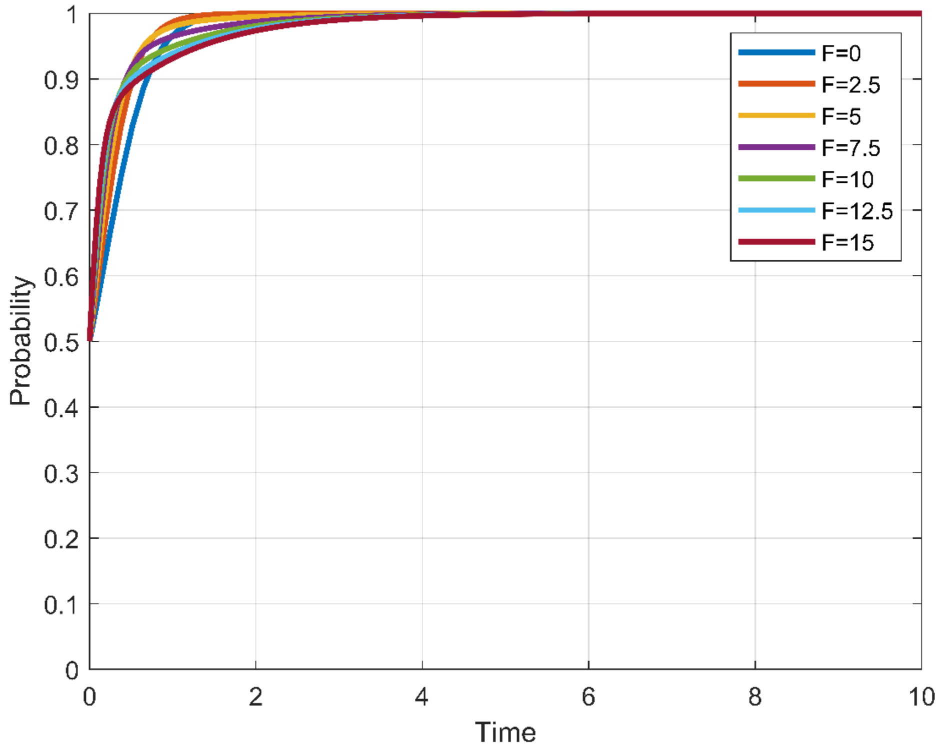

Figure 4-13 The impact of $\mathcal{F}$ on the evolutionary path of government.

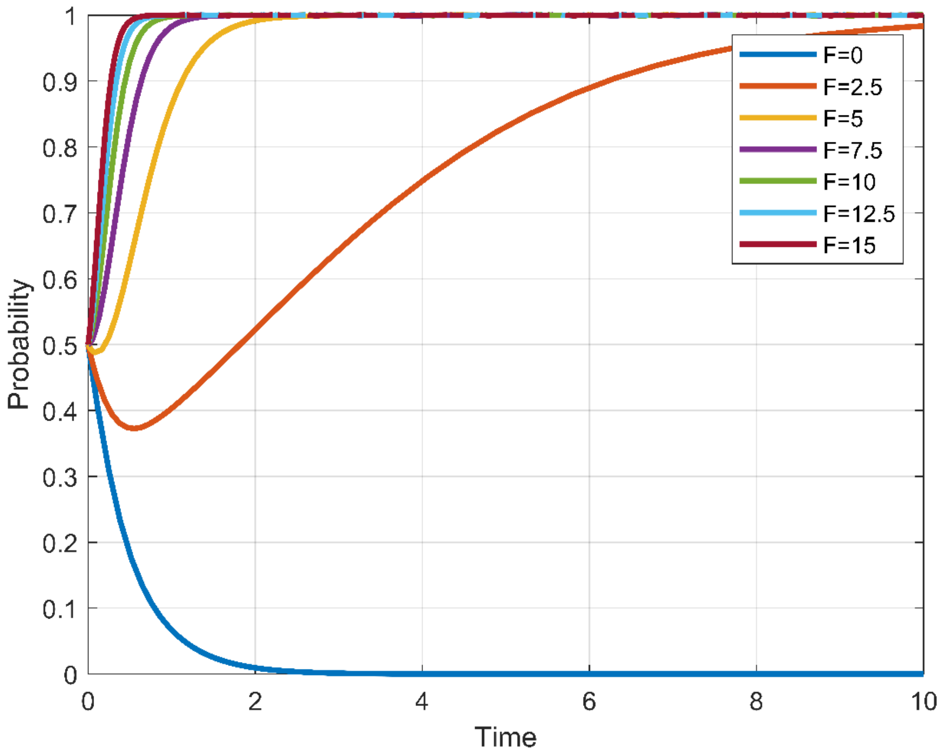

Figure 4-14 The impact of $\mathcal{F}$ on the evolutionary path of construction companies.

3) Keeping other parameters constant, let $\mathcal{R}$ =0,4,8,12,16,20, the initial probability for all players is 0.5. The impact of $\mathcal{R}$ on the evolutionary path of government and construction companies is shown in Figure 4-15 and Figure 4-16. The epidemic's impact on the participants of the evolutionary game is obvious. As the hazard level of virus, variants continues to rise, the speed of evolution of the government's choice to regulate rises. The probability that construction companies will choose to adopt ARC technology rises and evolves at an accelerated rate. This suggests that the hazard level of COVID-19 variant virus is the main factor influencing the technological innovation of ARC. On the one hand, a more severe variant of the virus would pose a greater challenge to the construction industry. On the other hand as the importance of virus hazards increases, governments and construction companies are willing to pay more costs for technological innovation to face the challenges of a pandemic.

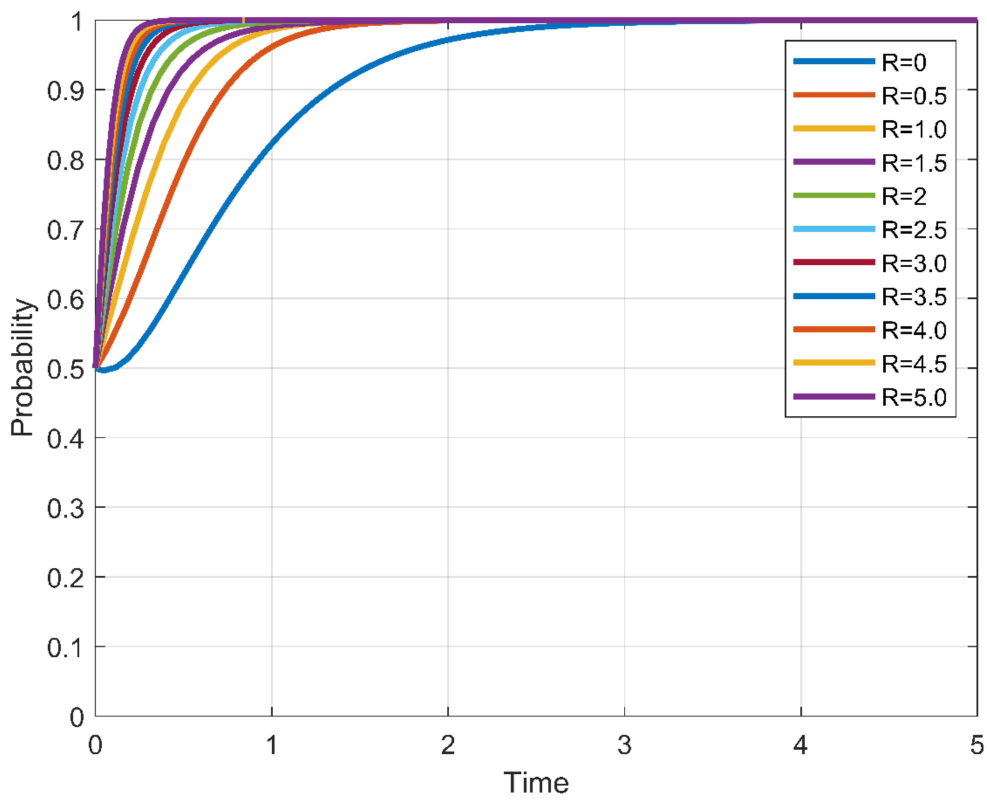

Figure 4-15 The impact of $\mathcal{R}$ on the evolutionary path of government.

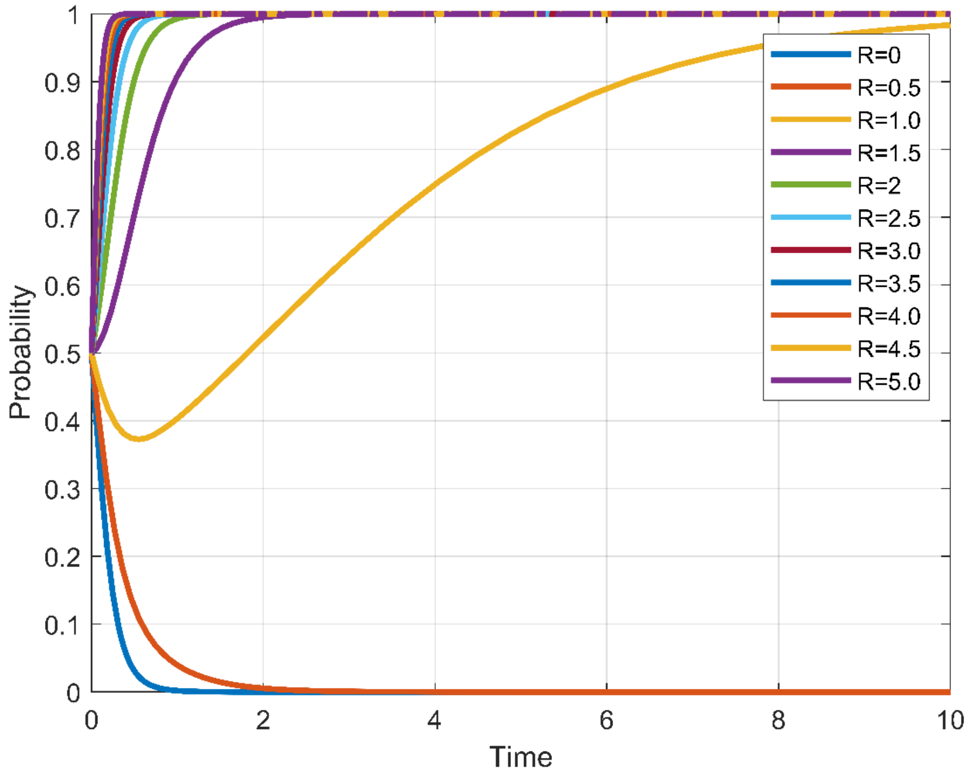

Figure 4-16 The impact of $\mathcal{R}$ on the evolutionary path of construction companies.

4) Keeping other parameters constant, let C_3 =0,4,8,12,16,20, the initial probability for all players is 0.5. The impact of C_3 on the evolutionary path of government and construction companies is shown in Figure 4-17 and Figure 4-18. For the government, the cost of innovation does not influence government decisions; the higher the cost of innovation, the faster the government chooses to evolve its regulation. For the government, the cost of innovation does not influence government decisions; the higher the cost of innovation, the faster the government chooses to evolve its regulation. This suggests that government and construction companies need to work together to reduce R&D costs through various means, making both parties willing to adopt aggressive strategies to develop ARC technologies.

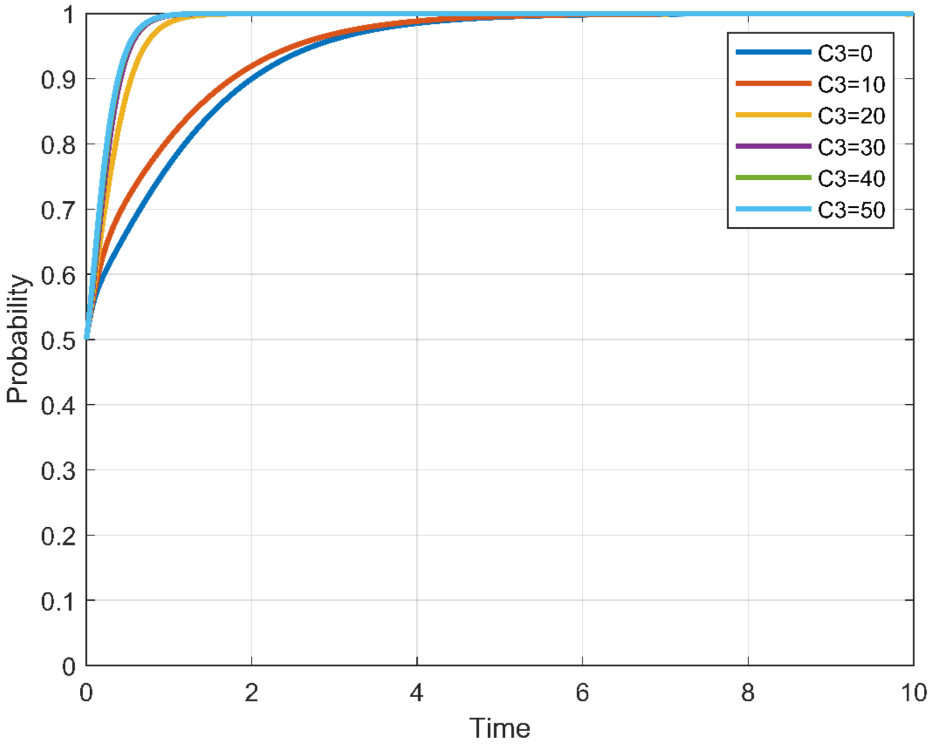

Figure 4-17 The impact of C_3 on the evolutionary path of government.

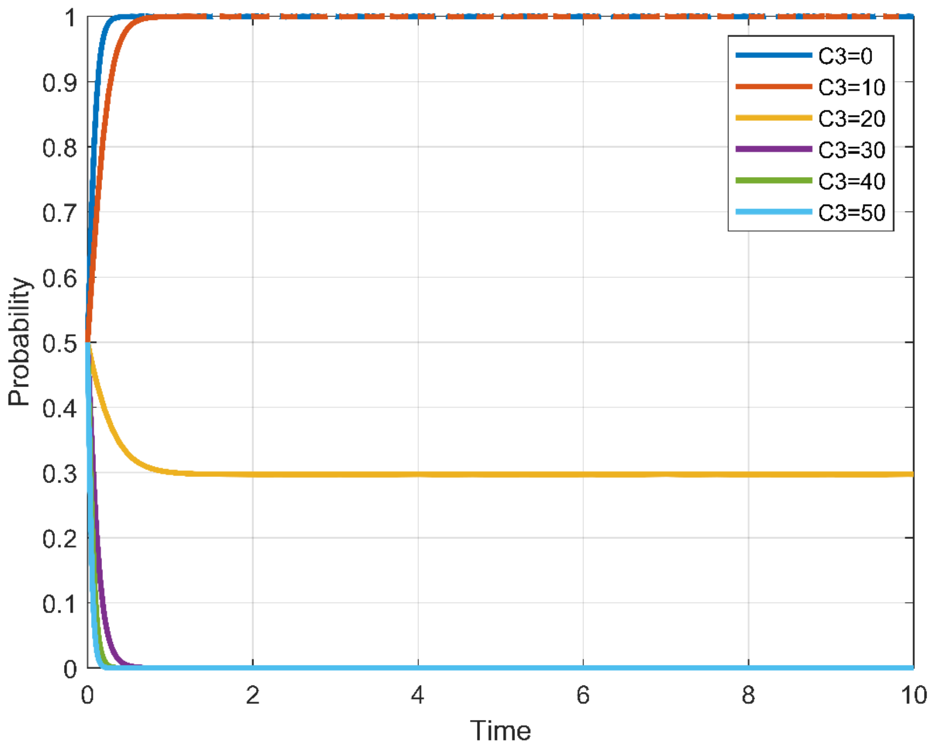

Figure 4-18 The impact of C_3 on the evolutionary path of construction companies.

4.5. Discussion and Policy Implications

4.5.1. Discussion

In this chapter, we analyze the strategic choices made by the government and construction companies in adopting ARC technology under the impact of COVID-19 pandemic by building an evolutionary game model. The following meaningful discussions were drawn from the results of the study.

1) There is a positive interaction between government and construction companies' adoption of ARC technology behaviors and strategies. Therefore ESS (Regulation, Adoption) can be achieved between government and construction companies.

2) A modest financial subsidy and penalty can accelerate the realization of ESS between the government and construction companies. However, excessive financial contributions can make government and construction company decisions unstable. Excessive fines will slow down the government's aggressive strategy.

3) Government and construction companies are sensitive to the hazard level of virus variants. The higher the degree of harm caused by the epidemic, the faster the government decided to regulate. At the same time, construction companies had to opt for technological upgrades in the face of the severe form of the epidemic. However, this is based on the government and society's importance to the pandemic. Some countries and governments have decided or intend to live with the virus and ignore its damage[11, 12]. This would make this influence non-existent; construction companies would not choose to adopt ARC technology depending on the evolutionary results.

4.5.2. Policy implications

Based on the study results and the above discussion, we give the corresponding countermeasures and recommendations as follows.

1) The government should establish a compound system of rewards and penalties to promote the adoption of ARC technology in the construction industry. On the one hand, the government should crackdown on construction companies that ignore the prevention policy and use traditional methods for intensive labor. On the other hand, the government should also provide support to help these companies tide over the difficult times by providing financial subsidies for companies with weak capital to even out the R&D costs. For companies with substantial capital provide reputational incentives to encourage them to innovate.

2) The construction cost is one of the most important factors preventing the widespread

adoption of ARC technology in the construction industry[13]. Ref[14] believes that equipment production, depreciation, and maintenance costs will drop significantly when the industry's overall capacity reaches a particular scale. Therefore, government should utilize policy instruments and market instruments to mobilize the development of the entire ARC industry chain and equalize the additional costs.

3) The COVID-19 pandemic has had a massive impact on economies worldwide, especially the construction industry, which is mainly a labor-intensive industry, has been hit particularly hard. However, the pandemic brings not only challenges but also opportunities. The study found that the higher the hazard level of the epidemic, the higher the probability that the construction industry will break out of its comfort zone and ignore the high R&D costs for industrial upgrading. The government and enterprises should work together to overcome difficulties and achieve industrial upgrading.

4) The epidemic's impact builds on the importance that the government places on the COVID-19 pandemic. Suppose the government abandons the fight against the epidemic for various reasons. Then companies will also lose the incentive to adopt ARC. This is harmful to the development of the industry in the long run. The government should pay attention to epidemic prevention and, at the same time, provide policy support to relevant enterprises to help them grasp opportunities and overcome difficulties.

4.6. Conclusions

Exploring the evolutionary relationship between government policy and construction company behavior on the application of ARC technology is vital for upgrading the construction industry and advancing the industry's sustainability. This study innovatively focuses on the construction industry under COVID-19, takes the epidemic hazard degree as an influencing factor in the evolutionary game model, constructs an evolutionary game model of government and construction companies, and analyzes the stable equilibrium point. The effects of different parameters on the evolutionary results were determined by simulation.

Research indicates that government-imposed regulation and corporate adoption of ARC's ESS is achievable. Establishing the appropriate incentives and penalties can speed up the evolution of government and construction companies. Emphasis on epidemic hazards and adherence to epidemic prevention can help achieve industrial upgrading of the construction industry. This chapter provides recommendations based on the findings and conclusions of the study to support the government in formulating relevant policies. This study still has the following shortcomings and space for further research. Firstly, this study considers only two stakeholders, the government and the construction company, and does not consider other participants in the industry chain. Future research needs to reflect more stakeholders for a more comprehensive discussion. Second, only the benefits gained or lost from the pandemic were considered, without considering its psychological impact and political considerations, which could be incorporated in future studies for more in-depth discussion.

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Chapter 5

CASE STUDY AND IMPLEMENTATION PROCESS OF PISAD

CHAPTER FIVE: CASE STUDY AND IMPLEMENTATION PROCESS OF PISAD

5.1 Contents

An architectural design process based on parametric design was developed, which improves the interaction between designers and demanders, and reduces the contradiction between small customization construction projects' need for individual customization and insufficient design budgets. The algorithm is combined with computer-aided modelling and simulation to establish the overall design style according to demander's requirements and provide several adjustable input parameters at the same time to achieve rapid fine-tuning of the design pattern and meet demander's needs for personalized customization. Shorten the design cycle and reduce the design cost. This method was implemented in a wood laboratory project at Kitakyushu University in Japan to validate its credibility.

The Section proposes a new design process based on parametric design: Parametric interactive script architectural design (PISAD) method is different from the traditional design process. While the designer completes the overall logic of the design according to requirements, it reserves adjustable Determine the input parameters of aesthetic details, visualize the adjustment process, allow users to adjust parameters while visually observing the changes in design results, helping users make decisions in a variety of design patterns, saving design time and reducing design costs.

5.2. Parametric interactive script architectural design method

5.2.1. *The needs for the PISAD method*

The development of parametric design is still in the initial stage of rapid growth and has broad application prospects in the future: On the one hand, parametric itself has excellent characteristics to adapt to technological development.; with the continuous improvement of the industrialization requirements, individualized buildings have received widespread attention in various places. In the pursuit of individualized building types, including township residential buildings, tourism real estate buildings, multi-functional venues, other comprehensive buildings, teaching establishments, and other cultural buildings[15]. The facilities mentioned above often do not have mass customization requirements and do not have sufficient design budgets. These small mass customization construction projects will face the contradiction between design costs and design requirements for a long time in the future. Using parameterization to digitize the design logic and visually present it to designers and demanders through visualized real-time feedback scripts can make the communication between the two parties more intuitive and time-saving while effectively controlling the design cost.

5.2.2. *Advantages of the PISAD method*

The cumbersome design time and design process are important reasons that affect the economics of architectural design. Simultaneously, with the continuous increase in labor costs, labor-intensive design methods have become one of the main reasons for architectural design's high expense. For unconventional customized construction projects, the economy and efficiency of the design process will be significantly challenged. Although digital and information tools are standard in the architectural design industry, the design process is still labor-intensive due to technical personnel's limitations or traditional design processes.

PISAD method makes full use of digital design tools and prefabricated construction technology, and its main features include the parametric design of the structural system and real-time visual feedback. Compared with the traditional model, PISAD's architectural production model's advantages are mainly reflected in its individuality and high efficiency. The industrialization of parametric design is expected to get rid of the intensive labor mode required by the traditional design industry and realize the economic predictions of early practitioners of parametric design-designing; a customized building is not more expensive than designing a standardized building, thus Provide a technical guarantee for the development of the personalized design industry of buildings.

5.3. Exploration of PISAD

The application of PISAD method has opened up a new model of architectural design. In the traditional design process, the demander will often put forward many subjective aesthetic opinions on the details when the design style is determined by the big frame and will be repeated many times before the plan is changed. Change of thinking is the main reason for the high design time and cost. Under PISAD method, the designer writes the abstract aesthetic design as a visual script, using adjustable parameters as the design details adjustment variables. These variables are straightforward and intuitive. Each adjustment can give feedback on the adjustment results, making the designer. The communication with the demanders is smoother, thereby reducing design time and design costs. On the one hand, parametric design architectural solutions have more customization possibilities; on the other hand, the PISAD method has higher economics in the long run, making personalized and customized architecture no longer the privilege of large-scale projects. It can be widely used in the construction of projects with a low design budget.

5.3.1. Meldia Research Institute for Advanced Wood

The author participated in the wood laboratory construction project in Wakamatsu District, Kitakyushu City— Meldia Research Institute for Advanced Wood (Figure 5-1) is a typical case PISAD production model for constructing small custom buildings. The building's exterior wall design attempts to integrate into the surrounding site, environment, and natural ecological resources organically through digital design methods. The design completed the rapid design through PISAD, took into account the construction cost and the design cost, met the demander's external wall form's specific aesthetic requirements under the most economical conditions, and explored the low-cost and high-efficiency design mode.

Fig. 5-1 Meldia Research Institute for Advanced Wood.

5.3.2. Digital design

Since the beginning of the invention, the façade has tried to echo the architectural structure as much as possible. The origami structure using large-span CLT (Cross Laminated Timber) panels[16] and establish a dialogue between contemporary architecture and the natural environment in the natural space gap. The building site is composed of two adjacent square homesteads. Galvalume flat steel plates of different sizes are designed for splicing allows design styles to be related to building materials. By changing the splicing sequence of aluminum sheets of various sizes, an "S"-shaped curve symbolizing "ridge" and "waves visually presented(Figure 5-2). Using digital design tools to simulate 3D models allows quickly to discuss a rough design plan with the demander.

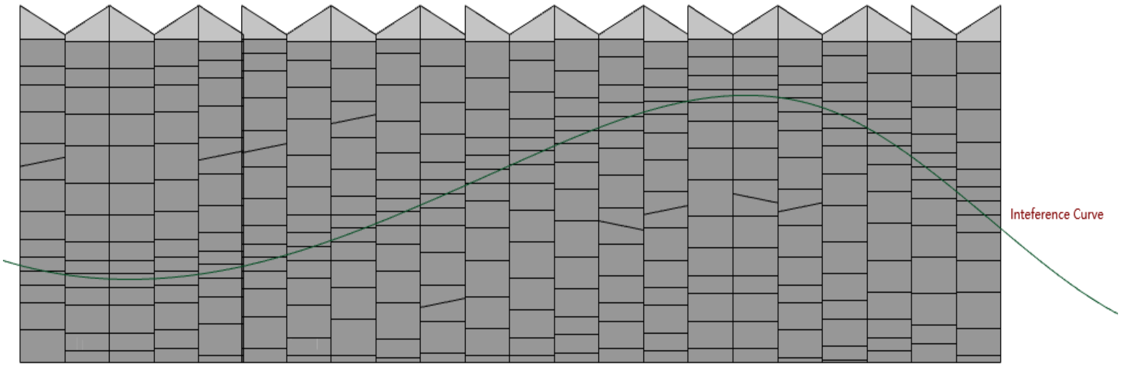


Fig. 5-2 Inteference Curve.

5.3.3. Parametric pattern design

The building's main structure is composed of two square workshops, and a semi-open corridor connects the middle of the building. In the building's longitudinal direction, four exterior walls are made up of several CTL panels with a height of 7895mm and a width of 1495.34mm in a fold-line shape. The parametric facade design uses the "S" curve as the main element. Taking the turn and the visual focus of each CLT board's front view as the fundamental point and taking the center's essential point, galactic flat steel plates of different sizes are arranged on both sides of the longitudinal direction. A visual effect consistent with the curve to achieved through parametric modeling. In this project, the parametric façade design comprises galactic flat steel plates with widths of 300mm, 400mm, 600mm, 700mm and 800mm. In the parametric model, all components' production material size and processing nodes' requirements can be accurately adjusted to achieve customized adjustments to the construction system. All flat unit generation programs are written in grasshopper and packaged and sealed. The reserved input ports with instructions allow the user to freely adjust the parameters to quickly generate different design results(Figure 5-3). Adjustable parameter input port allows users customize the plate size based on requirements. The edited pattern generation script can dynamically display the adjustment results to help users make decisions. The specific logic of the morphology generation script is as follows.

- Obtain the intersection of the interference curve projection with the centerline of each wood wall as the starting point(Figure 5-4).
- Arrangement of the plates to the top and bottom with the intersection point as the center according to the set plate size(Figure 5-5). And the input port of the plate size is reserved to allow subsequent real-time modification.
- Randomly select the largest size plate and slice it in a random direction to add interest to the design(Figure 5-6).

- Automatically calculates the number of plates for each size and generates a list(Figure 5-7).

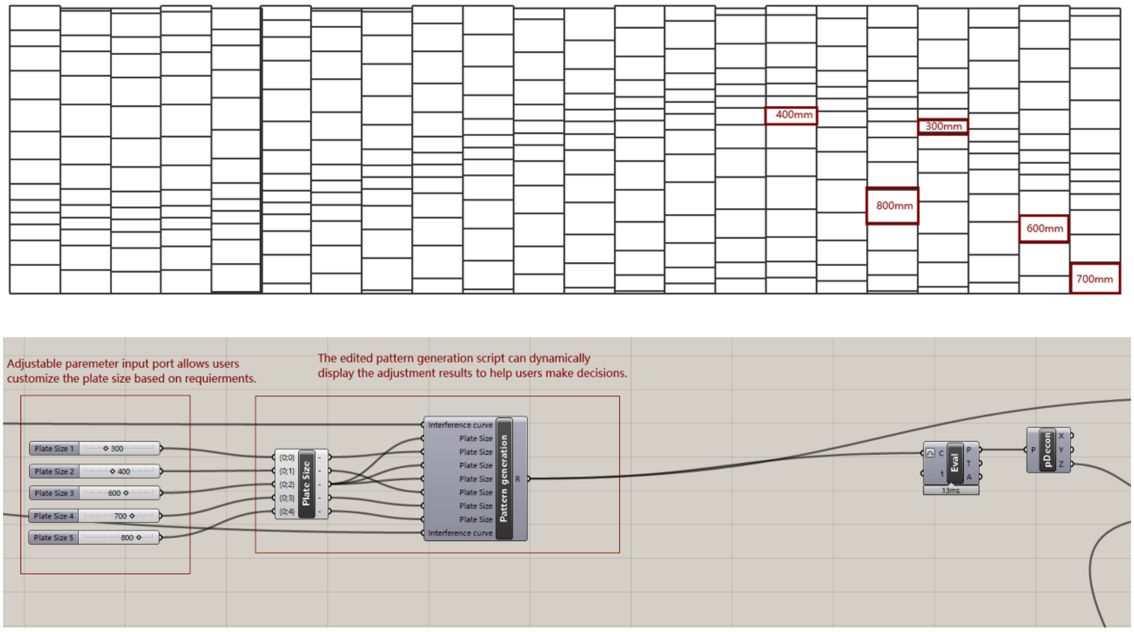


Fig. 5-3 Plate size value input port and pattern generation script.

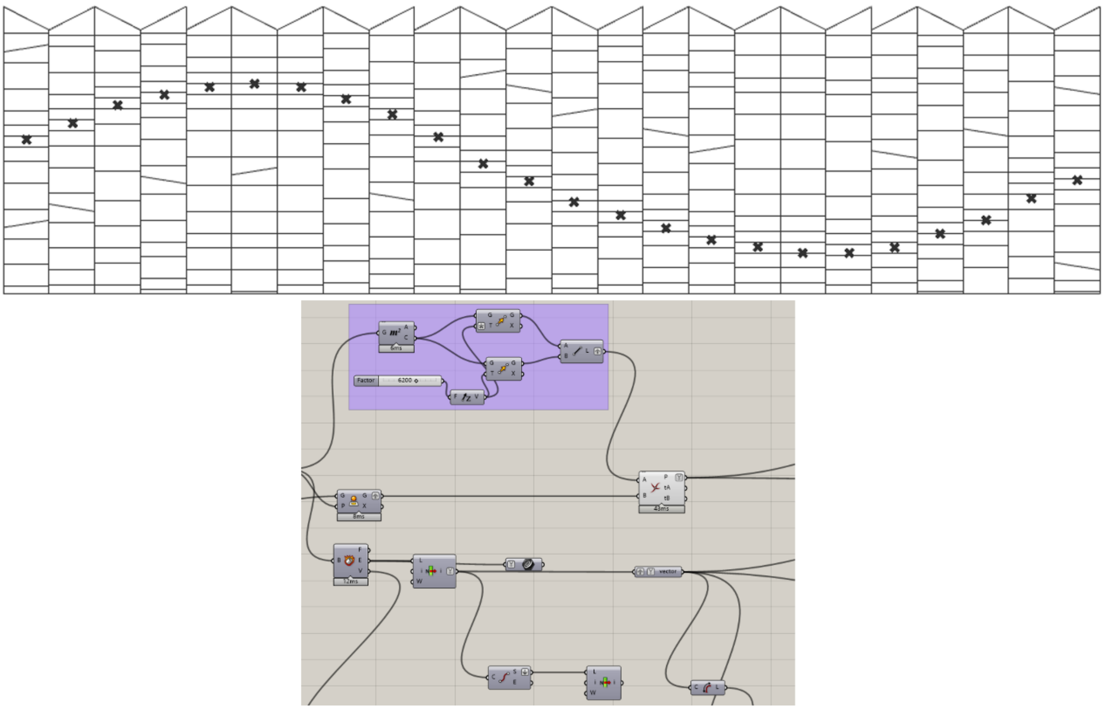


Fig. 5-4 Intersection of the interference curve projection with the centerline of each wood wall.

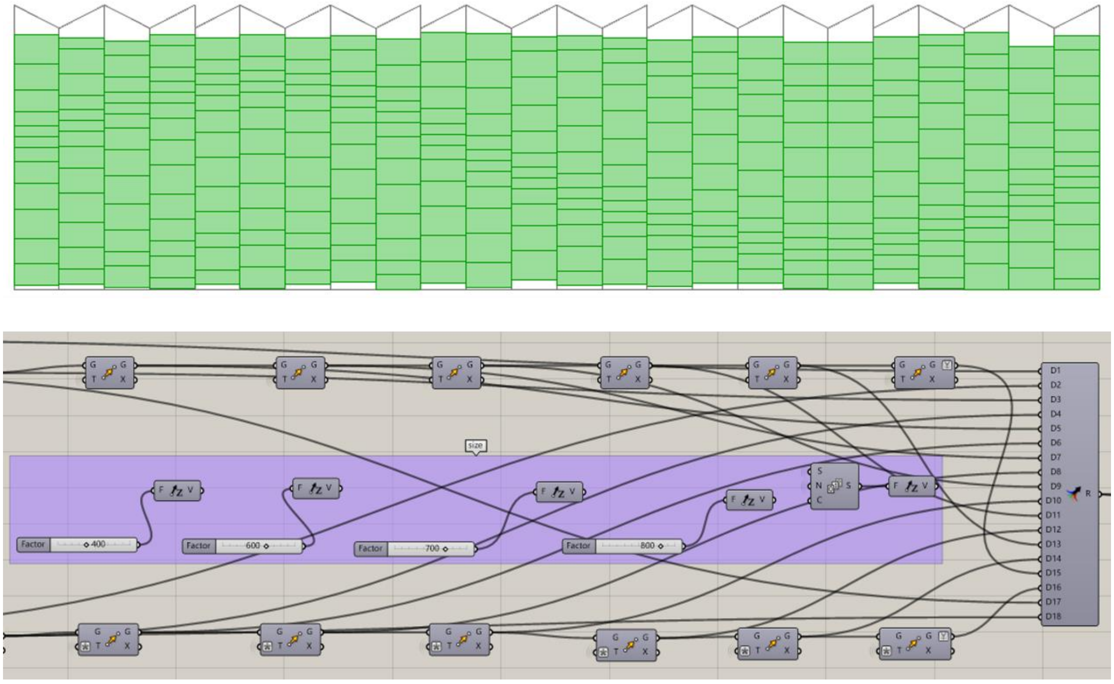


Fig. 5-5 Arrangement of the plates to the top and bottom with the intersection point as the center according to the set plate size.

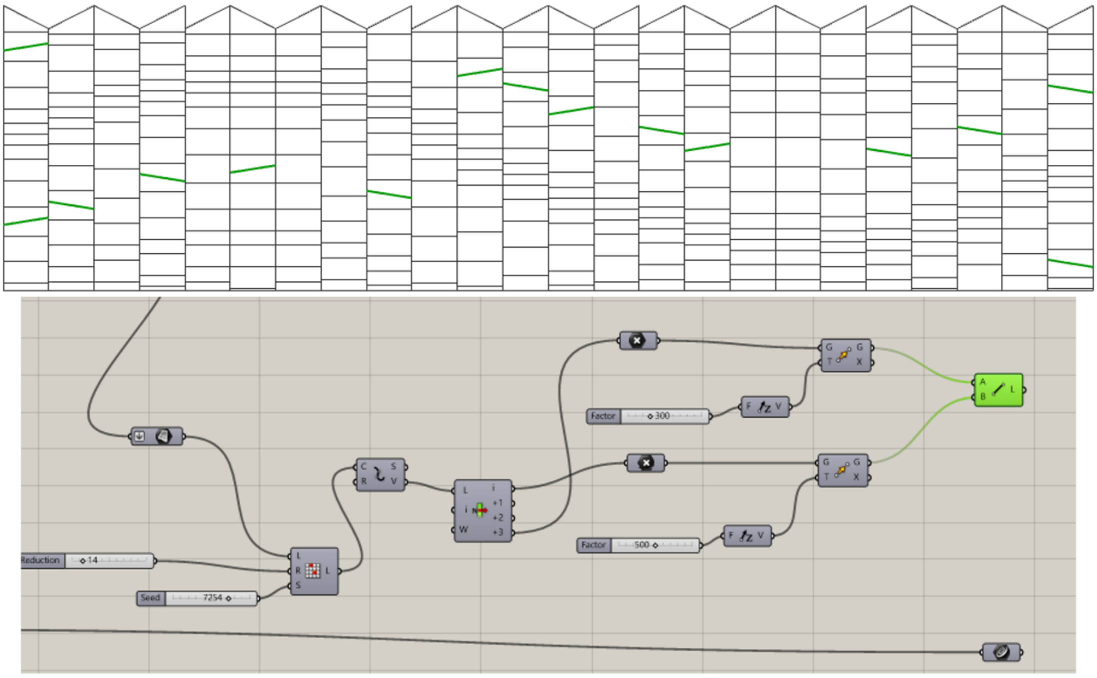


Fig. 5-6 Randomly select the largest size plate and slice it in a random direction.

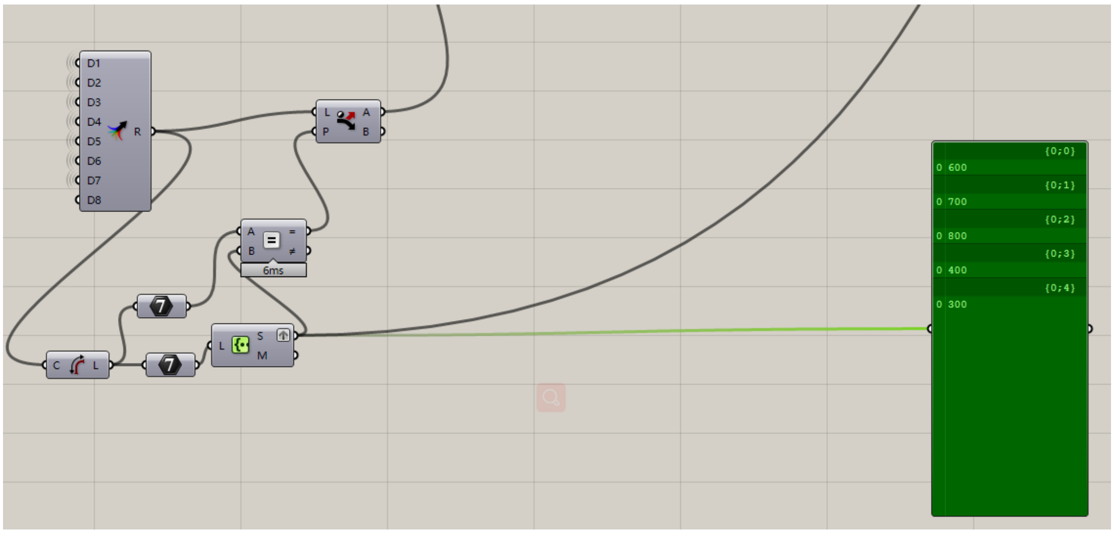


Fig. 5-7 Automatically calculates the number of plates for each size and generates a list.

5.3.4. Interactive design process and visualization of cost estimates

The parametric exterior wall system takes geometric prototypes, component sizes, and other elements as necessary input parameters, generates practical exterior wall designs with reference to cost analysis, and realizes them through parametric modeling. In this project, the parametric exterior wall system is composed of components of different sizes, which are arranged in a specific order to form a design pattern(Figure 5-8). In the parametric model, all parts' size and design pattern requirements can be precisely adjusted to realize the design system's customized adjustment. In this project, the components' size, arrangement, and interference curve are provided to the demander as interactive parameters, allowing the demander to visually observe the design pattern changes while adjusting the above parameters. In the design process, the ease of using design tools is one of the basic factors that restrict the demanders from participating in the design. In the traditional design process, because design tools require a long period of learning and training, the generation of design results highly depends on the designer's perception, cognitive ability, and aesthetic taste. After the requester submits a proposal to modify the proposal, the designer must change the design plan, which increases the design cost and design time. In this project, the input port to determine the aesthetic details has been integrated into the parameter design script, and a visual output port is provided. When making plan adjustments, the demander can intuitively change the input parameters and observe the design results' real-time changes. Simultaneously, the operation interface is straightforward and can be used without special training. The dynamic display of the plate quantity also allows the user to estimate the approximate construction period and construction cost, it enables the demander to quickly select the design result that meets its aesthetic requirements from various design results (Table 5-1).

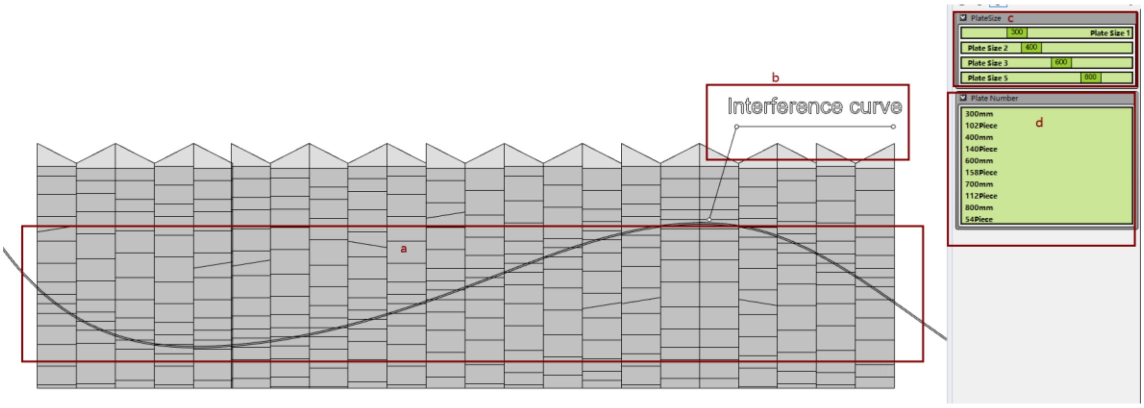
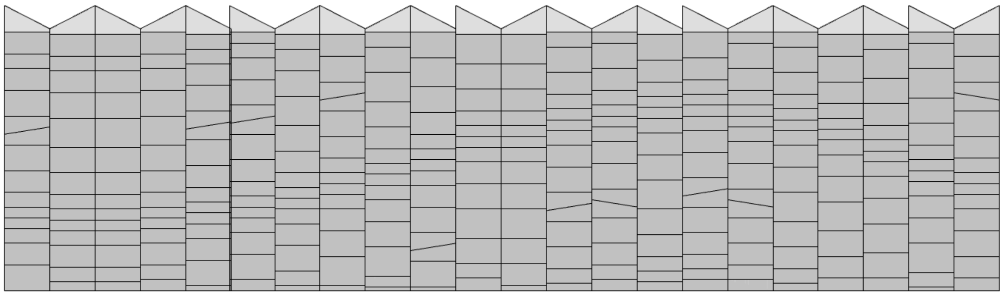
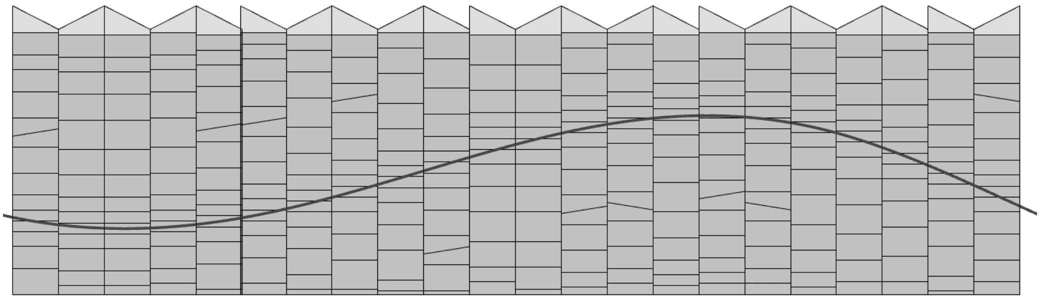


Fig. 5-8 Operation-friendly user interface (a): The interference curve can be adjusted quickly through several nodes, which is convenient for the user to make adjustments to the design shape; (b): Interference curve guidance, convenient for users to understand the function of the curve; (c): Input the parameter port, adjust the value through the form of a slider, allowing the user to set the plate size according to the material conditions provided by the material supplier. (d): The dynamic display of the plate quantity allows the user to estimate the approximate construction period and construction cost.

Table 5-1. Pattern generation results

Pattern	
Interference curve	

Parameter selection

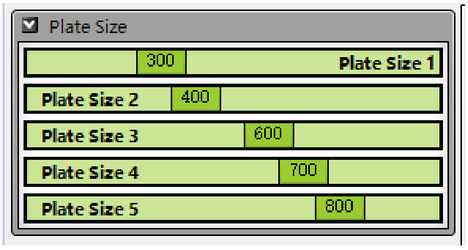
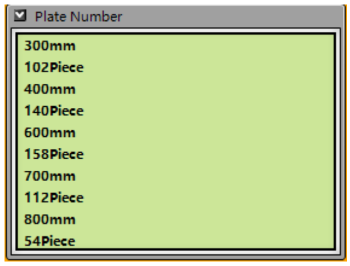
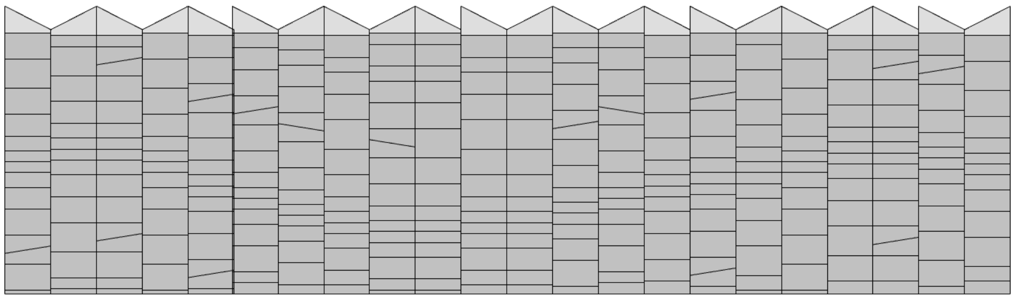


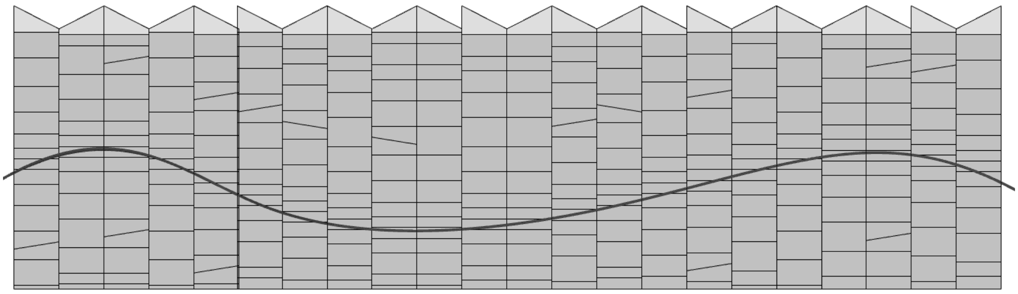
Plate Number



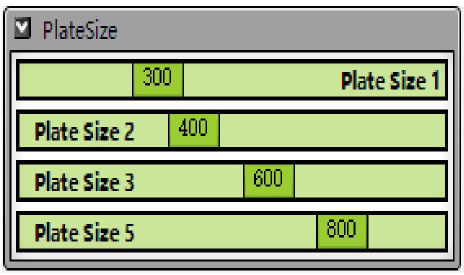
Pattern



Interference curve



Parameter selection



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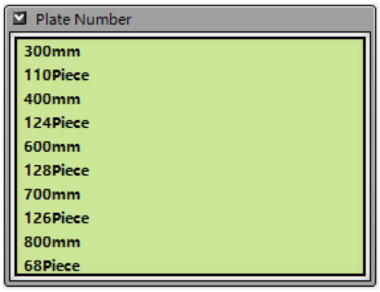
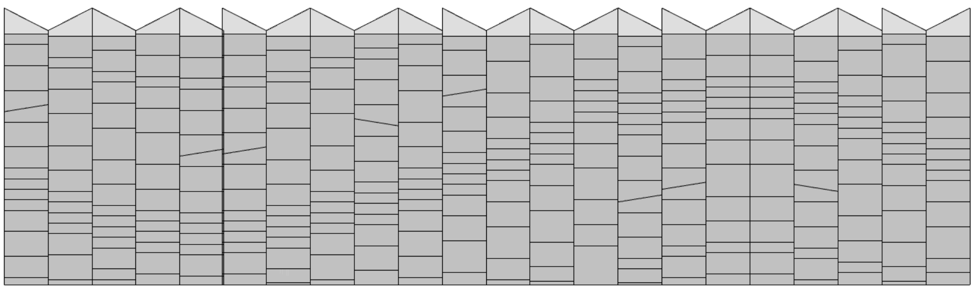
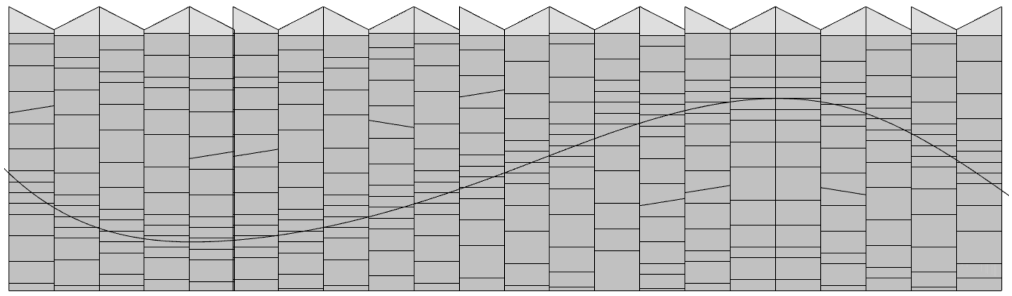


Pattern



Interference curve



Parameter selection

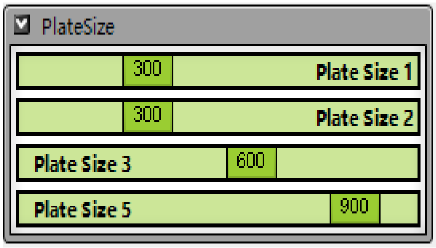
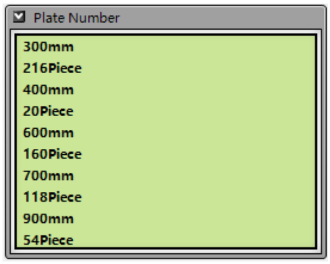


Plate Number



According to the dynamic adjustment results in this project, the user quickly chose the design result that meets his personal aesthetics. The user began to freely adjust the input parameters and interference curve to determine the final plan, only used about 1 hour Time, significantly reduced design time and reduced design cost from the completion of the design logic construction.

5.4. Setting

Meldia Research Institute for Advanced Wood was built in 2020 in Kitakyushu University, Kitakyushu, Fukuoka Prefecture, Japan, collaborating with FUKUDA Building Technology Research Laboratory and Meldia Group. After the main body of the building is designed, the user proposes individual requirements for the building façade. Due to the limited design cycle and cost, the design team introduced PISAD as a new attempt. In the north and south elevations of the building (Figure 5-9), parametric design is used to provide parameter ports that only affect the visual effect for the user to choose so that the design solution can be completed efficiently and cost-effectively in a limited time. The parametric design provides accurate panel size and quantity requirements for factory processing and production. The craftsmen checked the quality (dimensional progress, visual quality). According to the drawings, workers then transported the panels to the construction site where they were assembled like a two-dimensional puzzle (Figure 5-10, Figure5-11).

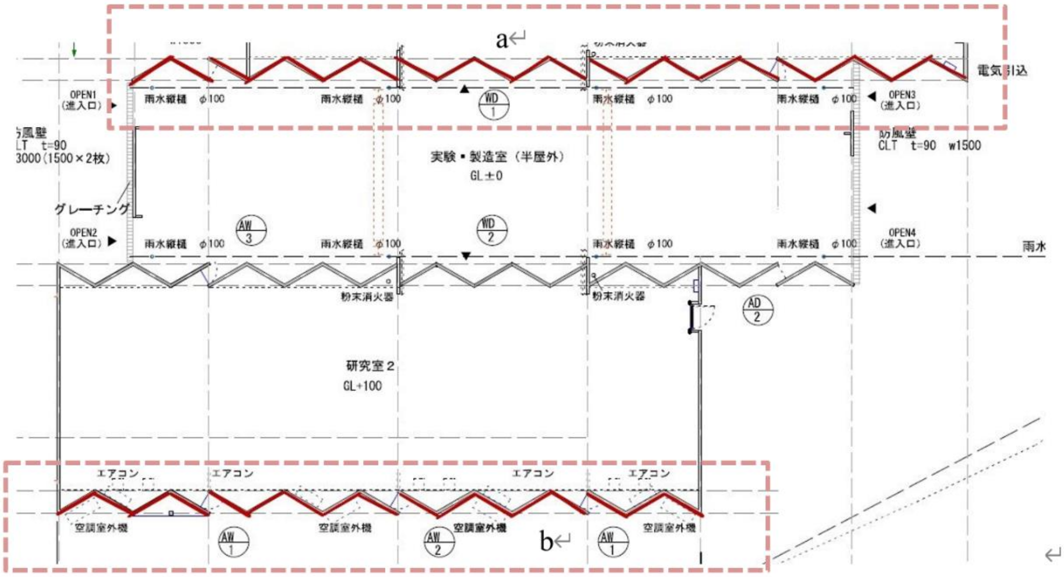


Fig. 5-9 (a)The north facade is inspired by the "sea", creating a interfering curve shaped like a wave. (b) The south façade is inspired by "mountains", creating a disturbing curve shaped like an extended mountain range.

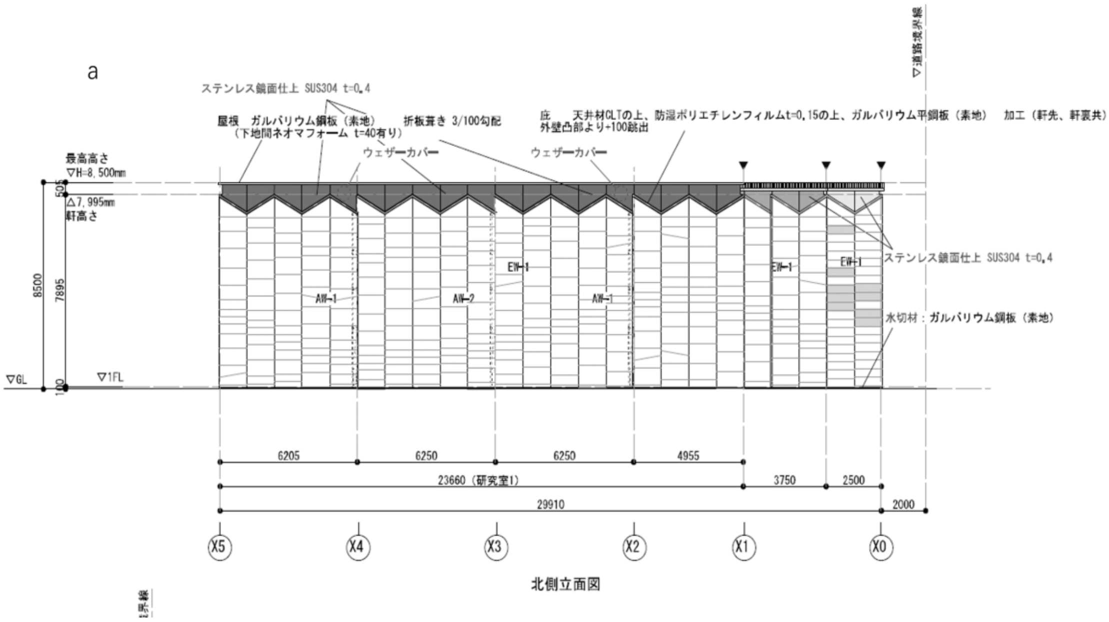


Fig. 5-10 Construction drawings, taking the north elevation as an example.

Fig. 5-11 Assembly according to drawings.

5.5. Conclusion and prospects of PISAD

5.5.1. Results and prospects of PISAD

The PISAD pattern shows unique advantages in small-scale building design. The PISAD pattern with parametric design as the core can efficiently design non-standard personalized forms and rapid communication with the demanders, thus forming a high-quality, low-cost design mode with flexibility and broad applicability. Most of the current PISAD technology is in the laboratory stage, and industrial application is limited. However, with the in-depth promotion and application, the future small-scale customized architectural design is expected to change the labor-intensive and low-customization efficiency existing in the traditional design industry. To promote the update and upgrade of customized architectural design models. In the future, customized architectural design will rely on PISAD to personalize the design process with high efficiency and provide the market with economical and flexible customized architectural design services. Through the full integration of virtual design and material construction, the building prefab production plant realizes the integration of design and production, effectively improving production efficiency and reducing construction costs. The PISAD model is expected to implement the customized design model for small buildings in the architectural field.

5.5.2. Conclusion and outlook

In conclusion, PISAD's vision is to use parametric design in combination to bring together the designer's design process, and the user's end desires at the core of the final project and construction process. Fundamentally, it enhances the efficiency of traditional design and improves the user-designer relationship. More importantly, PISAD pursues a fundamental evolution in design logic, a complex and efficient design process that can maximize the user's individual needs while controlling costs. In addition, this effort facilitated a new construction process, from the very beginning of design, through the different construction phases, until final realization, where design decisions coordinate the construction and manufacturing attributes that hit the force. Thus PISAD facilitates the penetration of information throughout the construction process, from the initial design visualization to reproduce user requirements to parametric design solutions to the production of individual skin parts, opening up new ideas for the physicalization of architectural design.

Chapter 6

CASE STUDY AND IMPLEMENTATION PROCESS OF HRITC

CHAPTER FOUR: CASE STUDY AND IMPLEMENTATION PROCESS OF HRITC

6.1 Contents

Harmonization of the environment, economy, and technology is the key to pursuing sustainability in modern society. Increasing productivity and economic efficiency can improve the sustainability of the industry. However, an assessment of the current construction industry shows that the efficiency of the current construction industry in terms of material use is very low, as is the degree of automation of the entire construction production process. In addition, the construction industry in China is facing a scarcity of experienced workers in the construction industry as fertility rates decline and aging societies intensify. The lack of skilled construction workers contradicts the increasing demand for individualized construction. The trend toward automated production development is evident. Since timber is one of the primary construction materials used worldwide, it is used extensively in the construction industry in China. This chapter will concentrate on the technical situation of automated timber construction, especially on the process and methods of automated production. In addition, a new construction process is presented through a practical example, where the parametric design and automated construction techniques are introduced to allow human-machine interaction to flourish, allowing an inexperienced layman to quickly complete the construction of complex wood structures with the assistance of a robot. Furthermore, this automated construction method's advantages, limitations, and potential pitfalls and the environmental, economic, and social sustainability aspects of design, production, and construction are also considered, providing a technical reference for the sustainable development of China's construction industry.

This section proposes an HRITC construction method based on parametric design and robotic automated construction, aiming to provide a new idea for the existing RTC research by combining the advantages of manual construction and robotic automated construction. The more costly and flexibility-demanding aspects are given to human workers, and the laborious and precision-demanding aspects are given to robots. The efficiency of robots and innovative digital technologies can support the flexibility of human workers, resulting in an efficient and flexible construction framework. Technological improvements such as these make new automated configurations involving human workers possible, while the low cost and low requirements for equipment sites make the diffusion and larger-scale adoption of the technology possible.

6.2. Construction method and material Selection

The Fukuda Building Technology Lab and iSMART Qingdao took advantage of their previous research on large-scale wood and automated robotic construction. In a two-month effort combined with the lab's expertise, a wooden arch(using 840 pieces of wood and 3155 nails) was fabricated at the iSMART Robotics Center at Qingdao University of Technology, taking 26 hours to produce the

8-part structure, which was then transported to the exhibition site and assembled. It captured the limelight with its complex structure and colossal size, reaching a height of 2.25 meters and a width of 4*4 meters. Since the project was to be used for educational work in student workshops, the limited conditions added many challenges to the program design: (i) The materials used in the design could not be too complex and expensive due to the limited funds and construction time. (ii) The construction program and script had to be universal. Allow the morphological design of the wooden arch to be designed by the students based on the determination of the general logic. The plans need only to be fine-tuned to the specific design used for construction. (iii) The human work steps must be safe and simple enough. The workers involved in the construction were all students with no construction experience, except for the equipment commissioners and safety operators who had the expertise to ensure the safe operation of the machines. (iv) The construction process must not be too demanding on the environment of the construction site. In summary, this chapter introduces the following approach to address these challenges.

6.2.1. Screw- and nail-gluing technique

The use of screw- and nail-gluing technique (SNGT) with high link strength instead of pneumatic nails, combined with a hybrid assembly technology of mechanical fasteners and adhesives, allows the manufacture of large-size composite structures[1]. The adhesive is applied to the junction of two separate boards and then tightened with threaded nails, making the connection stronger and allowing the board stack to be used in larger-scale construction(Figure 6-1). The building was cut into appropriately sized units, built-in horizontal stacks on the site, and each unit was finally assembled into a complete construction. The advantages of this construction method are that it can use the maximum proportion of wood as construction material and reduce the carbon emission generated by the building life-cycle; the construction method is simple enough for inexperienced workers to participate in the work.

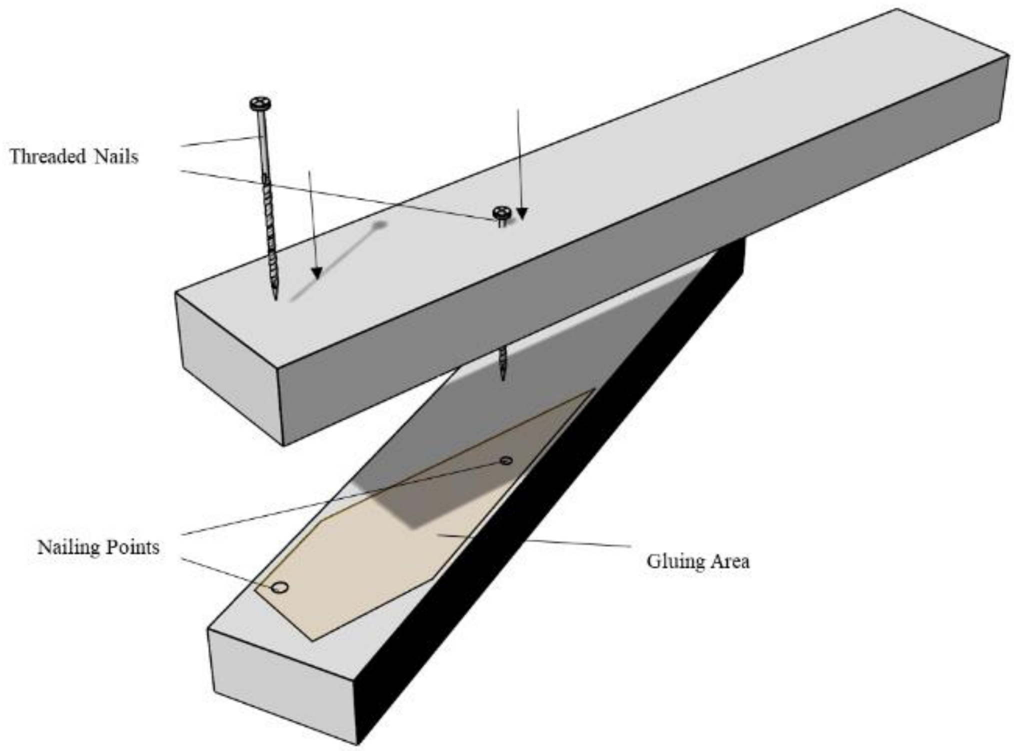


Fig. 6-1 Screw- and nail-gluing technique.

6.2.2. Wood selection

After comparing various types of wood from Aoshima and Fukuoka lumber mills, our solution was to use the low-cost method of Japanese hinoki because it is a popular building material that is reliable and easy to process. The history of plantation forestry in Japan dates back to the late 17th century. After many centuries of selection, hinoki has shown its unique advantages, such as short growth cycles and low plantation costs, making it one of the most common building materials on the Japanese market[2]. Moreover, the mechanical properties of this wood are good enough to ensure safety even after aging[3]. Using (50*100*650mm) wood bricks as the building material for this case, the uniform size reduces processing costs, allows for stacking without sorting, reduces construction difficulties and site requirements, and can make the construction process more universal.

6.2.3. HRITC workflow

The integrated digital automated planning of the iSMART wooden arch was an opportunity to develop and test the construction framework inductively. In order to push the applicability of this construction framework to large-scale programs, a new approach of HRI was adopted. Since the connection step has multiple unknown parameters, the flexible interaction between the construction worker and the computational model becomes the main factor for success. The framework proposes integrating humans into the automated construction process, thus addressing the construction steps with the most variables, leaving the processes requiring precision and tedious labor to the robots. Two parallel modeling environments were built using the Rhinoceros3D's Grasshopper plugin and custom code for KUKA|PLC. (1) the computational design model and (2) the robot construction simulation code model (Figure 6-2). During the initial design phase, dynamic feedback allows for tight integration of the leading manufacturing parameters, visualized design models, and build simulation processes that allow for real-time adjustment of manufacturing parameters. During the construction phase, the spatial information of individual components is used for the entire fabrication, from production processing to positioning and assembly. All the component details can be precisely controlled, enabling the efficient generation of comprehensive robot command codes directly from the construction simulation and the model based on the composition of the construction tasks.

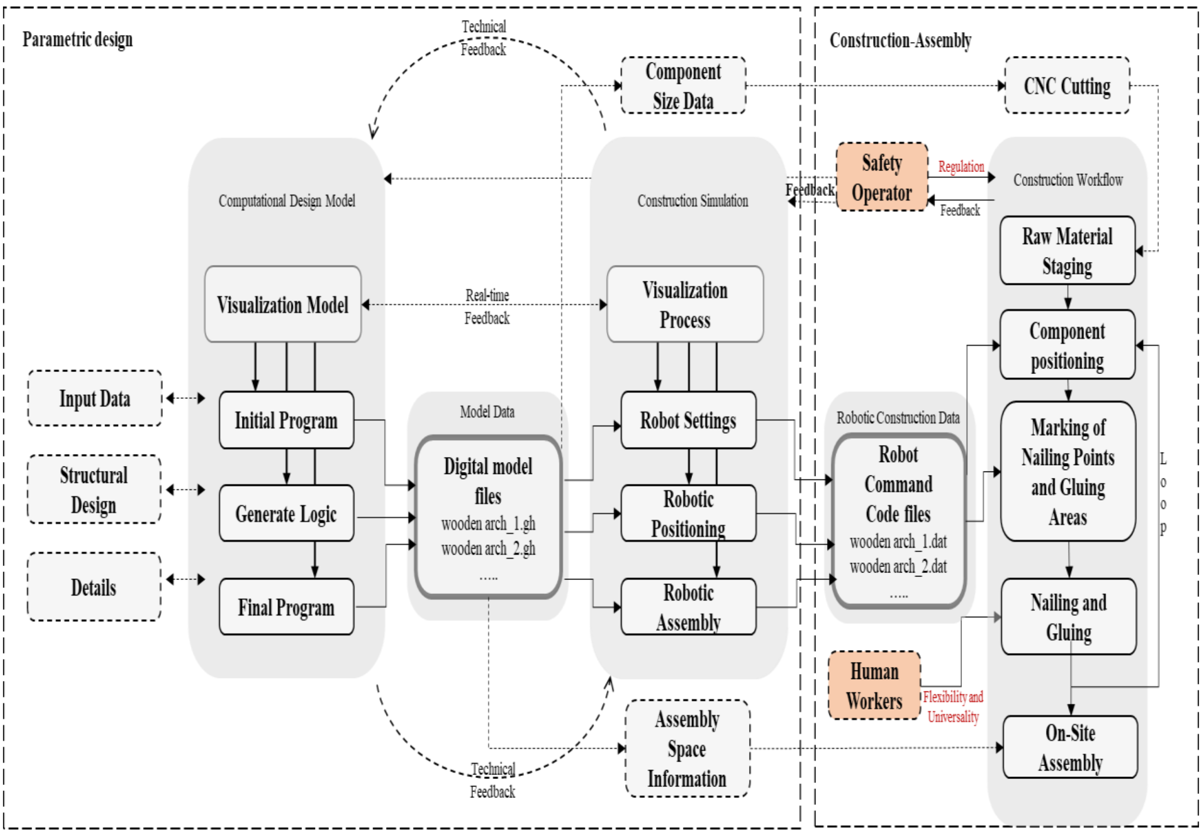


Fig. 6-2 HRITC workflow.

6.2.4. Feedback Strategies

Each step of the construction process is not independent; they are interrelated and affect each other. Establishing an appropriate feedback strategy allows the construction to be completed safely and efficiently. In order to coordinate the joint work between the various steps of the project, different feedback strategies were adopted throughout the various phases of the project:

Design models and construction simulations are generated visually within the computer. The initial design of the project geometry and the design of the robot's construction actions can be tightly linked digitally based on key geometric parameters[4](timber size, intersection area, and the number of nails). The structural generation design of the wooden arch directly incorporates feedback from the construction simulation, allowing design solutions to be proposed in mechanical form space.

While numerical feedback is a practical design method, it is frequently ineffective in extending the design solution to excessive levels for the parameters in real projects. There appear to be multiple additional parameters that directly impact the construction steps and resulting geometric design in the actual construction process. However, the computational implementation throughout the design process is almost unnecessary and can lead to double counting and increased design costs. Typically, these parameters are feedback prior to construction and are effectively addressed in discussions among all planners. The solution is integrated back into the design model only after a collective decision is found.

6.2.5. Simulation and code generation for robot fabrication

In the design model, the primary manufacturing parameters of the components are defined directly through computational feedback from structural design and construction simulations; this allows the basic spatial information of the components to be used directly for robot action code generation once the geometric dependencies of the build setup have been established. The model then establishes the basis for the simulation of the assembly process. These programs can be simulated in the Grasshopper-based KUKA|plc simulation environment, and the robot movements adjusted according to the simulation results allow the direct generation of robot command codes. These scripts are programmed in Grasshopper. The design and manufacturing parameters can be coordinated and orchestrated in the same platform, allowing increased uniformity throughout the project and contributing to the organizational flexibility of the construction process.

6.3. Project Implementation

6.3.1. Construction flow

This section summarizes the entire construction process is grouped into three main steps. Position placement, glue application, and nailing[5]. These three steps were optimized, and robots were used to participate in the construction process (Figure 6-3). Limited by the working range of the robot, we divided the overall structure into several appropriately sized construction groups and used robot-assisted manual construction for each group, and then combined them into the overall structure.

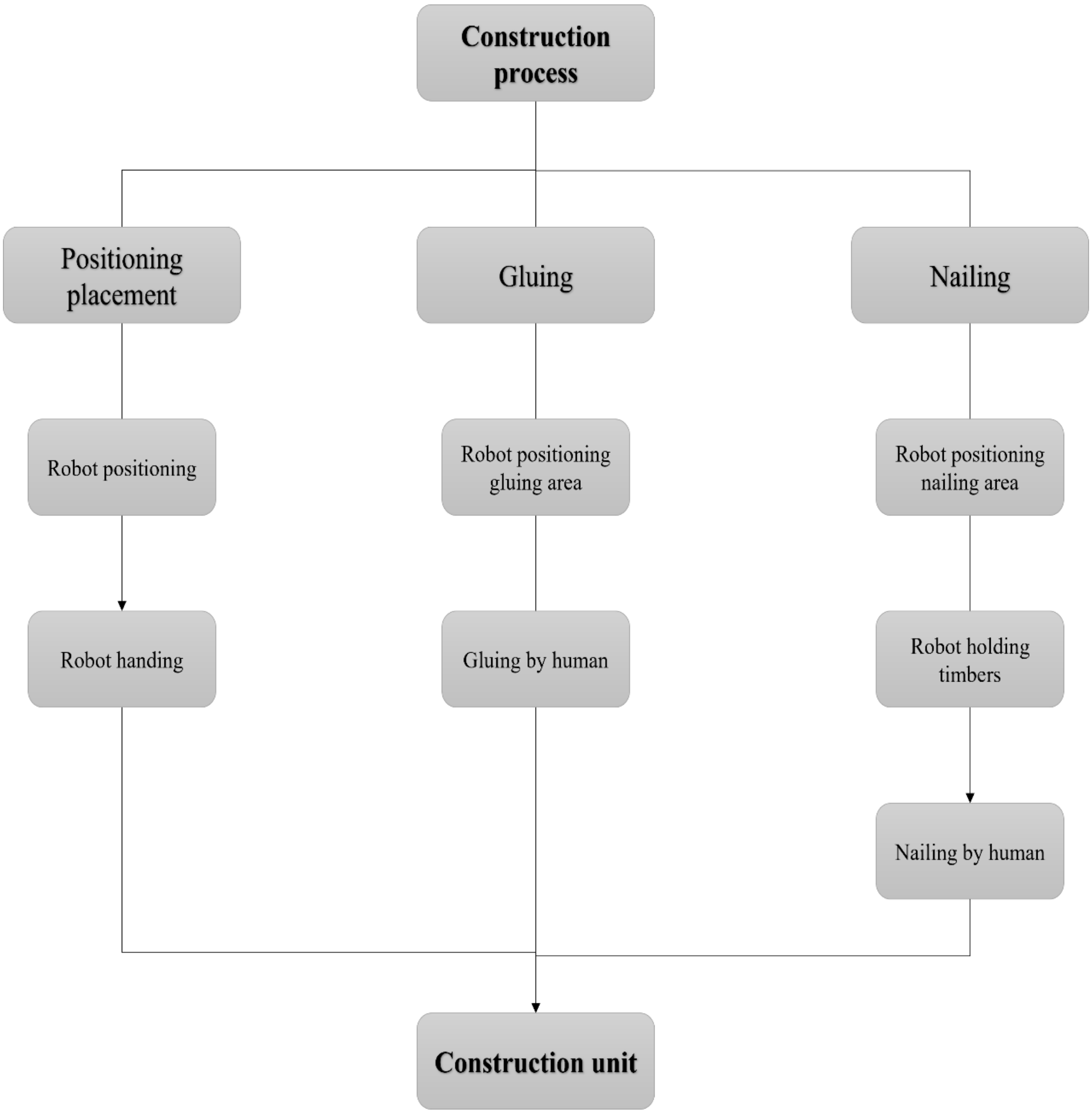


Fig. 6-3 Customized Tools.

6.3.2. Robot setup

A 6-axis KUKA kr30/60/H.A. robot was applied in this experiment. The robot operates at a speed of 2 m/s, with a vertical range of motion of +35° to -135° and an extensive bi-directional turning range of 185˚.

1) Tool setting

In order to optimize the construction process, three tools were customized to suit the construction needs. These tools are mounted on a joint base for quick positioning. These tools include (Figure 6-4):

- A customized pneumatic suction sucker for gripping wood with a maximum payload of 8kg.
- A customized laser emitter for locating the nailing point and glue area of each piece of wood.
- A customized pneumatic suction gripper for fixing the wood allows the workers to finish the glue and nailing.

A pneumatic calibration table was set up next to the reclaimer to recalibrate the position as each piece of wood was processed. Toolheads specially tailored to the suggested build features of the simulation build can be adapted to subsequent constructs. All tools are integrated on a platform based on the same operational axes, allowing construction without changing the primary coordinates of the tool head, improving the efficiency of constructs.

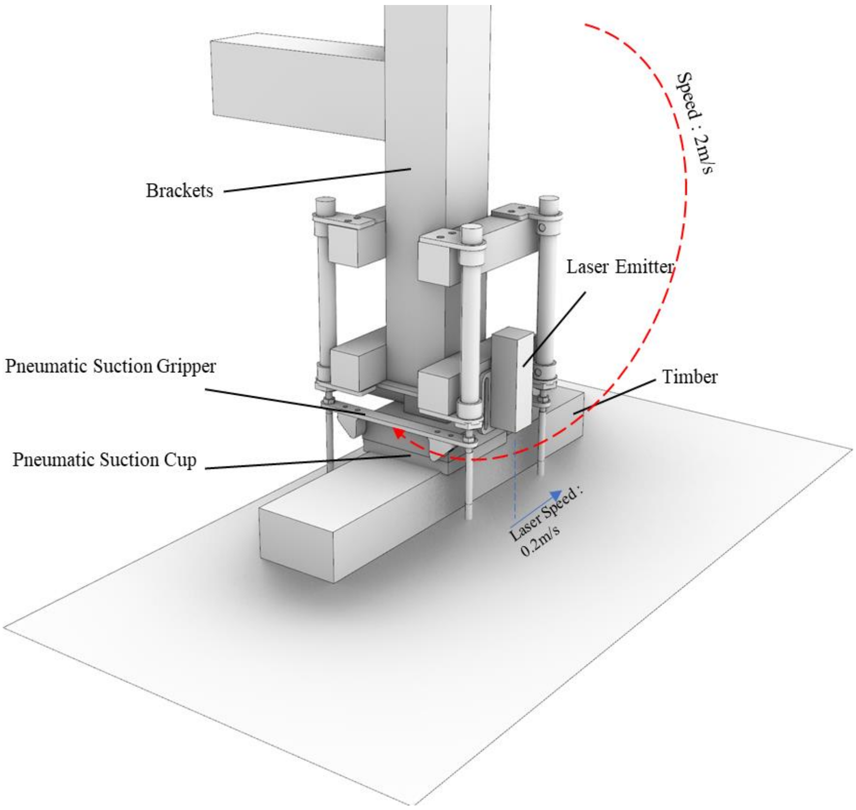


Fig. 6-4 Customized Tools.

2) The Robot Work Area

The work area measures 2.35 meters wide by 2.5 meters long and by 3.56 meters tall, dictating the maximum construction area of the robot. The area is arranged in a fan pattern with two parts, the first part for material storage and the other part for construction. Each part is linked with the safety control system of the robot and activates an emergency stop if a limit or error occurs during robot operation to tackle the uncertain impact of the complex construction site interaction environment and unsafe factors. A safety operator is configured with the smart-pad during each construction operation for joint operation with remote control with supreme control is on the construction site to ensure that construction is carried out safely (Figure 6-5). If an emergency occurs, the machine can be manually stopped. Next to the material stacking area, a positioning rack is placed in a suitable location allowing repositioning of each piece of wood to ensure that their center coordinates are accurate.

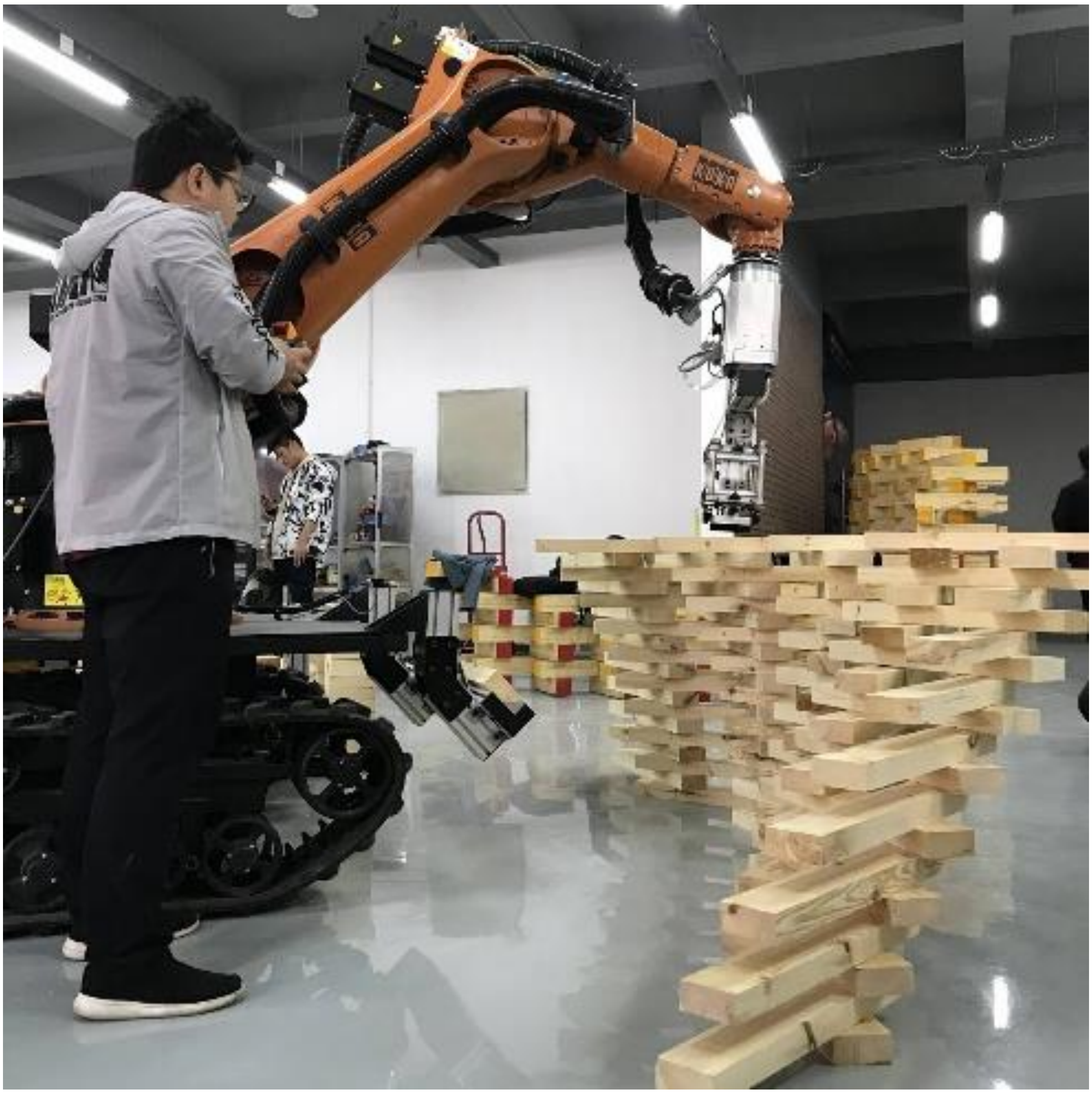


Fig. 6-5 Safety Operator.

3) Calibration and speed setting

Each tool is carefully measured and calibrated for optimal performance to take advantage of the high accuracy of the robot. The integrated tool's TCP (tool center point) is measured with an accuracy of 0.01mm-0.05mm. The suction cups have undergone a series of optimizations to grip the vacuum pressure and crawl speed to the expected values. Regarding the laser, the distance to the wood surface was adjusted to 5 mm, which is the optimal focal distance to mark the nail point and glue range to the burning wood surface. The laser was processed at a speed of 0.2 m/s, providing a clear mark (Figure 6-6).

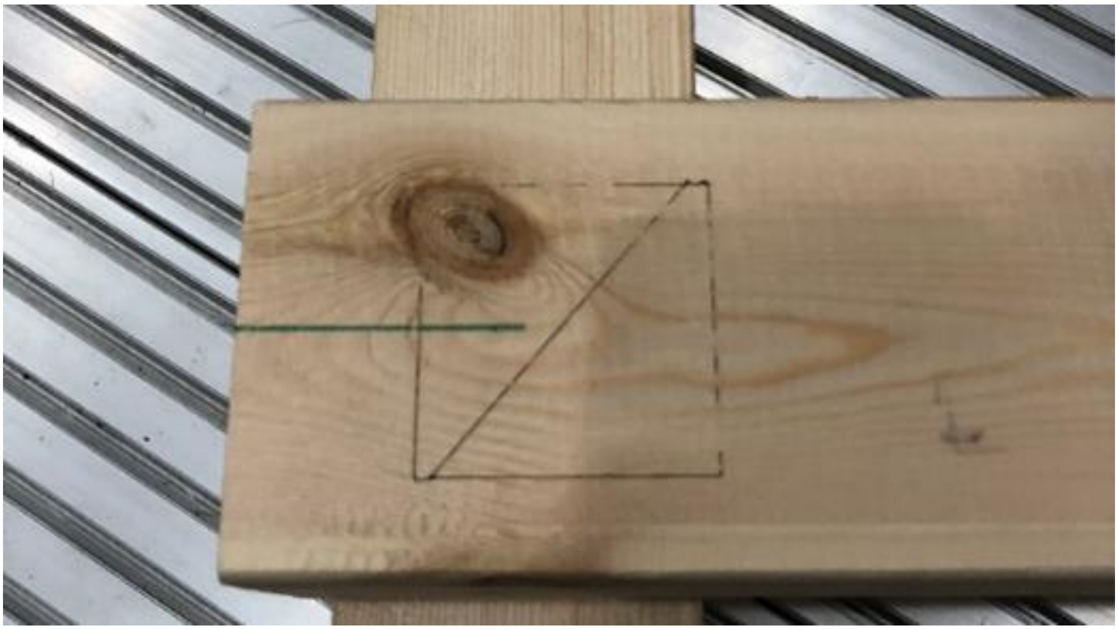


Fig. 6-6 Laser Mark.

6.3.3. Program design

Considering that the complex interactions between robots and their surroundings are difficult to simulate and predict, the overly complex geometric dimensions of the components can lead to the accumulation of tolerances or the emergence of unsafe factors (e.g., unforeseen collisions during simulation). The authors found that using an additive manufacturing technique similar to 3d printing[6] allows the 3-dimensional construction environment to be transformed into two dimensions without compromising the final product's visual effect and structural strength. The basic logic was designed on this basis, and the design task was given to the academics involved in the construction for teaching purposes. The most suitable one was chosen and the best visual effect among the many designs. A 4-sided symmetrical wooden arch was explored within the booth's 5*5 meters area at the exhibition hall, with the basic theme of two sets of symmetrical construction units. Grasshopper was used to divide those four units into eight construction teams and divide the surfaces into the center plane of timber, modeled in Rhinoceros 3d into its elements and generate.

Considering the wingspan of the robot and the practical use of the structure, it was decided to set the plane size of a building unit to 2m*2m.(Figure 6-7). According to the principle of the hanging method two corners of the base surface are fixed first as anchor points, and the remaining two points are lifted upward to simulate the change of gravity[7], so that the overall model becomes a well-stressed arch. At this point the resulting arch is a centrosymmetric model, so it can be mirrored arbitrarily, copied symmetrically, and combined randomly to obtain different modeling combinations. Theoretically, all the basic units can be built with only one construction procedure, but a variety of different design combinations can be accomplished (Figure 6-8). In this chapter, only two sets of basic units and two mirror units are used to complete the target arch structure. Since the design surface, the UV structure lines of the base surface are extracted, the u is segmented according to the length of the fixed wooden strip, and then the adjacent line segments are misaligned to the v-side with the width of the fixed wooden strip. Then, the two-line segments are rotated by a certain angle in the opposite direction. Finally, a wooden bar is generated based on the line segments (Figure 6-9). Also, the above logic is programmed with grasshoppers and all parameters can be controlled in real time (Figure 6-10), so there is a high degree of freedom in optimization and building material selection.

Concepet generating

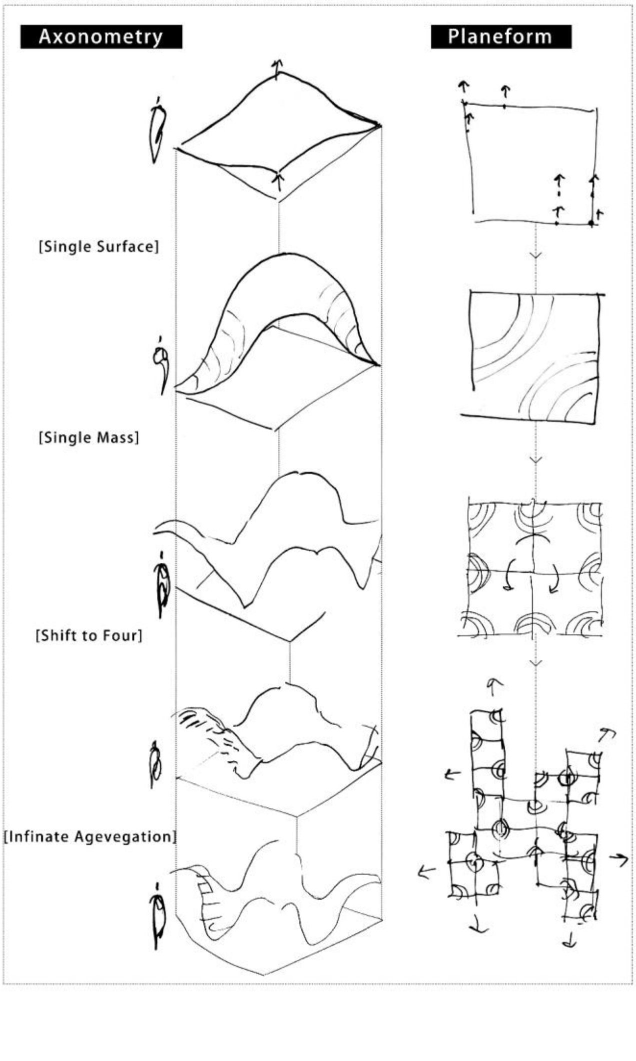


Fig. 6-7 Concept generation.

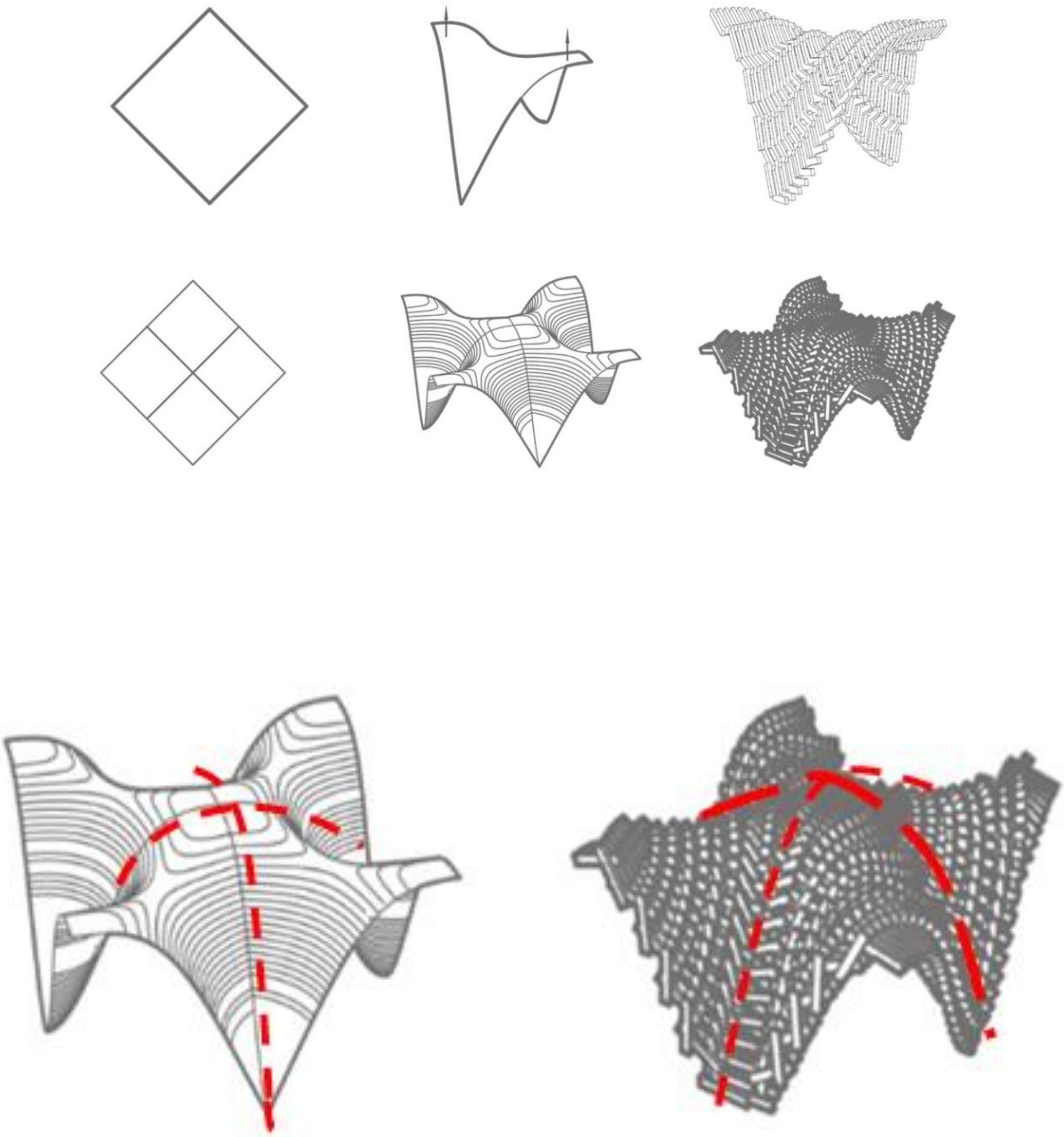
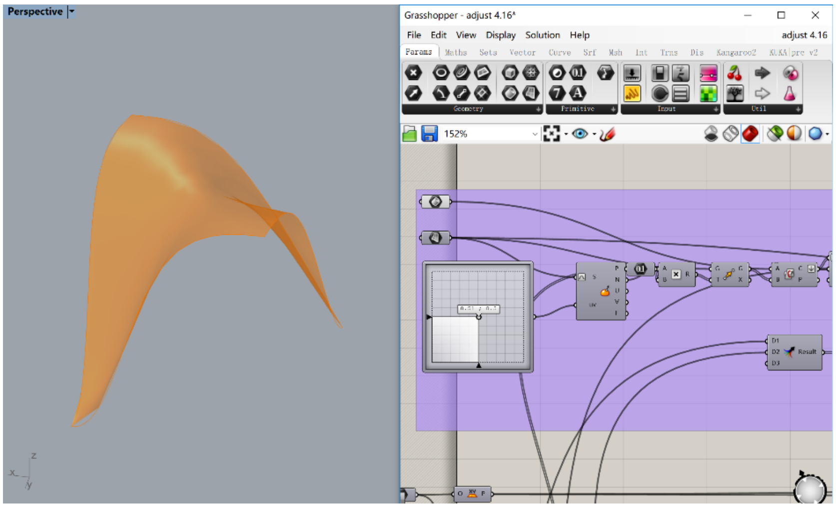
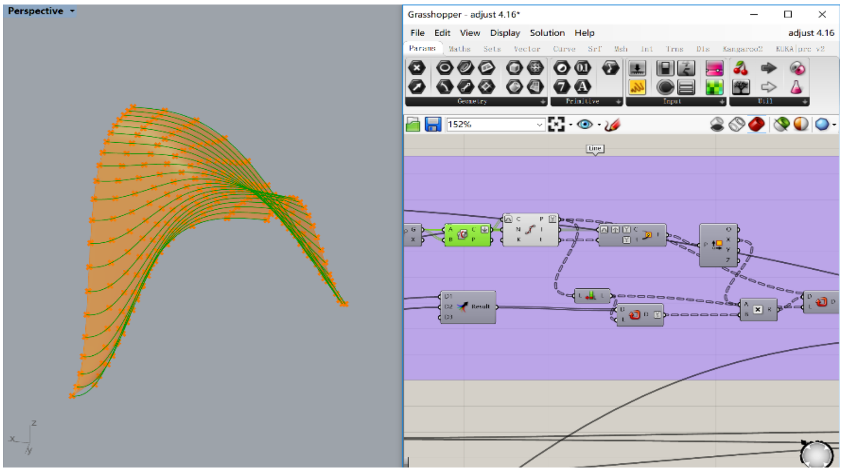


Fig 6-8 Model of the design.


Perspective
Grasshopper - adjust 4.16*
File Edit View Display Solution Help
adjust 4.16
152%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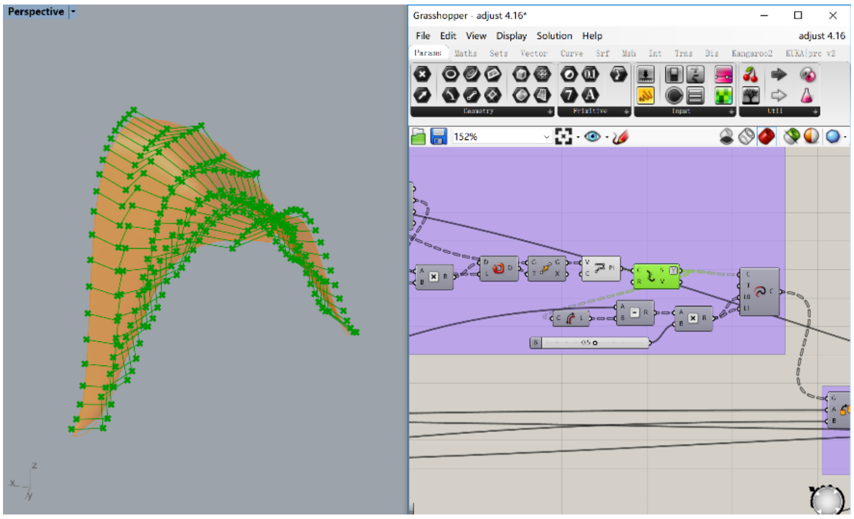
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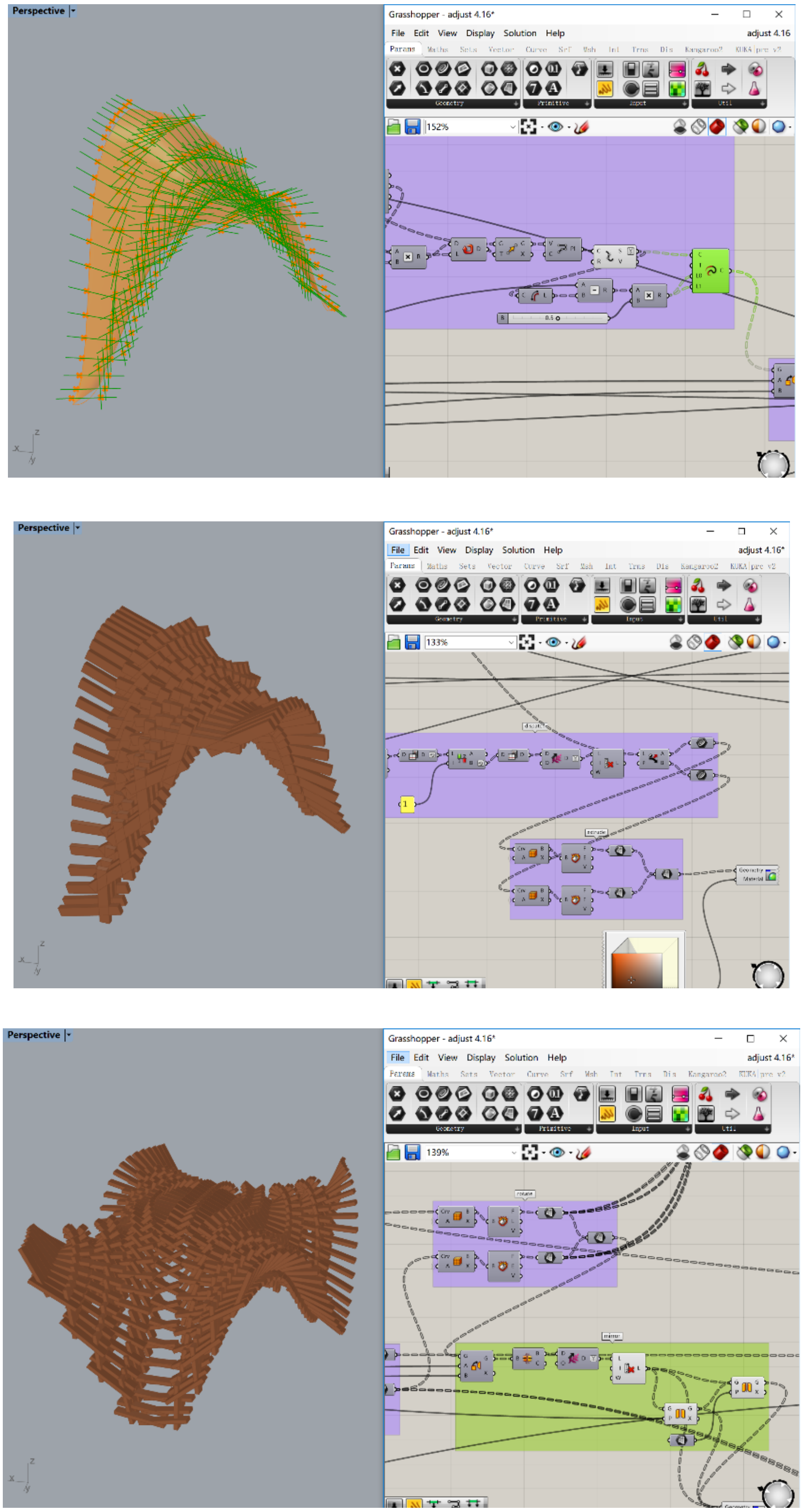


Fig 6-9 Timbers generation

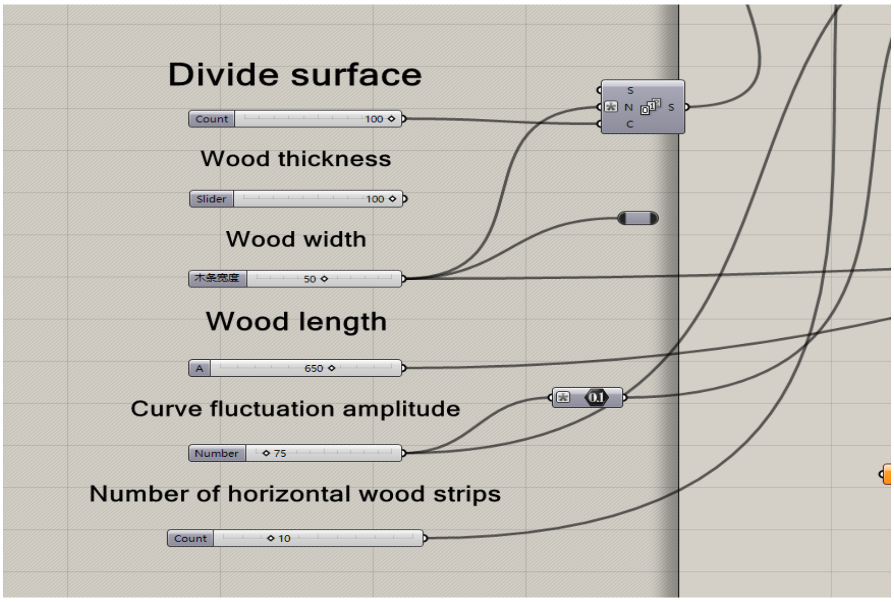


Fig 6-10 Model control parameters in Grasshopper

The SNGT model was used to join them. The digital model's positioning of nail points and gluing ranges was done automatically using Grasshopper's custom script. The nail points and gluing areas are mapped to the woodblock connections in point coordinates. The main parameters of the partition surface geometry script are used to adjust the position of the nail points and the size of the gluing area:

- Timber Thickness
- Timber Length
- Timber Width
- Timber Rotation Angle

Using the custom script for Grasshopper, surfaces of the construction team are divided into polyline contours, every timber thickness along the y axis. Polylines are divided into lines based on timber length. Rectangular profiles are extruded along the resulting linear according to the timber width and length. Using KUKA|plc plugin for Grasshopper, provide input data by design output subsequently by the assembly. These input data include:

- Timber Thickness
- Timber Center Plane
- Timber Center Lines
- Nailing Points Plane

- Gluing Area Line
- Press Points Plane

Rotate the whole structure 90 degrees along the y-axis as the construction form—timber geometry organized by construction order.

Using the Grasshopper Gluing area script, the overlapping area of the two layers of timber is offset inward by 15mm to generate the glued area. Primary parameters of Grasshopper Nailing points script used to generate the nailing points planes:

- The Maximum Diameter of The Glue Range
- Nail Collision Radius
- Nail Length
- Glue Range Center Points

According to the experience of manual construction, unplanned nailing will cause the top and bottom nails to collide from time to time, which will not only affect the work efficiency but also the overall structural strength. Therefore, the robot is used to accurately locate the nail points to speed up the work efficiency and improve the overall strength of the structure. Similar to the process of locating the gluing range, the connection area was first extracted, a single layer was selected, and then the glued wireframe was divided into 30 points (Figure 6-11). From these, randomly select a point as the first pegging point, judge the distance between the remaining points, and select the one with the farthest distance as the second pegging point (Figure 6-12). Draw a circle with a radius of 5 cm on these two points and move these two circles to the upper and lower layers so that there is a Boolean difference between these two circles and the points in the upper and lower layers of the wireframe. Then the remaining points repeat the operation of the single layer to filter out the pinned points (Figure 6-13) After getting the pinned points also perform command insertion and matching grouping. (Figure 6-14).

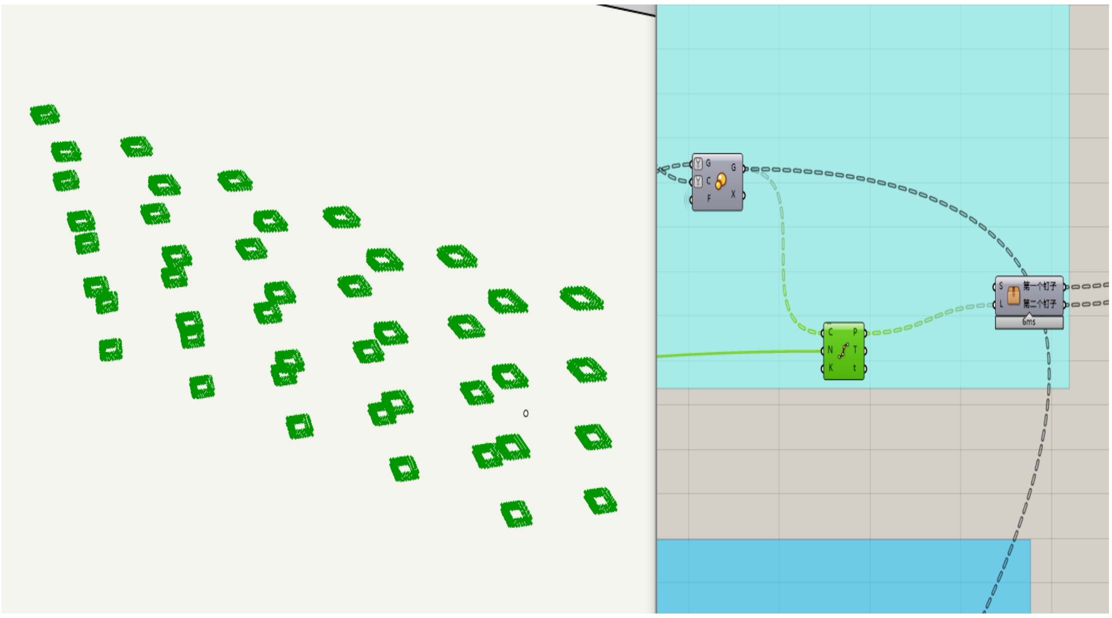


Fig. 6-11 Divide the glued wireframe into 30 points.

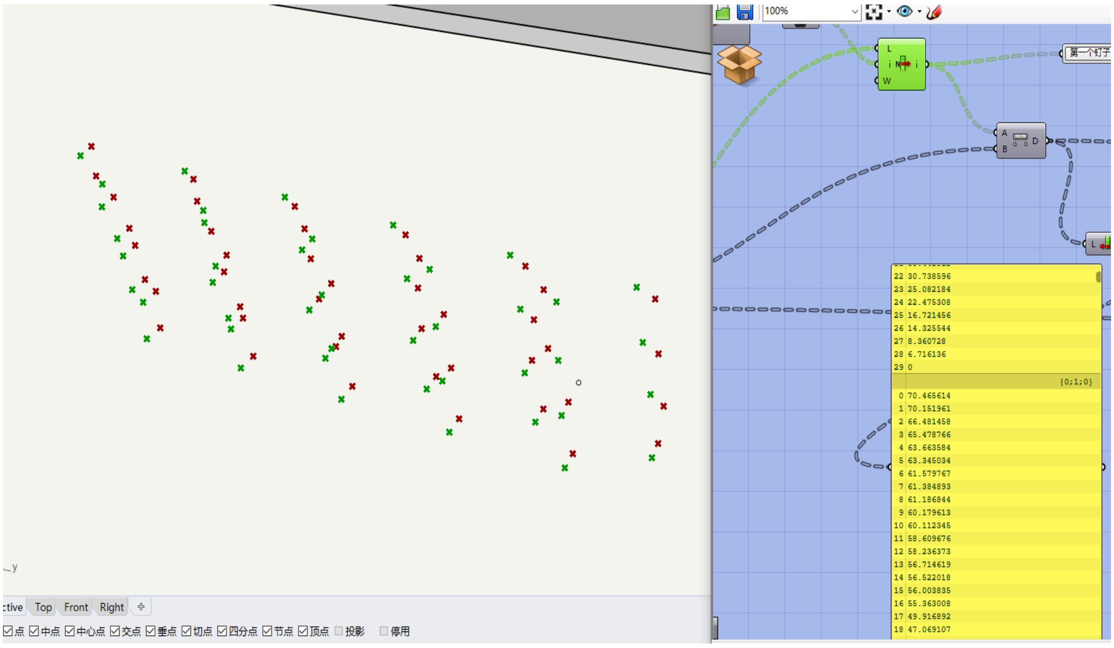


Fig 6-12 Select the optimal set point according to the distance value.

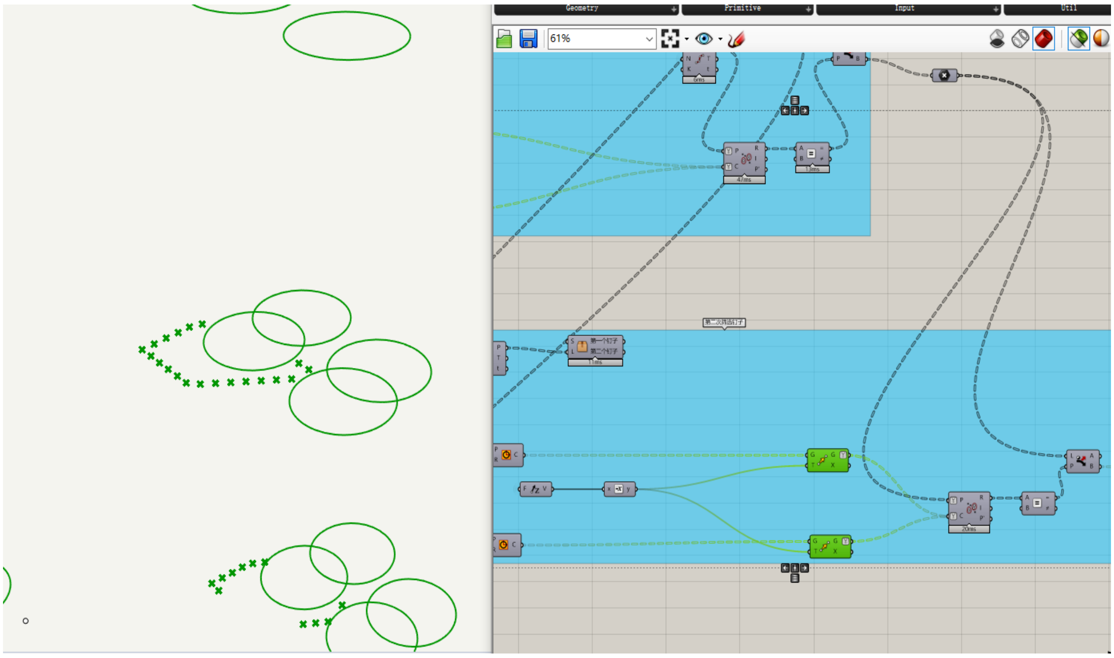


Fig 6-13 Filter even-numbered nails based on the collision range of a single layer of nails.

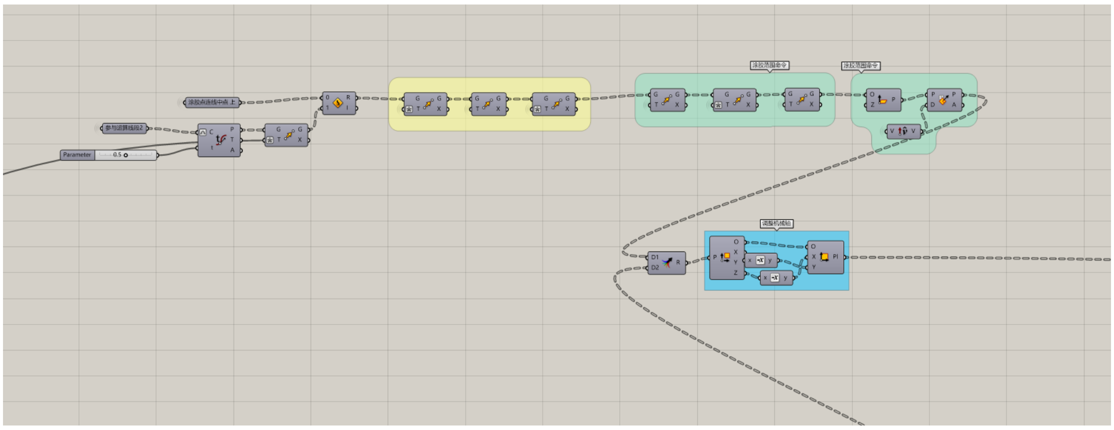


Fig 6-14 Nail grouping matches wood group.

Using the Grasshopper gluing area script, glue range is shown visible, adjusting timber length and rotation angle to optimize the glue area to a suitable size and a suitable shape (quadrilateral); four terminal points of glue range are identified for primary rail and laser emitter, moved by order of endpoints along the length from both endpoints. The wooden arch design is encapsulated in a computational model where the gluing area and the positioning of the nailing points are used to computationally generate a "blueprint" of the structure, based on a custom grasshopper script that integrates the original architectural design into Rhinoceros3D(Figure 6-15). The construction sequence is used as the gluing range. Two nail points are selected by the maximum distance of the gluing area minus the nail's top and bottom collision range (to avoid conflicts) and assigned to each main rail. All nails are assigned to the geometry and organized into nail points in construction order. The center points of the two gluing ranges on the same wood are assigned to each main rail as pressing points (to hold the wood for nailing and gluing).

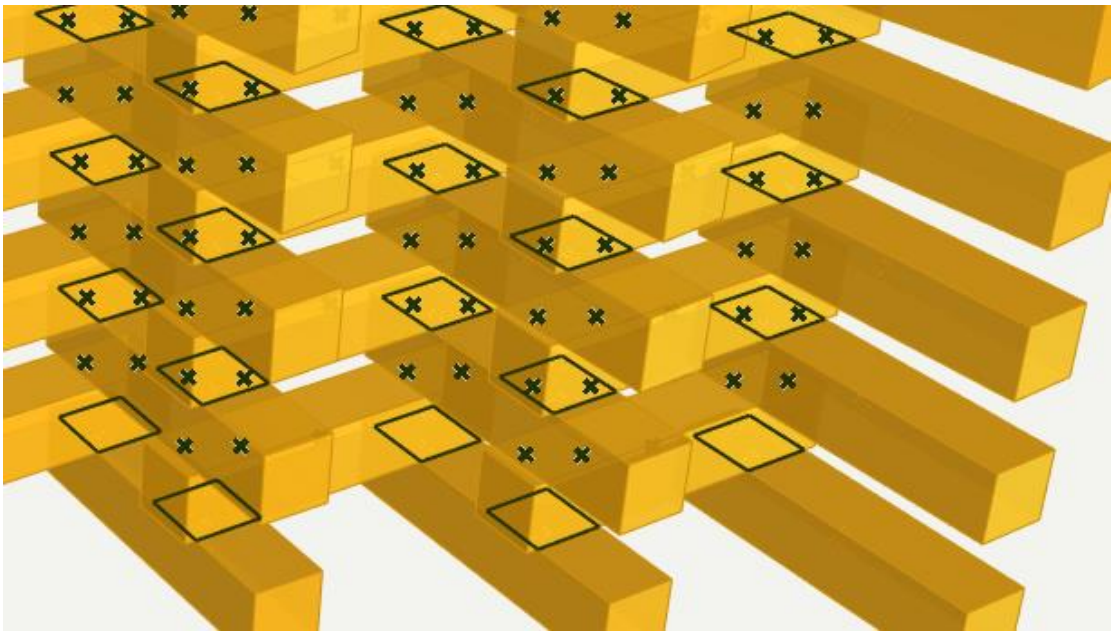


Fig. 6-15 Visualization of the spatial information of nailing and gluing areas in Rhinoceros3DArtificial involvement.

Although the HRITC process is automated, some manual processes are involved in manufacturing and post-processing. The complex internal structure of the logs and the uncertain torques generated by the nailing process makes it difficult to automate the nailing process. However, such work requiring flexibility is straightforward for humans. 840 logs, measuring 50*100*650 mm, were supplied from the lumber yard and stacked on site. Unskilled workers nailed 3115 nails. Since the robot marked out the nail locations and glue ranges, nailing and gluing were very easy, and unskilled workers needed only simple training to complete the job.

6.3.4. Structural optimization

In order to ensure the final construction results can have good strength and stability, but also to ensure the convenience of the construction process, the overall analysis and optimization. In this chapter, stress analysis and optimization are mainly performed, as well as analysis and optimization of joint contact surfaces.

Stress analysis and optimization: The generated model is analyzed using the force analysis plug-in in grasshopper, and the load map can be identified by color. The more blue the color, the lower the mechanical utilization rate[8], and the more reddish the area is, the higher the utilization rate is(Figure 6-16).

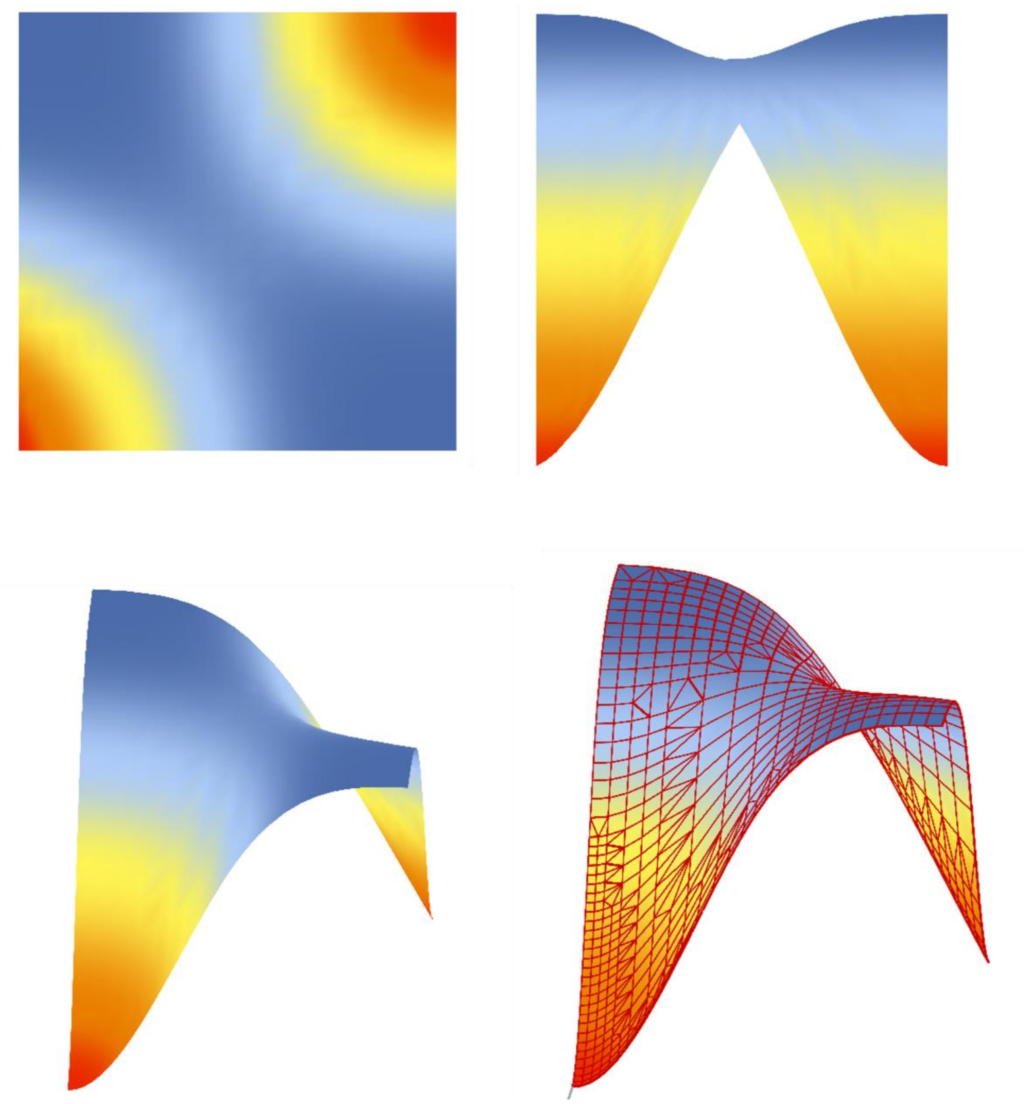


Fig. 6-16 Stress analysis.

The highest part of the forces on each group of building units can be seen to be in the triangular part in contact with the ground. Therefore, the higher the perpendicularity of the timber in this area to the ground, the greater the vertical component of gravity in the overall structure and the smaller the horizontal component, and the more stable the overall structure. Therefore, the wood in the grounding section should be as vertical to the ground as possible without affecting the aesthetics and practicality. However, due to the limitation of the shape, the grounding area of the structure will inevitably be relatively small. To make the structure more stable, additional bases are required to stabilize the overall structure (Figure 6-17).

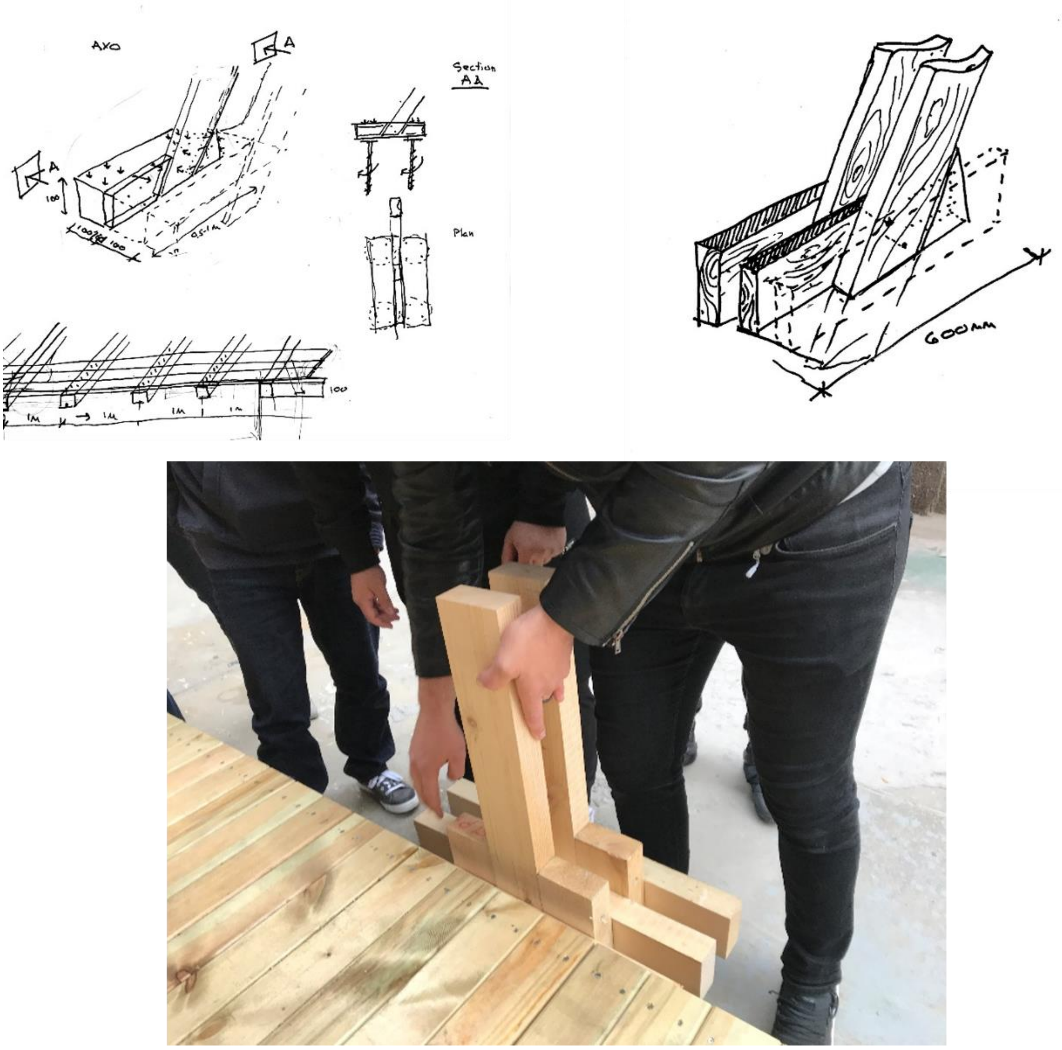


Fig. 6-17 Base bracket.

6.3.5. Connection contact surface optimization

The size of the contact surfaces will be very important since the overall structure is free of defects and all the weight depends on the glue and nails between the wood. First, the same method as in Chapter 3 is used to determine the intersection of each surface by finding the nearest point and finding the area of the intersection by Boolean operations, thus greatly reducing the amount of calculations and increasing the speed of computer operation (Figure 6-18). After obtaining the frame lines of the contact surfaces, the area of each contact surface can be further determined. By modifying a series of parameters previously set, the size of the contact surface can be changed, and the actual parameters are continuously modified to finally determine the optimal parameters, including wood selection, the number of subdivisions in the u-direction, and the intersection angle of two pieces of wood (Figure 6-19).

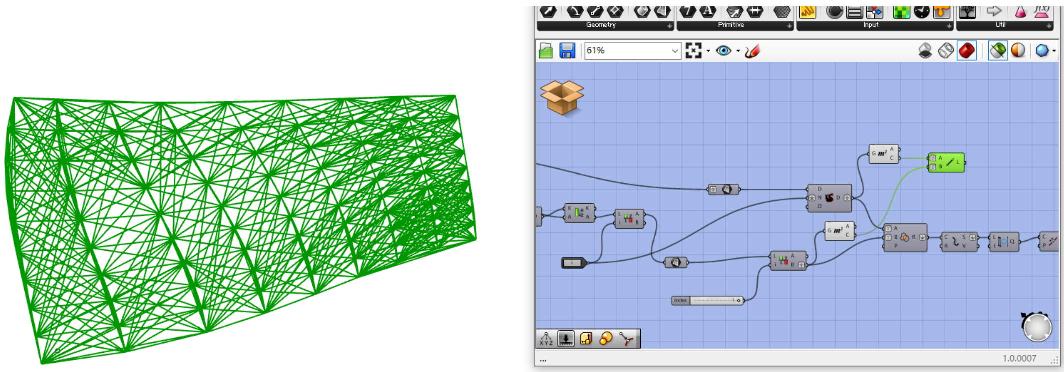


Fig. 6-18 Cross the nearest face to improve computer processing speed.

Fig. 6-19 Change parameter adjustment to optimize interface size.

6.3.6. Maximize construction efficiency

The biggest limitation of robotic construction is the construction sequence and size of the structure. This chapter uses some clever methods to simplify the extremely complex arches in space to facilitate the construction of building units. An attempt is made to complete a complex shape with a simple and effective construction method, while taking full advantage of the stability and accuracy of the robot to reduce the manual part to the most basic and error-free part. This minimizes manual deviations and improves the strength and appearance of the structure.

The final wooden arch consists of two basic units and two mirror elements. The spatial structure of each unit is too complex to be built by a robot, but if its Y and Z axes are swapped, the hybrid spatial structure can be turned into a simple superimposed structure (Figure 6-20). This will greatly facilitate the construction of robots. Theoretically, one cell can be built at a time to accomplish the highest strength and stability of the overall structure. It is not possible to build a set of 2 m * 2 m building units at a time due to the size limitation of the robot. In order to minimize the strength of the overall structure, the building units were divided only once (Figure 6-21). Then the coordinates of the centroid plane of each strip were extracted and sorted from bottom to top (Figure 6-22).

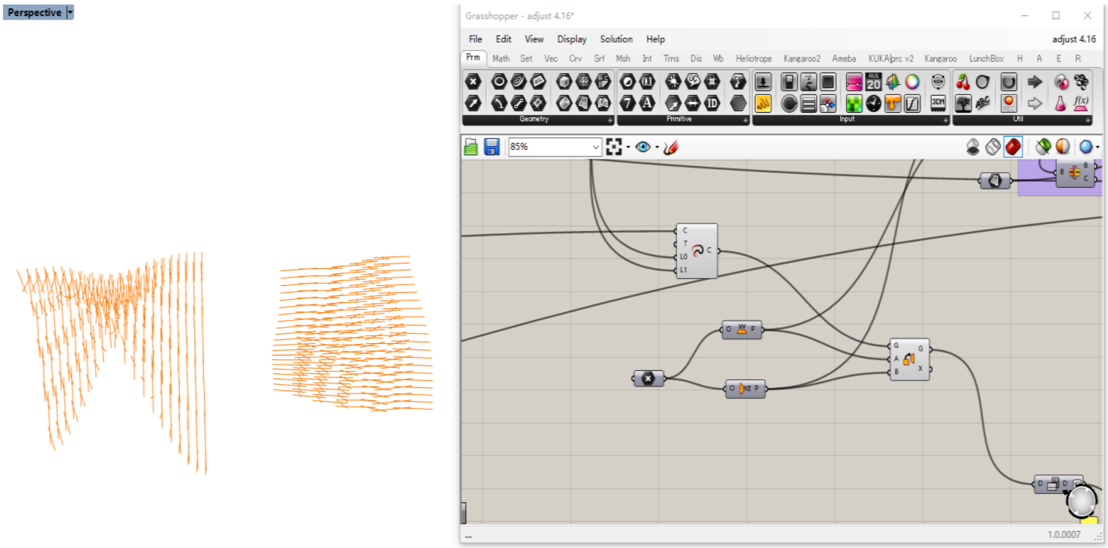


Fig. 6-20 Interchange Y, Z axis.

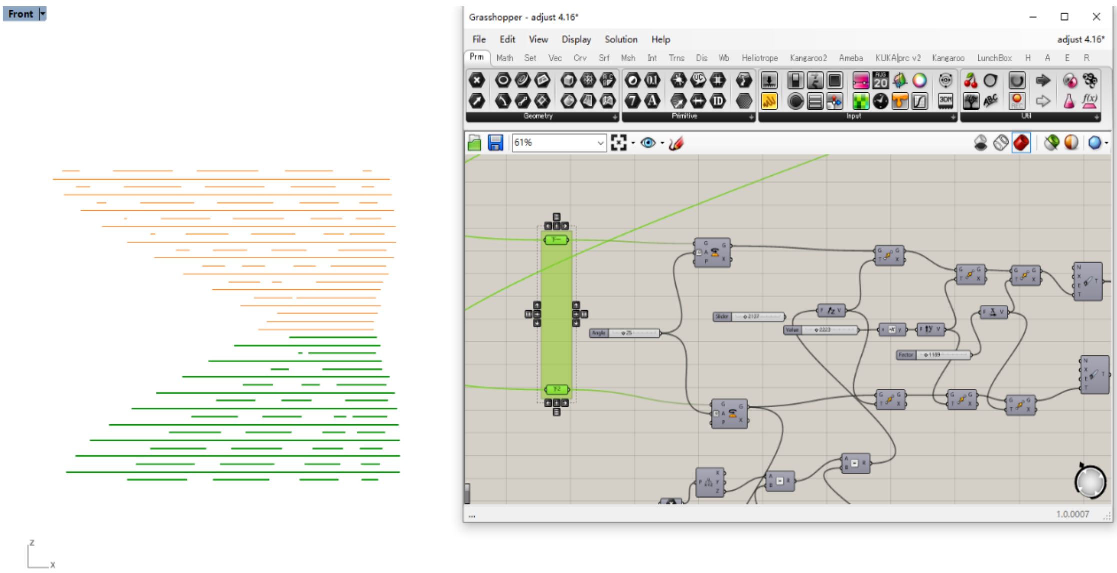


Fig. 6-21 Split one unit into two parts.

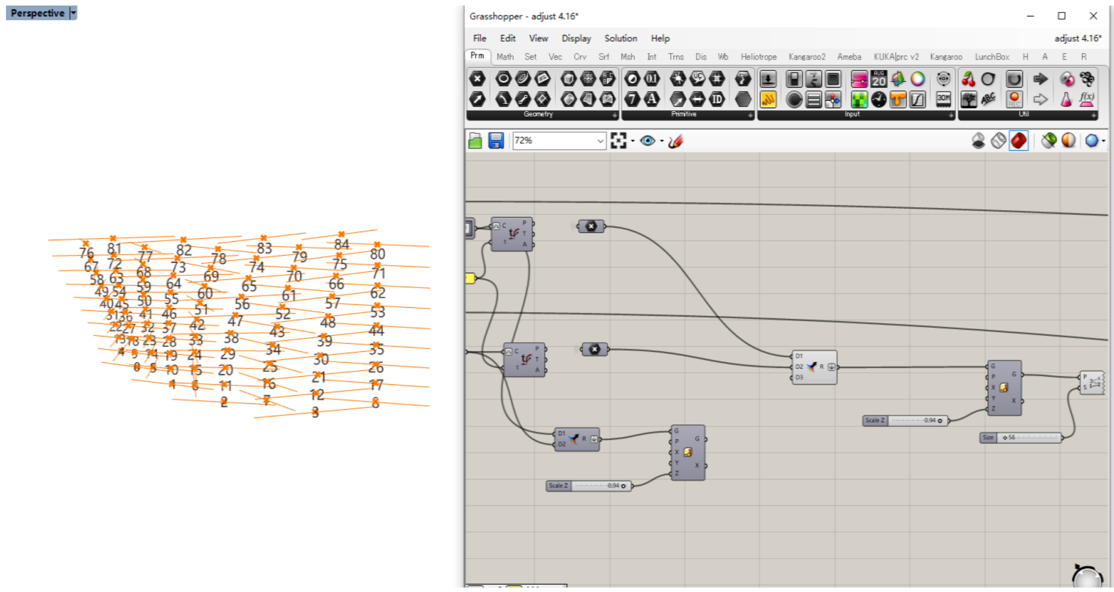


Fig. 6-22 Extract center points and sort.

Although the basic cell was built in two parts, the split size was still large. Its construction coordinates are only at a very extreme position relative to the robot, so that the robot can be used to complete the construction task without collision, and the fluctuation range of this coordinate position is only a few millimeters (Figure 6-23), which would take a lot of time and effort to adjust by hand, so a genetic algorithm is used, allowing the computer to perform thousands of calculations to finally find the optimal solution. Genetic algorithm is a stochastic search method that comes from the law of evolution in biology (survival of the fittest, the genetic mechanism of survival of the fittest). It was first proposed by Professor J. Holland in the United States in 1975. Its main features are the direct operation on structural objects, without the constraints of derivation and function continuity[9]; the inherent implicit parallelism and the better global optimization capabilities (Figure 6-24). Several parameters that affect the final construction trajectory, the x and y coordinates of the building unit, and the rotation angle of the entire xy plane, are used as inputs for the genetic algorithm to calculate the unit (Figure 6-25). To know if the final construction is feasible and if the robot has reached its limits, it is necessary to analyze and view the motion analysis of the robot's 6 axes (Figure 6-26). Where the corrugated lines of each color represent the rotation angle of the mechanical axis. Where the corrugated lines of each color represent the rotation angle of one mechanical axis. If the angle is too large, the robot has reached its limit. Also, you can observe the output value of REACHBILITY in the analysis output of the KUKA robot operator (Figure 4-67). Looking at the magnitude of this output value, you can tell how the robot is moving. The smaller this value is, the easier the robot will run and the less likely it will have limits (Figure 4-68). Therefore, this value is associated with the output of the genetic algorithm operator, which is used by the genetic algorithm to find the minimum value of the analyzed value. After a long automatic calculation, the optimal solutions for the X, Y values and angle values are obtained (Figure 4-69).

Then all the optimal solutions are selected and the one with the smoothest track is found as the final construction solution.

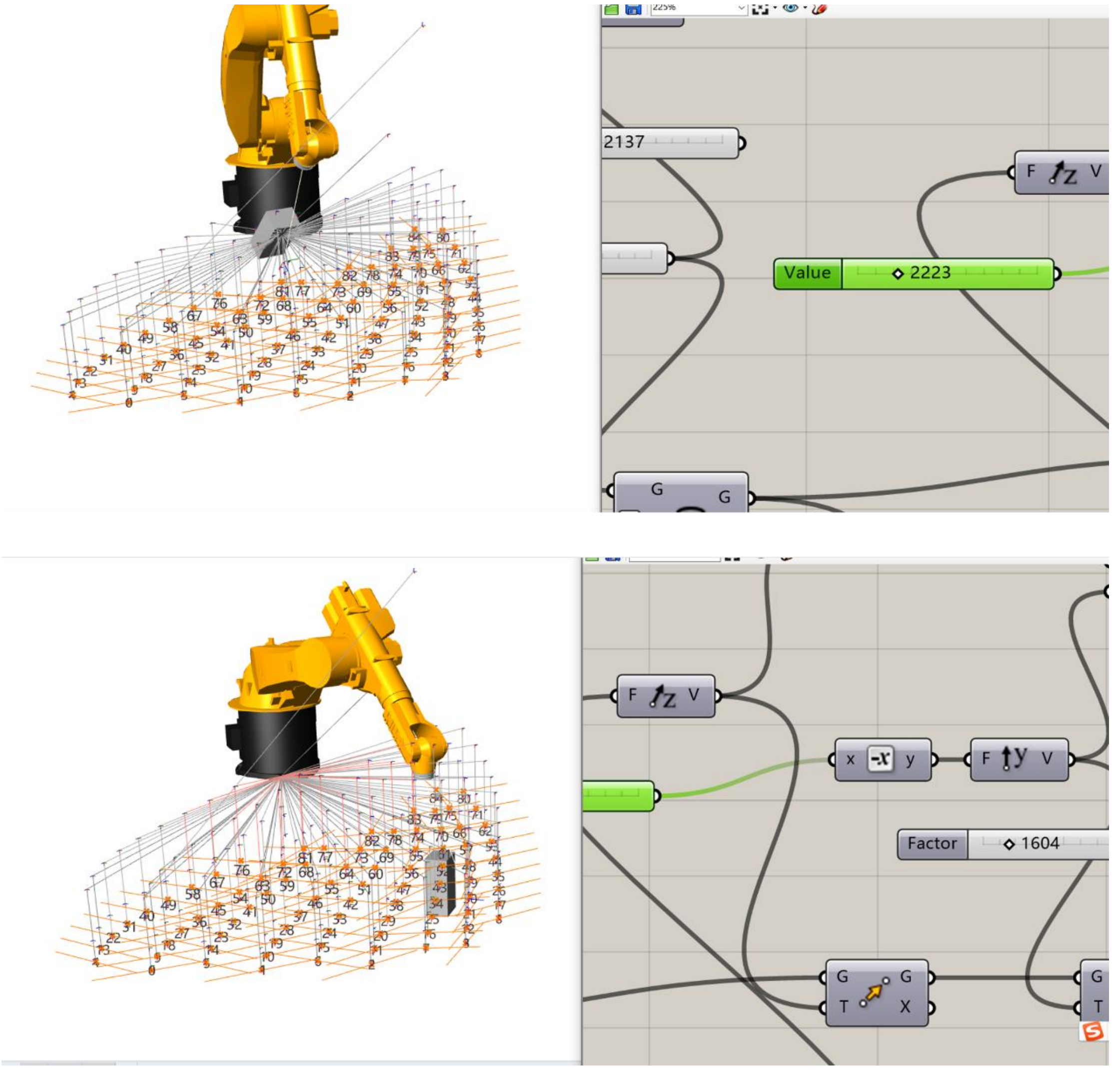


Fig. 6-23 The fluctuation range of this coordinate position is only a few millimeters.

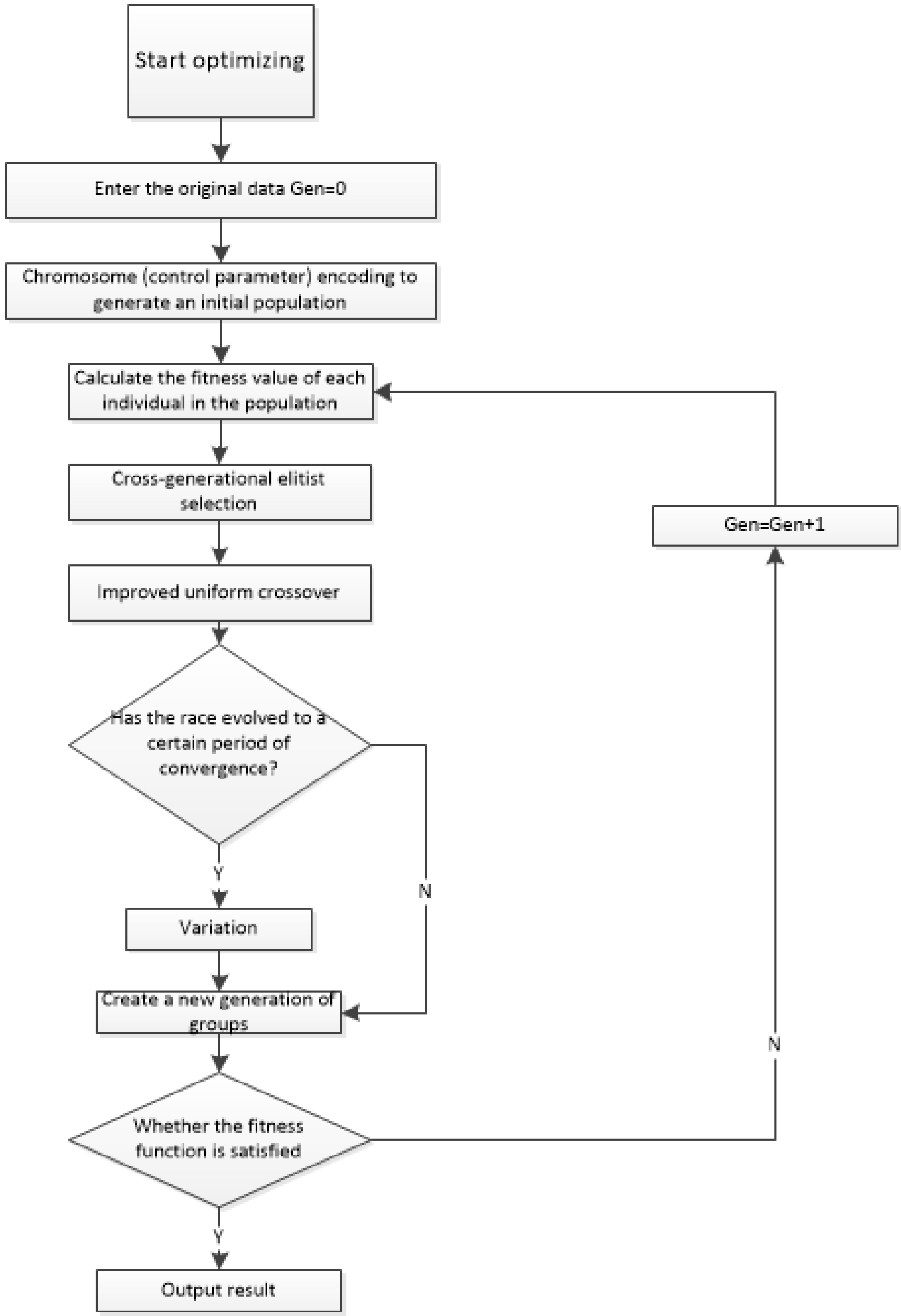


Fig. 6-24 Principle of genetic algorithm.

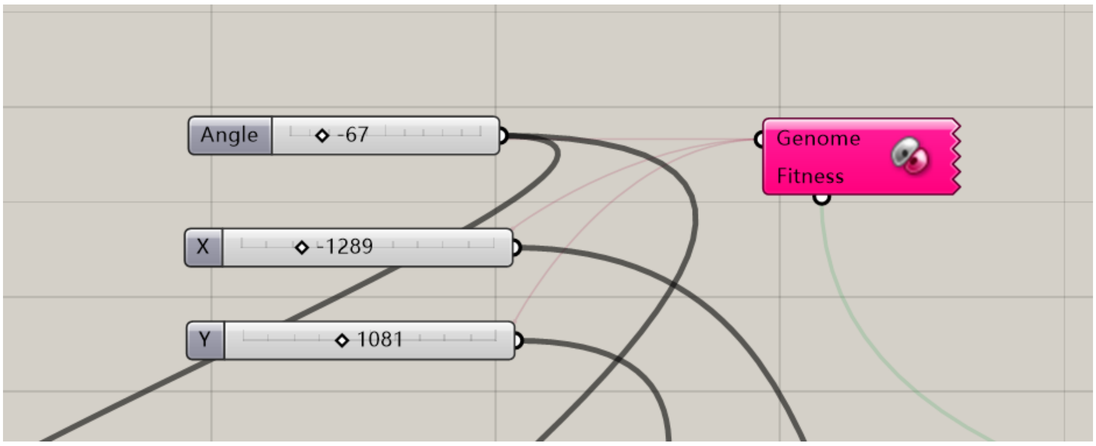


Fig. 6-25 Influencing parameters.

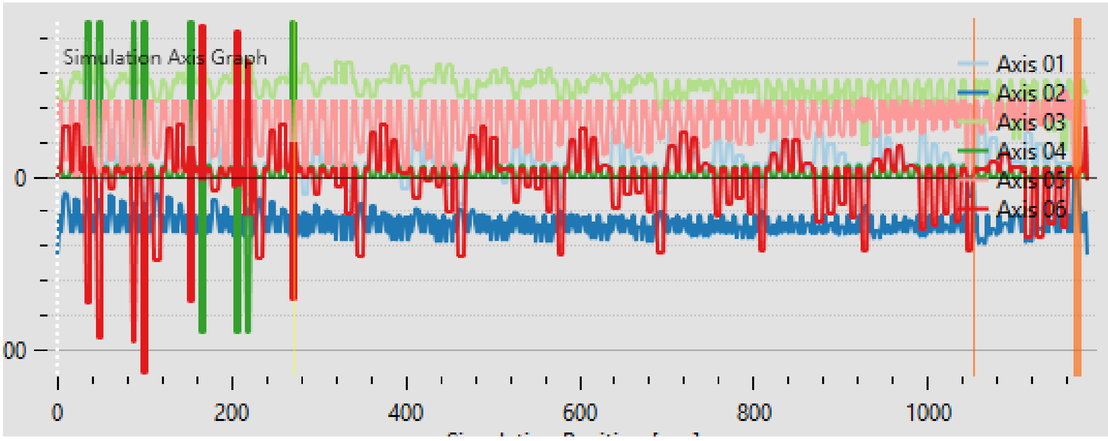


Fig. 6-26 Robot 6-axis analysis results.

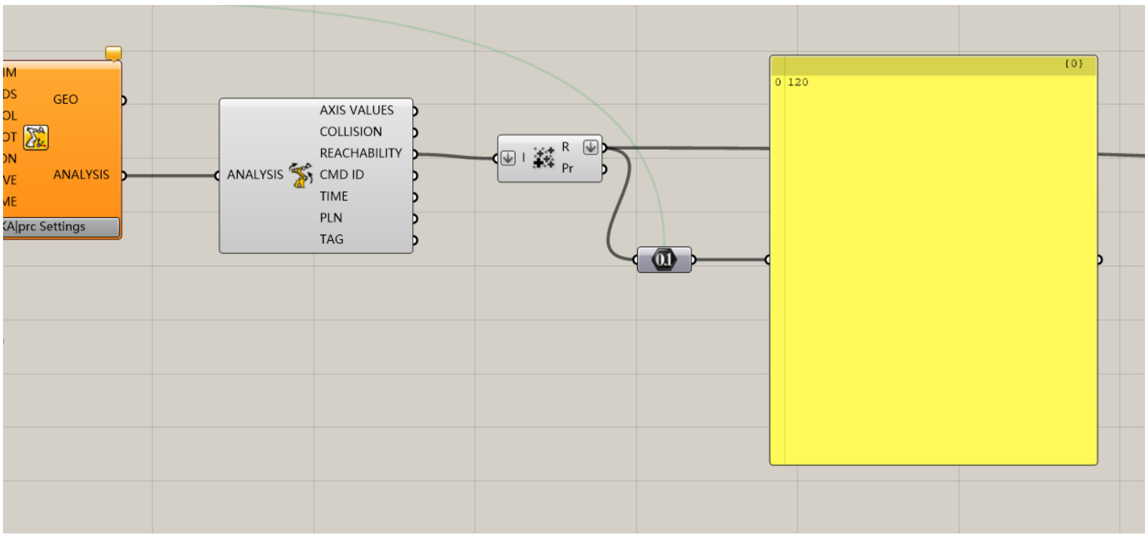


Fig. 6-27 Robot motion analysis output value.

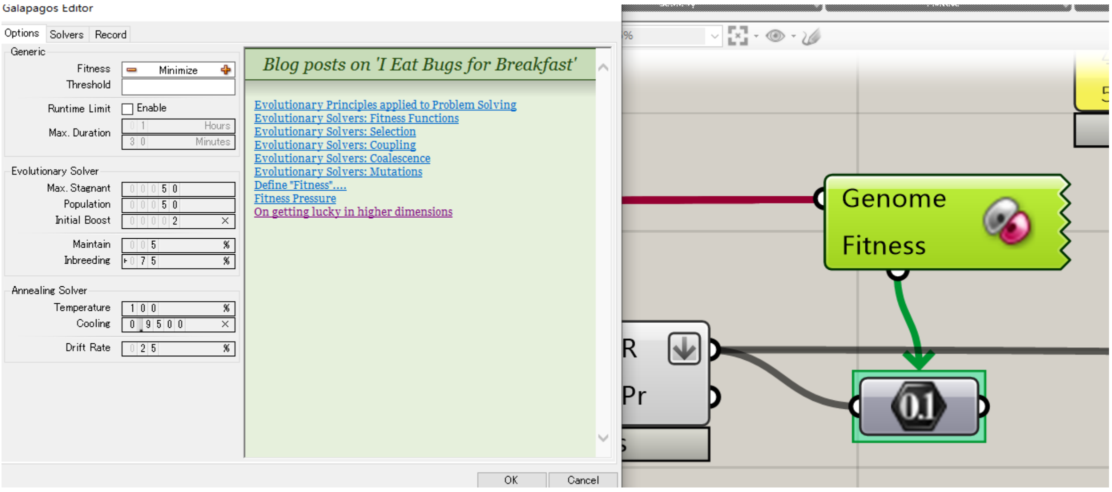


Fig. 6-28 Using genetic algorithms to find the minimum.

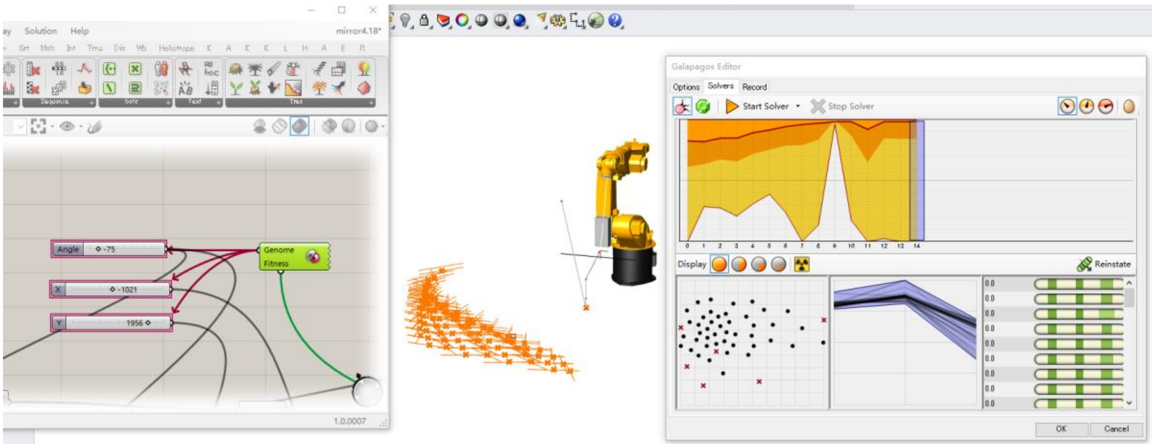
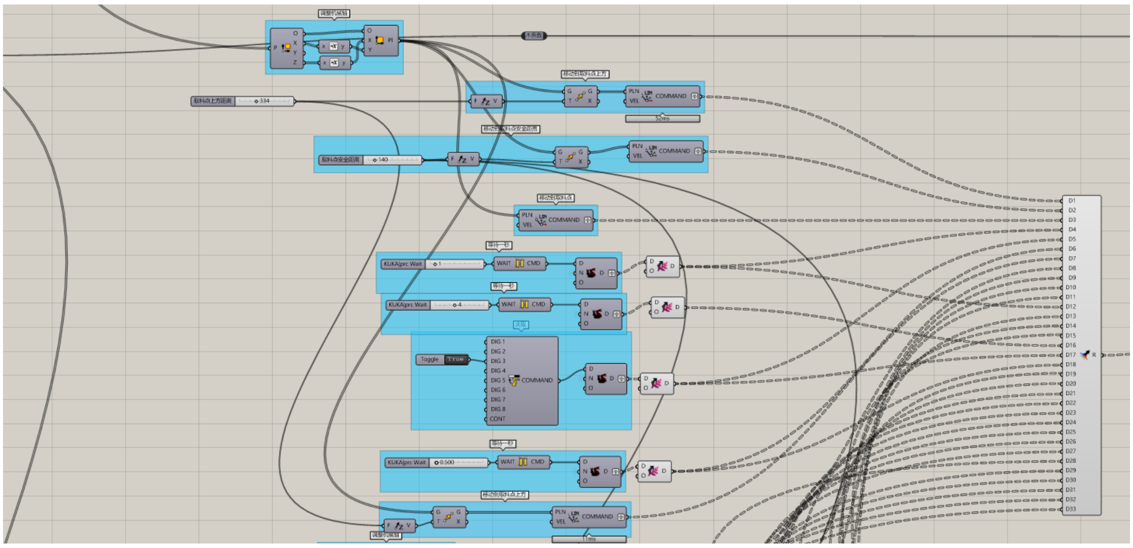
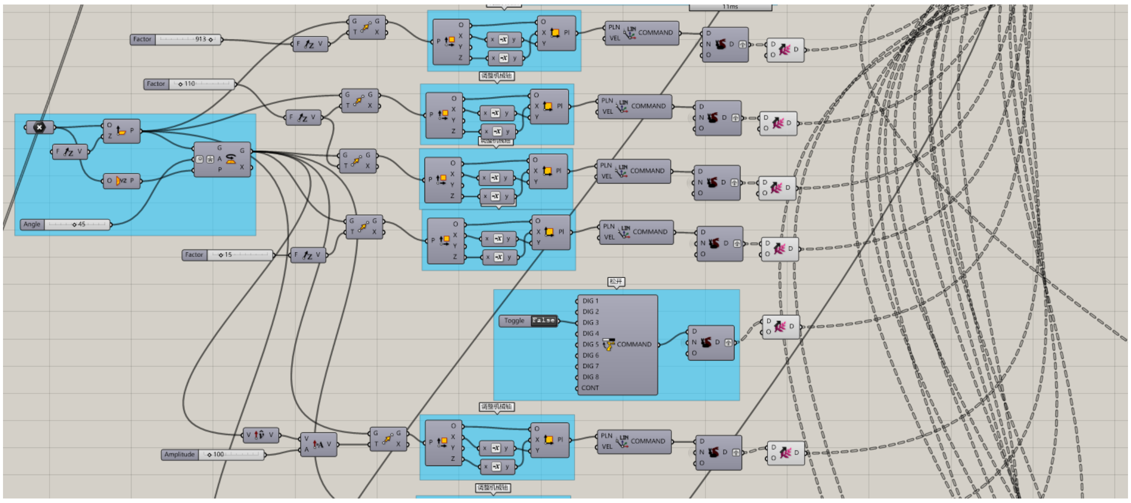


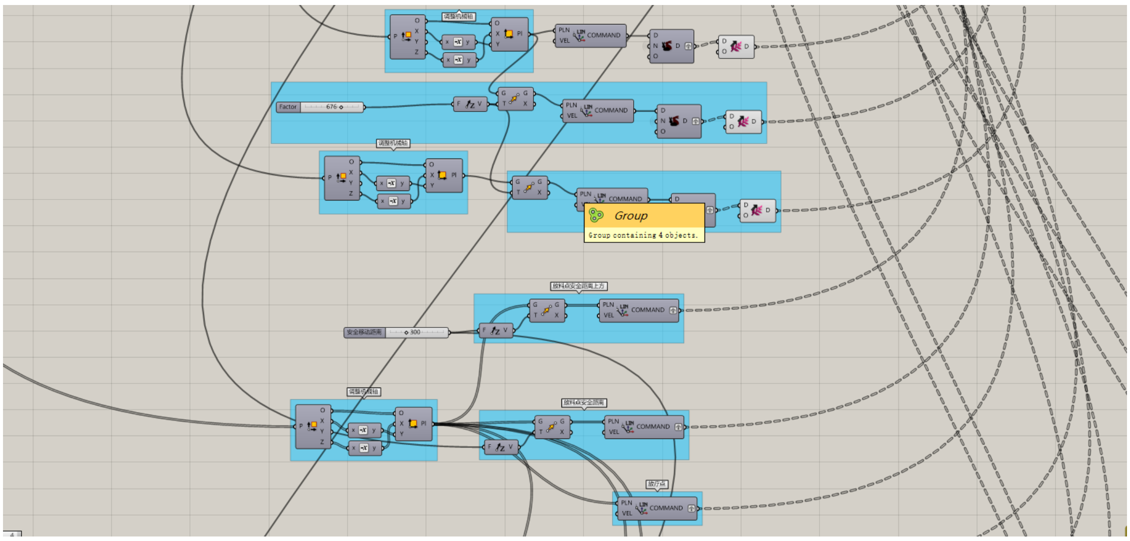
Fig. 6-29 Genetic algorithm to find the optimal solution.

6.3.7. Robot language converter

Upon completion of the positioning and grouping of the coating range and nail points, the center plane of each wood strip is extracted, and the coordinate information and spatial direction information of each point is extracted. Input these data into the conversion module of the written robot language (Figure 6-30) Convert the spatial coordinate information and robot things into robot language (Figure 6-31).






Group
Group containing 4 objects.

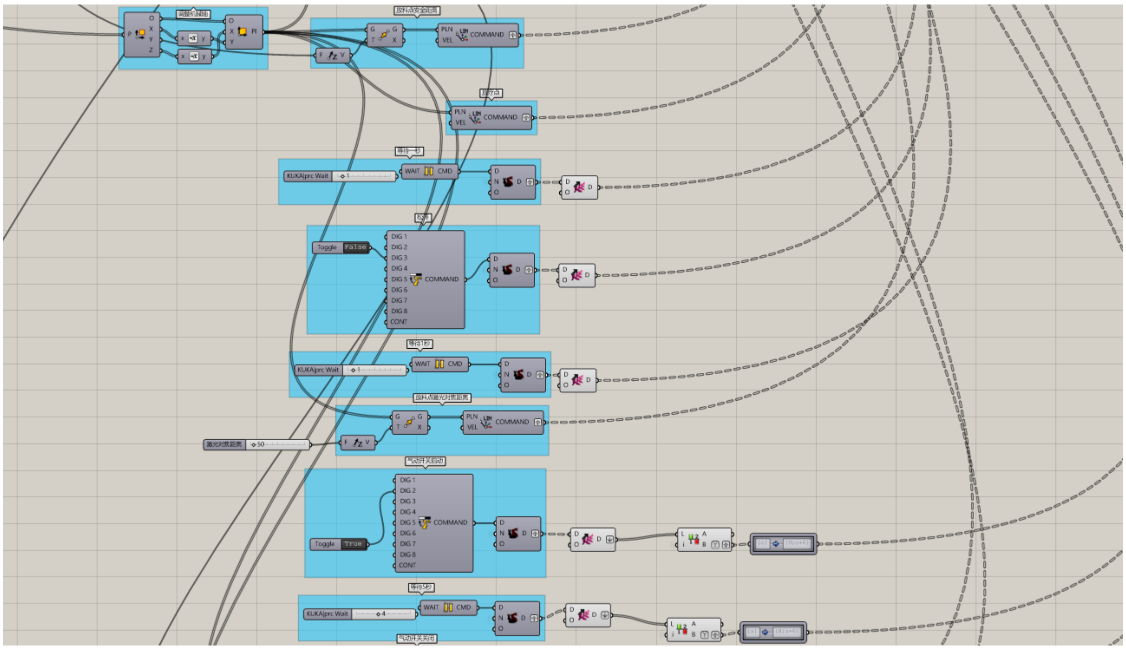


Fig. 6-30 Robot language conversion module.

```
&ACCESS RVP
&REL 1
&PARAM TEMPLATE = C:\KRC\Roboter\Template\vorgabe
&PARAM EDITMASK = *
DEF a1 ( )


;FOLD INI
;FOLD BASISTECH INI
GLOBAL INTERRUPT DECL 3 WHEN $STOPMESS==TRUE DO IR_STOPM ( )
INTERRUPT ON 3
BAS (#INITMOV,0 )
;ENDFOLD (BASISTECH INI)
;ENDFOLD (INI)

;FOLD STARTPOSITION - BASE IS 8, TOOL IS 9, SPEED IS 100%, POSITION IS A1 0,A2 -120,A3 120,A4 0,A5 0,A6 0,E1 3000,E2 0,E3 0,E4 0
$BWDSTART = FALSE
PDAT_ACT = {VEL 100,ACC 100,APO_DIST 100}
FDAT_ACT = {TOOL_NO 9,BASE_NO 8,IPO_FRAME #BASE}
BAS (#PTP_PARAMS,100)
PTP  {A1 0,A2 -120,A3 120,A4 0,A5 0,A6 0,E1 3000,E2 0,E3 0,E4 0}
;ENDFOLD

;FOLD LIN SPEED IS 2 m/sec, INTERPOLATION SETTINGS IN FOLD
$VEL.CP=2
$APO.CPTP=100
$ADVANCE=3
$ACC.CP=2
;ENDFOLD

PTP {E6POS: X -4204.94, Y 5947, Z 1346, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0, S 'B 110'} C_PTP
$OUT[2]=TRUE
LIN {E6POS: X -4204.94, Y 5947, Z 1346, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -4204.94, Y 5947, Z 1152, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -4204.94, Y 5947, Z 1012, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
WAIT SEC 1
$OUT[2]=FALSE
WAIT SEC 0.5
LIN {E6POS: X -4204.94, Y 5947, Z 1346, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3220.94, Y 3597, Z 1346, A -90, B 0, C 180, E1 3597, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3084.829, Y 4722.473, Z 437.752, A -37.81, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
```

Fig. 6-31 Robot language program.

6.3.8. HRITC process

The KUKA|plc plugin is applied to transform outputs from the design script into the construction process and execute robotic commands. The Software used for the HRITC process are:

- Rhinoceros 3D (modelling)
- Grasshopper(scripting)
- KUKA|plc Plugin (robot communication and simulation)

An accurate simulation of RTC was created for a visual understanding of the work process of the HRITC and to adjust main parameters in time according to simulation results. The script generates the whole process of HRITC. Standardized Timber allows the stacks not to need order; using the calibration device also allows the wood place unprecise, reducing the difficulty of placing stacks. Output construction data is oriented and centered on the building site, giving the designer a visual understanding of the structure built. A series of subroutines are programmed, outlining the overall construction process(Table 6-1). The following is a brief description of the HRITC process:

- **Material Preparation:** The Japanese hinoki with the size of 50*100*1950mm purchased from the market is put into a large CNC machine and prefabricated into a 50*100*650 timber. Then neatly placed on the pick-up pile, the components used in the overall construction are all of the same sizes, so there is no need to indicate. It is also convenient to replace the components of substandard quality.
- **Site preparation and security clearance:** Before the construction process begins, a safety officer needs to tour the site to check that the construction materials are stowed as required, that the robot is operating correctly, that the construction site is clean (to prevent collisions), and that the site is free of safety hazards. Once confirmed, construction can begin.
- **Construction cycle - robot assembly part:** The construction process consists of several cycles with different paths but repeated actions. At the beginning of each build cycle, the robot first grabs the timber from the pick-up table in order and places it on the calibration table at the front of the platform, waits for the timber to be calibrated, and then places it in the designated position. Then, the robot switches to the laser tool and reduces the running speed. Wait for the laser beam to carve out the nailing points (two-line endpoints) and the gluing area (a 4-sided shape) on the top of the wood(Figure 6-32). Afterward, the robot holds the timber in place with a pneumatic gripper and waits for the worker to enter to complete the nailing and gluing operation.
- **Construction cycle - human assembly part:** After the robot completes the assembly work, it will temporarily stop operation and wait for the manual work to be completed. When the worker enters the site, he or she will first observe whether the wood meets the specifications (any breakage or fracture). If the wood is found to be broken, it will be appropriate for the operator to repeat the cycle and replace the broken wood, guaranteeing the final product's overall quality. Afterward, following the marked guidelines, woodworking glue is applied, and threaded nails are driven in the designated areas at the designated points. After completing these tasks, the worker leaves the site and starts the next building cycle.
- **Safety operator supervision:** The robotic system has safety restrictions and motion collision avoidance machine restrictions. However, the actual build environment is full of

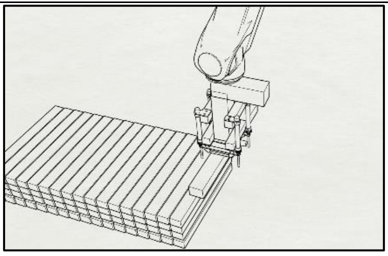
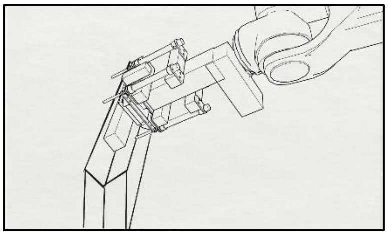
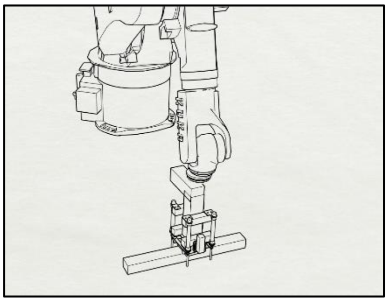
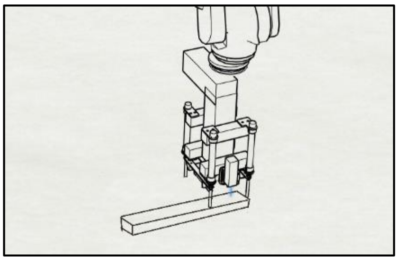
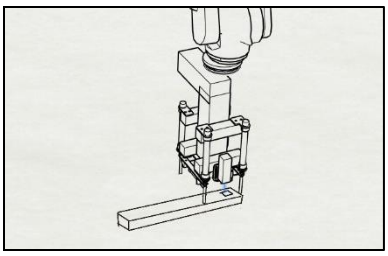
unknowns and variables. In order to place safety accidents, the safety operator has the highest machine control and can stop the machine at the touch of a button when an emergency occurs and place the accident. It also allows repeating the completed build cycle to correct broken building materials or human-generated errors.

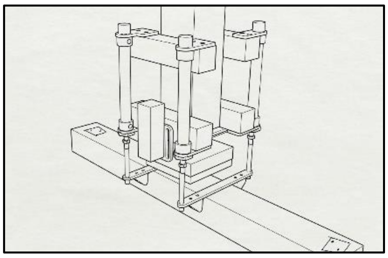
- **Reprocessing and site cleanup:** After all construction work is completed, the robot resets and stops, the workers move in to transport the completed units to the assembly site. And clean up any debris or clutter from the site. The safety officer enters the site to inspect the robot status and site environment to check if it conforms to the requirements, and then can start the next set of construction tasks, or power off and close the construction site.

Every step of the construction was gradually sped up to maximum capabilities without affecting performance and quality. Each step of picking up the timber to nailing it in place would take 1 minute 42 seconds. For 840 members, total construction time amounted to 24 hours, and it takes 2 hours to assemble on-site.

Figure 6-32 Marking of the gluing area and nailing position

Table 6-1 The HRITC Process

	ROBOT MOVEMENT	IMAGE
Get Timber From Stack	· Select Timber in Order · Turn on Air Pump · Get Timber from Stack	
Calibrate Timber	· Place Timber on Calibrator · Calibrate Timber · Pick up Timber	
Place Timber on Site	· Place Timber on Site · Release Air Pump · Move to Safe Distance	
Draw Gluing Range With Laser	· Move to Gluing Start Point · Turn on Laser · Transform Robot Speed to 0.2m/s · Move Along Endpoints · Turn off Laser	
Draw Nailing points With Laser	· Move to First Nailing Point · Turn on Laser · Move to Second Nailing Point · Turn off Laser · Transform Robot Speed to 2m/s	

Fixe Timber	· Move to Center Point · Turn on Gripper · Nail and Glue Timber · Turn off Gripper	

6.3.9. On-site assembly

To limit the size of each building component, we considered robot arm length limits, manual handling, transportation, and assembly logistics. These limits were a maximum extension length of 2 meters and a height of no more than 1.5 meters per part, which ensured that each part made by the robot could be lifted and carried by six people to a mobile truck and erected on site. Each part is drawn with cross lines to adjacent parts, which helps align the modules precisely. This simple modular technology enables unskilled workers to quickly assemble complex structures with essential tools.

Using a parametric workflow was necessary to manage the quality data for 840 individual pieces of wood with 3,155 nails. The relationship of the digital model allowed this extensive data to be flexible, changing as the tests affirmed or denied our initial settings. After completing the construction work, the four building units were moved and assembled in the exhibition hall. The overall appearance is a smooth arch, as expected - a substantial visual impact from the massive volume. The standardized wood placed along a double curve allows the viewer to visualize the surface information. Each timber construction cycle consists of three calibration steps (picking-positioning-compacting). Structural optimization and construction location optimization during the design phase also yielded amazing results. During construction, the robot made full use of the space available for construction and completed the cell construction under very extreme conditions (Figure 6-33). After completing the construction of 8 groups of units, the assembly began. Now 8 groups of units, grouped up and down, spliced into 2 building units and two mirror units (Figure 6-34). Then splicing a group of building units and a group of mirroring units into a half wooden arch(Figure 6-35). Finally, the two wooden arches are spliced and combined into a finished wooden arch pavilion(Figure 6-36). The final construction results in intolerances of +-1mm, allowing for a very smooth assembly process on site. Workers followed the drawings and placed the four completed assemblies on the display site.

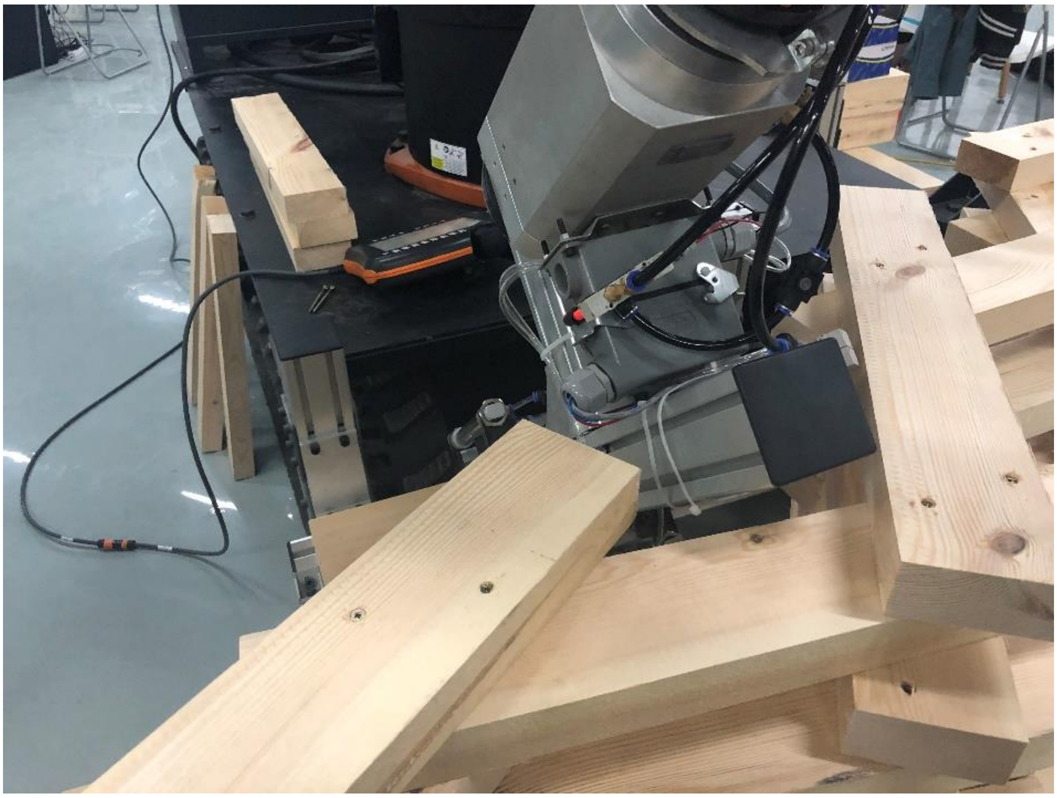


Figure 6-33 Extreme position construction

Figure 6-34 One construction unit

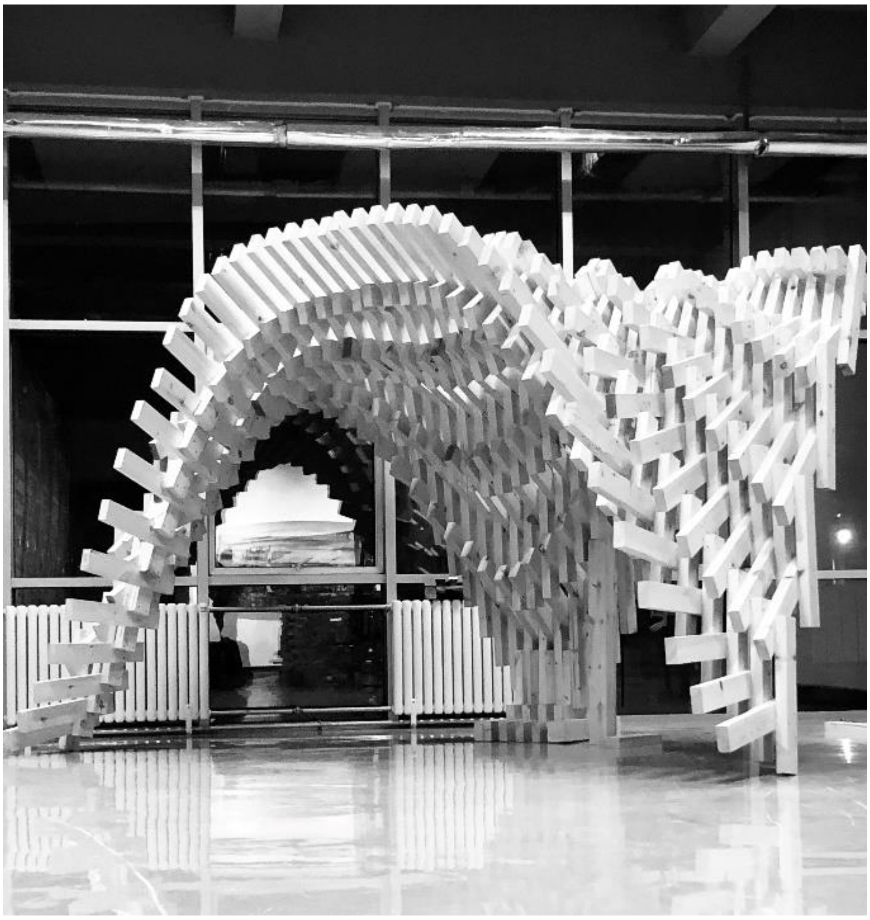


Figure 6-35 Half wooden arch

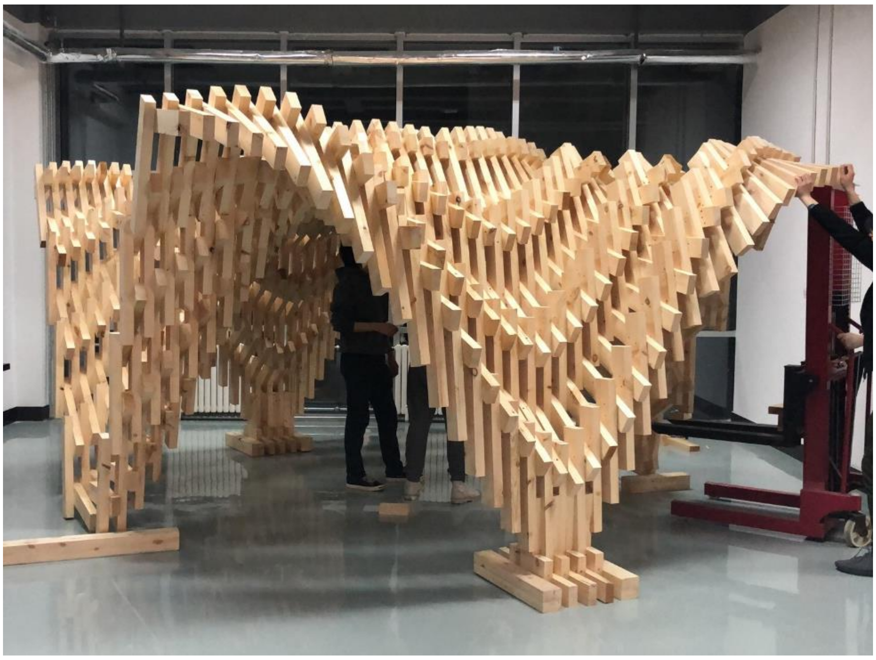


Figure 6-36 Wooden arch pavilion

The final construction results were very satisfactory. On average, each building unit took 2 hours, and 8 sets of building units took about 16 hours. For a building with such a complex structure, such efficiency is very satisfactory. Likewise, due to the precision and stability of the robot, the final product was very accurate and the angles between the woods changed to form beautiful curves, so that the changing curves with logic did not cause any difficulties in construction (Figure 6-37). Also, the strength of the body after force analysis is high. After testing, even with the weight of 1.2 tons, the wooden arch can still bear the huge weight and is very stable (Figure 6-38).

Figure 6-37 Wood strip angle change curve

Figure 6-38 Wooden arch bearing good load

6.4. Process performance evaluation

6.4.1. Production time

Productivity is a criterion to evaluate the performance of a robotic automation system[10]. The production time includes material transportation, milling, and assembly. With a construction area of 16m2, the average fabrication efficiency was 106.04min/m2, which is considered quite successful because the entire construction process was digitally managed and the complexity and precision of the construction were supported, drastically limiting unnecessary material waste. After the building site was set up as expected, the average time required to complete a fabrication cycle from the time the first timber was grabbed from the pick-up pile to the time it was assembled was 1 minute and 42 seconds (102s). The assembly time for each component depends on the size of the gluing area and the number of nails to be driven. The milling time depends on the length of the component. Since the same size member was used in this case, the milling efficiency increased significantly, with an average of 10s to complete one (Figure 6-39).

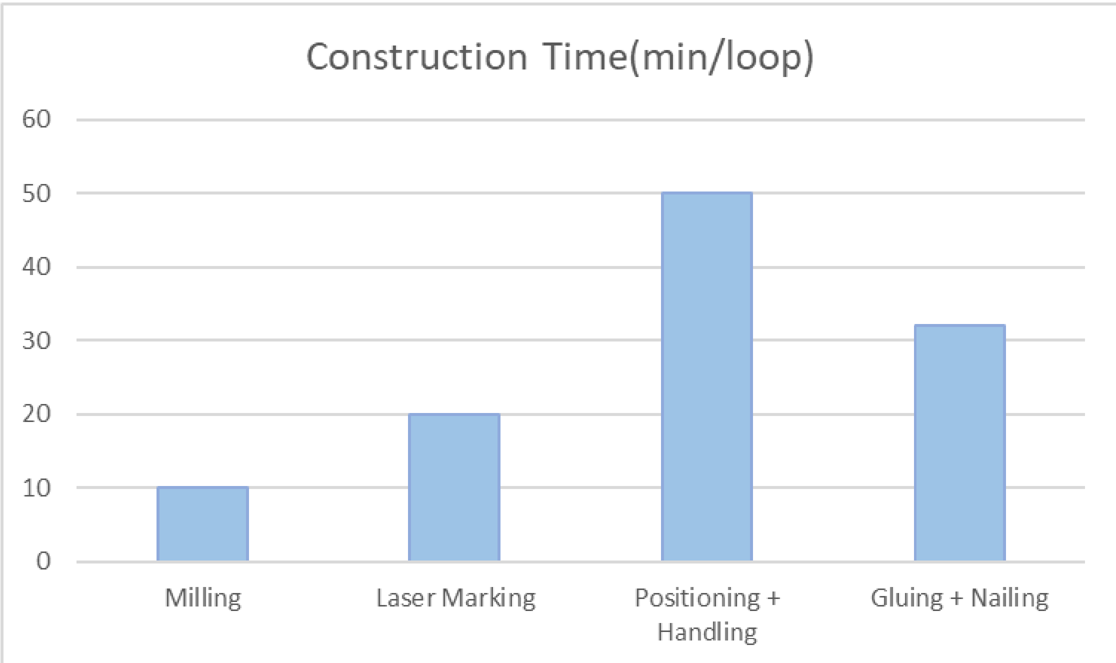


Figure 6-39 Construction Result

6.4.2. Safety and security

To guarantee that the complete production process of iSMART wooden arches can operate safely in a sequential collaboration between robots and human workers. The construction site is equipped with a safety inspector holding the smart-pad with the highest control authority of the robot, and a unique safety protection mechanism[10] is established to guarantee the safety of the workers whenever the craftsmen need to enter the robot site to carry out the construction workshop. In addition, the robot itself also has a safety monitoring system. Whenever the speed is too fast or the robot happens to be limited, the machine will automatically stop and wait for the safety inspector to check correctly before manually turning on the machine.

6.4.3. Construction tolerance

The structural system of the case relies on the direct connection between all building components. The digital aesthetics that the designer wants to express also relies on the precise arrangement of all the wooden elements. This requires a building system with close to zero tolerances. The overall design-build process was digitally managed. The physical information of each building component was parametrized to generate a code fed directly to the machine for production, which was successfully validated by three calibrations during the construction process. The average deviation of the final construction was less than 1 mm. This level of precision allowed workers to quickly assemble all components on the show site in just 2 hours.

6.4.4. Portability, cost, and construction environment requirements of HRITC

HRITC's construction platform is placed on a removable, stable tracked vehicle(Figure 6-40) that allows the construction system to be transported to any solid, horizontal ground (the construction environment must be powered and protected from rain due to equipment constraints). After transportation is complete, a simple calibration procedure is completed, and the operation can start. So far, all build sites have been set up under typical indoor temperatures and humidity, and it remains to be proven whether the build platform can be allowed in harsh environments. Construction costs are divided into labor and equipment, and labor costs are low compared to traditional construction processes due to the simplicity of the construction process, which allows inexperienced non-specialists to participate in the construction after simple safety training. As for the equipment cost, since the platform was developed in a research environment, it is not easy to assess the equipment cost in an industrial setting and market environment. The equipment cost for this study is the purchase cost of an entry-level industrial robotic arm plus the customization cost of a custom tooling platform.

Figure 6-40 Movable tracked vehicle

6.5. Discussion and Conclusion

6.5.1. Discussion

The vision of HRITC is to make improvements to the currently available RTC research. Combining digital design and automated manufacturing with human-machine collaboration to address the paradox of inefficiency and shortage of experienced labor in the construction industry is at the center of this project and the construction process. HRITC pursues scaled-up applications for complex and efficient non-standard wood structures that can be realized from simple timber elements. SNGT enhances structural strength and allows for larger-scale use of wood components instead of concrete or steel elements, reducing the carbon footprint of the building cycle. Digital design-led HRI construction allows inexperienced workers to build complex structures simply and efficiently with the assistance of robots. The integration of people into the design-build cycle is the basis for tight integration of the individual components, especially in large-scale, full-scale application construction.

In addition, this effort demonstrates a new design-build process. From the beginning of the design process through the different stages of prototype refinement to final realization, practitioners from multiple disciplines collaborated to decide on a wide range of structural constraints and manufacturing options. At the same time, HRITC facilitated the information penetration of the construction process, digitizing information from the design plan to each timber bar to the final HRITC assembly, opening up new ideas for the realization of architectural design to physicalization. Although HRITC presents a new vision for the construction industry, the full-scale adoption of HRITC is still in its early stages. It poses many challenges to the education and training of practitioners, to overall structural engineering, and the construction industry.

6.5.2. Conclusion

This chapter discusses the current state of RTC technology and summarizes the disadvantages and drawbacks of fully automated construction. Through a real case study, the possibility of HRITC technology is explored to introduce manual labor into the construction process to complement its advantages and disadvantages. The following conclusions can be drawn:

- Applying automated construction and robotics to wood construction can improve sustainability in all dimensions (economic-environmental-social) and efficiency in all processes (design-production-construction).
- If the research is oriented towards the possibility of fully automated generation(LoA 7), which makes concessions to the problems that arise in the construction process and does not allow for broader applications, by subtly introducing manual labor in some of these steps, although the level of automation will be reduced (LoA 4-6), the flexibility and applicability of the construction will be significantly increased. They can be applied to a broader scale of construction.
- The complexity of the construction environment is the current challenge for HRI. If the construction process is too complex or involves multiple dimensions, it will require construction workers' too much skill level and education. Given the current shortage of skilled workers that China faces[11], reducing the difficulty of construction and the cost of worker development is key to HRITC's ability to adapt to the market. Human participation is not a compromise for automated construction development. The flexibility and adaptability of human workers can significantly enhance the scale of HRITC applications, reduce construction costs, and lower technical requirements. It is a future research direction to carry HRITC to a broader market.
- Safety is also one of the issues faced by HRI. Introducing real-time feedback from safety operators and site workers in the HRITC process can protect the safety of site workers and prevent equipment failures during the construction process to the greatest extent possible while safeguarding construction efficiency.
- Complete digitalization has not yet been possible along the design-simulation-to-build

process chain. The construction site lacks a way to communicate with the digital model in real-time. Issues arising in construction cannot be feedback directly to the digital model; more research needs to be done to bridge them to improve overall efficiency and flexibility.

- The production potential of HRITC is enormous. The implementation of automation provides more design flexibility and allows for individual customization at an affordable cost. At the same time, the skill requirements for construction workers are minimal, significantly reducing the economic and time costs of training workers.
- HRITC technology imposes new adjustments and requirements on the existing construction industry chain. All need to be innovated, from the education of designers to the production of equipment to workers' training. New challenges will bring new opportunities. Although it is not yet directly marketable, HRITC may be a viable solution for future construction projects.

6.5.3. Insufficient and future work

Since the processing of wood is done manually, it cannot be guaranteed that the size of each piece of wood is exactly the same as the predetermined specification, and the final cumulative deviation still exists, which affects the beauty and stability of the structure. In addition, the high volume of manual processing tends to cause worker fatigue, resulting in lower construction efficiency.

- Future work. Use robotic CNC as the processing method, design robot processing procedures, design special tool heads, and add processing procedures to the robot construction process.

Although the glue application process has robot-assisted positioning, the application process is still done by hand. Although the efficiency is still considerable, the labor cost and time cost will be greatly reduced if the whole process is automated.

- Future work. Design the robot's gluing program, design the gluing device to ensure accurate gluing position and stable gluing output, and the gluing process should be added to the robot to establish the action cycle.

The process of nailing is also done by hand. Although there are robots to assist in positioning, the nailing process is still very troublesome and laborious. The impact of the nail gun is very strong and workers are easily fatigued. At the same time, the excessive torque tends to shift the position of the nails. This affects the final construction effect.

- Future work. The impact nail guns used today have a high impact and torque. The texture of each piece of wood is different. The speed and strength of the nails are also different.

The robot does not adapt well to this process and can easily cause damage to the equipment. The connection between the woods is mainly provided by glue, and the nails only serve as a fixation, so consider using an air nail gun for the connection. Combine it to the robot's tool head and write a program to add the nailing process to the robot's action cycle.

Although the current robotic construction process is hardwired, it is very rigid. If the foundation changes, the whole construction will fail. So great care must be taken during construction to avoid collisions and displacements

- Future work. Considering the inclusion of the robot vision recognition program, the robot has the possibility of self-adjusting self-recognition. The visual recognition is very necessary for both the change of the base and the adaptation to the mobile construction. In the future, we will design and integrate the visual recognition device on the existing tool head. Design visual recognition self-adjustment program to perform visual recognition before the start of each action cycle, adjust deviations and enter the cycle.

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Chapter 7

CONCLUSION AND FUTURE WORK

CHAPTER SEVEN: CONCLUSION AND FUTURE WORK

7.1 Conclusion

The construction industry has always been an important part of the world economy, yet it is facing many adjustments. On the one hand, the construction industry is less industrialized and still maintains a labor-intensive work pattern. On the other hand, with decreasing birth rates and an aging society, there is a severe labor shortage. The construction industry has low productivity, low efficiency and low sustainability, and the need for technological transformation is imminent. On this basis both design and construction require new technologies. In order to figure out what are the barriers to the actual adoption of robotics and automated buildings, this paper designs two evolutionary game models in the normal case and in the COVID-19 context to analyze the evolutionary trends and explore the factors influencing the practical application of RAAC. It provides a theoretical reference for the decision making of stakeholders. For the design aspect, many researchers point out that parametric design is a promising emerging technology, and although there have been many applications of parametric design, it has mainly been adopted for experimental instances and large projects. For a wide range of small design projects there has been little research. In this paper, we propose a rapid interaction design process based on parametric design through an example and explore the feasibility of applying parametric design to small custom projects. On the construction side, a human-machine collaborative construction process is designed to address the challenges of complex parametric designs that are difficult to build manually on the one hand, and to reduce the reliance on labor and improve the productivity and sustainability of construction on the other. It allows inexperienced laymen and robots to collaborate with each other to build complex wooden structures efficiently, easily, and accurately.

The main works and results can be summarized as follows:

In Chapter 1, RESEARCH BACKGROUND AND PURPOSE OF THE STUDY. Chapter 1 presents the research background of parametric design and robotic automated construction, including the current status and bottlenecks of integrated technology development. and the significance of digital transformation in the construction industry. Then, the development and current status of robotic automated construction in the world and China are presented. It is pointed out that the combination of parametric design and robotic construction is crucial to achieve digital transformation in the construction industry. Finally, the purpose of the study and the logical framework are presented to help reviewers understand the content of this paper.

In Chapter 2, LITERATURE REVIEW OF PARAMETRIC DESIGN AND ROBOTIC AUTOMATED CONSTRUCTION. This chapter provides a review of the relevant studies in this paper. It includes the development and current status of parametric design, the current development of robotic automated construction and the development of digital-related technologies in the construction industry. In addition, the significance and scope of use of the evolutionary game model is explained. Based on the previous studies, this paper helps to combine them to understand and explore the influencing factors that affect the application of robotic automated construction and contribute to its development and implementation.

In Chapter 3, FOR THE EVOLUTIONARY GAME ANALYSIS OF RAAC IMPLEMENTATION UNDER NORMAL CONDITIONS. This chapter begins with an analysis of the current problems in the construction industry, namely low productivity and poor sustainability, while noting that both China and Japan are facing the challenges of low population growth and increasing aging. While there have been many studies that point to robotics and automated construction as the key to breaking the ice, there has been little practical application. This paper analyzes the interests of the government, construction companies, and public universities by analyzing the relationship between them. A three-way evolutionary game model is developed to analyze the evolutionary trends of decision making under different conditions and explore the influencing factors that affect the actual adoption of RAAC. It provides a reference for the decision making of stakeholders.

In Chapter 4, EVOLUTIONARY GAME ANALYSIS FOR RAAC IMPLEMENTATION IN THE CONTEXT OF COVID-19. This section builds on the previous chapter by introducing COVID-19 as an influencing factor. In the face of the COVID-19 pandemic, the global construction industry received an unprecedented shock, with the epidemic leading to labor shortages, expenditures on epidemic prevention costs and changes in the labor environment, leaving a large number of construction companies facing bankruptcy. However, the pandemic also brought new opportunities. On one hand, the high cost of pandemic prevention made construction companies desperately in need of new construction models, and on the other hand, it also broke the traditional concept of construction mode change. This chapter analyzes the interests of the government and construction companies in the context of COVID-19 and develops an evolutionary game model. The evolutionary trends under different conditions are analyzed to explore the key parameters affecting the evolution. Theoretical references are provided for the decision-making choices of the government and construction companies.

In Chapter 5, CASE STUDY AND IMPLEMENTATION PROCESS OF PISAD. This section presents a rapid interaction design process based on parametric design that allows designers to invite users to participate in design decisions. The feasibility of the flow is verified through an example. The aim is to address the challenge of insufficient design cost and design time faced by small design projects, but users have individual customization needs.

In Chapter 6, CASE STUDY AND IMPLEMENTATION PROCESS OF HRITC. This chapter goes through a practical construction case. A building process for collaborative human-robot construction of complex wood structures is presented, allowing inexperienced laymen to build complex wood structures simply, efficiently, and accurately with the assistance of robots. It allows for the actual construction of parametrically designed 3d models. The purpose of this chapter is to first resolve the paradox that parametric design solutions are too complex and difficult to achieve with manual construction. The second is to verify the potential of robotic and automated construction to improve the efficiency, productivity and sustainability of the construction process. Finally, the problems of high cost of full automation, too much technical difficulty and too many restrictions on construction sites are solved by human-machine collaboration.

In Chapter 7, CONCLUSION AND FUTURE WORK. Conclusion and future work of the chapters are concluded.

Based on the above, the following conclusions can be drawn

1) Through EGT analysis, the strategic decisions of the government, construction companies and public universities interact with each other to achieve ESS (incentive, innovation, and cultivation). Financial incentives can motivate construction companies to innovate and universities to cultivate talent. However, once the financial incentives are too strong, the government faces financial pressure and thus chooses not to incentivize. Improving reputational incentives for construction firms and academic evaluations of public universities can increase the probability that construction firms and universities will respond to promote RAAC innovation and accelerate the achievement of the tripartite ESS. high financial subsidies do not necessarily have good results. Our study shows that higher financial subsidies tend to make the final decision of the three parties uninnovative. In contrast, appropriately higher reputational and academic evaluation incentives can effectively increase the likelihood that construction firms and public universities will choose RAAC innovation. For the government, construction firms, and public universities to achieve the ultimate ESS, they need a reasonable set of compound incentives. The government should set reasonable financial costs and reputational returns for the incentives. Construction companies need to accelerate technology upgrades and reduce the cost of innovation. Public universities need to accelerate the construction of experimental environments to prepare for the training of relevant technical talents.

2) Exploring the evolutionary relationship between government policies and construction enterprises' behaviors in the application of ARC technology is essential to enhance the construction industry and promote the sustainable development of the industry. This study innovatively takes the construction industry under COVID-19 as the research object, takes the epidemic hazard level as the influencing factor of the evolutionary game model, constructs an evolutionary game model between the government and construction enterprises, and analyzes the stable equilibrium point. The effects of different parameters on the evolutionary outcome were determined through simulations. The study shows that the regulation implemented by the

government and the adoption of ARC's ESS by the enterprises are achievable. Establishing appropriate incentives and penalties can accelerate the evolution of the government and construction companies. Focusing on epidemic hazards and adhering to epidemic prevention can help achieve industrial upgrading in the construction industry. This chapter makes recommendations based on the findings and conclusions of the study to support the government in developing relevant policies.

3) PISAD's vision is to use parametric design in combination to bring together the designer's design process, and the user's end desires at the core of the final project and construction process. Fundamentally, it enhances the efficiency of traditional design and improves the user-designer relationship. More importantly, PISAD pursues a fundamental evolution in design logic, a complex and efficient design process that can maximize the user's individual needs while controlling costs. In addition, this effort facilitated a new construction process, from the very beginning of design, through the different construction phases, until final realization, where design decisions coordinate the construction and manufacturing attributes that hit the force. Thus PISAD facilitates the penetration of information throughout the construction process, from the initial design visualization to reproduce user requirements to parametric design solutions to the production of individual skin parts, opening up new ideas for the physicalization of architectural design.

4) The application of automated construction and robotics to timber frame construction can improve sustainability at all levels (economic-environmental-social) and the efficiency of all processes (design-production-construction). If the research is directed towards the possibility of fully automated generation (LoA 7), making concessions to the problems that arise in the construction process and not allowing wider applications, by subtly introducing manual labor in some steps, although the level of automation will be reduced (LoA 4-6), the flexibility and applicability of construction will be greatly increased. They can be applied to a wider range of construction scales. The complexity of the construction environment is a current challenge for human resource investment. If the construction process is too complex or involves multiple levels, it will require an over-skilled and educated construction workforce. Given the shortage of skilled workers that China is currently facing[, reducing the difficulty of construction and the cost of worker development is key to HRITC's ability to adapt to the market. Human participation is not a compromise to the development of automated construction. The flexibility and adaptability of human workers can greatly enhance the scale of HRITC applications, reduce construction costs, and lower technical requirements. Taking HRITC to a broader market is the direction of future research. Safety is also one of the issues faced by HRI. The introduction of real-time feedback from safety operators and site workers in the HRITC process can protect the safety of site workers and maximize the prevention of equipment failure during

the construction process while safeguarding construction efficiency. Complete digitalization in the design-simulation-build process chain has not yet been achieved. The construction site lacks a way to communicate with the digital model in real time. Problems that arise during construction do not feed directly into the digital model; more research is needed to bridge these issues to improve overall efficiency and flexibility. the production potential of HRITC is enormous. The implementation of automation provides more design flexibility and allows for individual customization at an affordable cost. At the same time, the skill requirements for construction workers are low, significantly reducing the economic and time costs of training workers. HRITC technology places new adjustments and demands on the existing construction chain. Innovations are needed from the education of designers to the production of equipment to the training of workers. New challenges will bring new opportunities. Although it is not yet directly marketable, HRITC may be a viable solution for future construction projects.

7.2 Future work

Although the research in this paper has initially explored the digital transformation path from the design side to the construction side of the construction industry, it still has many limitations. First of all, for design, PISAD only leaves ports for parameters that can be changed for aesthetic directions that do not change the construction logic, and the scope of application is quite limited. In order to explore more ways of application, the overall building structure can be quickly adjusted to the user's needs without affecting the functionality and safety of the building. For the construction aspect, the experiments conducted in this paper have been quite relaxed though, with no excessive restrictions on the construction environment and worker selection. However, in the face of the complex actual construction environment, there are still shortcomings, and the construction process and algorithm need to be optimized in the future, so that it can still work properly in the complex and changing construction environment, and at the same time can complete the task efficiently and accurately. For the theoretical study, this study still has the following shortcomings and room for further research. First, this study only considered a few stakeholders and did not consider other participants in the chain. Future studies need to reflect more stakeholders for a more comprehensive discussion. Second, only the benefits gained or lost from the pandemic were considered, without considering its psychological impact and political factors, which could be included in future studies for a more indepth discussion.

Appendix

RAAC robot construction program(One loop)

```
&ACCESS RVP
&REL 1
&PARAM TEMPLATE = C:\KRC\Roboter\Template\vorgabe
&PARAM EDITMASK = *
DEF a1 ( )
;FOLD INI
;FOLD BASISTECH INI
GLOBAL INTERRUPT DECL 3 WHEN $STOPMESS==TRUE DO IR_STOPM ( )
INTERRUPT ON 3
BAS (#INITMOV,0 )
;ENDFOLD (BASISTECH INI)
;ENDFOLD (INI)
;FOLD STARTPOSITION - BASE IS 8, TOOL IS 9, SPEED IS 100%, POSITION IS A1 0,A2 -120,A3 120,A4 0,A5 90,A6 0,E1
3000,E2 0,E3 0,E4 0
$BWDSTART = FALSE
PDAT_ACT = {VEL 100,ACC 100,APO_DIST 100}
FDAT_ACT = {TOOL_NO 9,BASE_NO 8,IPO_FRAME #BASE}
BAS (#PTP_PARAMS,100)
PTP {A1 0,A2 -120,A3 120,A4 0,A5 90,A6 0,E1 3000,E2 0,E3 0,E4 0}
;ENDFOLD
;FOLD LIN SPEED IS 2 m/sec, INTERPOLATION SETTINGS IN FOLD
$VEL.CP=2
$APO.CPTP=100
$APO.CVEL=50
$ADVANCE=3
$ACC.CP=2
;ENDFOLD
PTP {E6POS: X -4224.04, Y 5740.07, Z 1331.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0, S 'B 010'} C_PTP
LIN {E6POS: X -4224.04, Y 5740.07, Z 1331.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -4224.04, Y 5740.07, Z 1137.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -4224.04, Y 5740.07, Z 997.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
WAIT SEC 1
$OUT[3]=TRUE
WAIT SEC 0.5
```

```
LIN {E6POS: X -4224.04, Y 5740.07, Z 1331.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 1407.14, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 604.14, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 604.14, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 509.14, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
WAIT SEC 1
$OUT[3]=FALSE
LIN {E6POS: X -3171.694, Y 5268.811, Z 564.851, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 494.14, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
WAIT SEC 4
$OUT[3]=TRUE
WAIT SEC 0.5
LIN {E6POS: X -3171.694, Y 5198.1, Z 1170.14, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 1170.14, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3231.199, Y 4519.899, Z 517.752, A -58.584, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3231.199, Y 4519.899, Z 357.752, A -58.584, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3231.199, Y 4519.899, Z 217.752, A -58.584, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
WAIT SEC 1
$OUT[3]=FALSE
WAIT SEC 1
LIN {E6POS: X -3231.199, Y 4519.899, Z 267.752, A -58.584, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3316.293, Y 4385.902, Z 267.752, A -58.584, B 0, C 180, E1 4385.902, E2 0, E3 0, E4 0} C_VEL
$VEL.CP=0.02
$OUT[8]=TRUE
WAIT SEC 0.5
LIN {E6POS: X -3367.496, Y 4354.615, Z 267.752, A -58.584, B 0, C 180, E1 4354.615, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3336.833, Y 4303.037, Z 267.752, A -58.584, B 0, C 180, E1 4303.037, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3285.631, Y 4334.323, Z 267.752, A -58.584, B 0, C 180, E1 4334.323, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3316.293, Y 4385.902, Z 267.752, A -58.584, B 0, C 180, E1 4385.902, E2 0, E3 0, E4 0} C_VEL
$OUT[8]=FALSE
$VEL.CP=2
WAIT SEC 0.5
LIN {E6POS: X -3231.199, Y 4519.899, Z 267.752, A -58.584, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3231.199, Y 4519.899, Z 357.752, A -58.584, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3231.199, Y 4519.899, Z 517.752, A -58.584, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -4224.04, Y 5840.07, Z 1331.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_VEL
```

```
LIN {E6POS: X -4224.04, Y 5840.07, Z 1137.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS

LIN {E6POS: X -4224.04, Y 5840.07, Z 997.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS

WAIT SEC 1

$OUT[3]=TRUE

WAIT SEC 0.5

LIN {E6POS: X -4224.04, Y 5840.07, Z 1331.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS

LIN {E6POS: X -3171.694, Y 5198.1, Z 1407.14, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS

LIN {E6POS: X -3171.694, Y 5198.1, Z 604.14, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS

LIN {E6POS: X -3171.694, Y 5198.1, Z 604.14, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS

LIN {E6POS: X -3171.694, Y 5198.1, Z 509.14, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS

WAIT SEC 1

$OUT[3]=FALSE

LIN {E6POS: X -3171.694, Y 5268.811, Z 564.851, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS

LIN {E6POS: X -3171.694, Y 5198.1, Z 494.14, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS

WAIT SEC 4

$OUT[3]=TRUE

WAIT SEC 0.5

LIN {E6POS: X -3171.694, Y 5198.1, Z 1170.14, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS

LIN {E6POS: X -3171.694, Y 5198.1, Z 1170.14, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS

LIN {E6POS: X -3250.218, Y 4096.3, Z 517.752, A -59.537, B 0, C 180, E1 4096.3, E2 0, E3 0, E4 0} C_DIS

LIN {E6POS: X -3250.218, Y 4096.3, Z 357.752, A -59.537, B 0, C 180, E1 4096.3, E2 0, E3 0, E4 0} C_DIS

LIN {E6POS: X -3250.218, Y 4096.3, Z 217.752, A -59.537, B 0, C 180, E1 4096.3, E2 0, E3 0, E4 0} C_DIS

WAIT SEC 1

$OUT[3]=FALSE

WAIT SEC 1

LIN {E6POS: X -3250.218, Y 4096.3, Z 267.752, A -59.537, B 0, C 180, E1 4096.3, E2 0, E3 0, E4 0} C_DIS

LIN {E6POS: X -3137.508, Y 4081.423, Z 267.752, A -59.537, B 0, C 180, E1 4081.423, E2 0, E3 0, E4 0} C_VEL

$VEL.CP=0.02

$OUT[8]=TRUE

WAIT SEC 0.5

LIN {E6POS: X -3189.226, Y 4051.003, Z 267.752, A -59.537, B 0, C 180, E1 4051.003, E2 0, E3 0, E4 0} C_VEL

LIN {E6POS: X -3158.565, Y 3999.427, Z 267.752, A -59.537, B 0, C 180, E1 3999.427, E2 0, E3 0, E4 0} C_VEL

LIN {E6POS: X -3106.848, Y 4029.848, Z 267.752, A -59.537, B 0, C 180, E1 4029.848, E2 0, E3 0, E4 0} C_VEL

LIN {E6POS: X -3137.508, Y 4081.423, Z 267.752, A -59.537, B 0, C 180, E1 4081.423, E2 0, E3 0, E4 0} C_VEL

$OUT[8]=FALSE

$VEL.CP=2
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WAIT SEC 0.5
LIN {E6POS: X -3340.265, Y 3962.257, Z 267.752, A -60.589, B 0, C 180, E1 3962.257, E2 0, E3 0, E4 0} C_VEL
$VEL.CP=0.02
$OUT[8]=TRUE
WAIT SEC 0.5
LIN {E6POS: X -3391.983, Y 3931.836, Z 267.752, A -60.589, B 0, C 180, E1 3931.836, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3361.16, Y 3880.356, Z 267.752, A -60.589, B 0, C 180, E1 3880.356, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3309.442, Y 3910.778, Z 267.752, A -60.589, B 0, C 180, E1 3910.778, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3340.265, Y 3962.257, Z 267.752, A -60.589, B 0, C 180, E1 3962.257, E2 0, E3 0, E4 0} C_VEL
$OUT[8]=FALSE
$VEL.CP=2
WAIT SEC 0.5
LIN {E6POS: X -3296.857, Y 4068.867, Z 267.752, A -59.537, B 0, C 180, E1 4068.867, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3250.218, Y 4096.3, Z 357.752, A -59.537, B 0, C 180, E1 4096.3, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3250.218, Y 4096.3, Z 517.752, A -59.537, B 0, C 180, E1 4096.3, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -4224.04, Y 5940.07, Z 1331.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -4224.04, Y 5940.07, Z 1137.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -4224.04, Y 5940.07, Z 997.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
WAIT SEC 1
$OUT[3]=TRUE
WAIT SEC 0.5
LIN {E6POS: X -4224.04, Y 5940.07, Z 1331.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 1407.14, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 604.14, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 604.14, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 509.14, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
WAIT SEC 1
$OUT[3]=FALSE
LIN {E6POS: X -3171.694, Y 5268.811, Z 564.851, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 494.14, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
WAIT SEC 4
$OUT[3]=TRUE
WAIT SEC 0.5
LIN {E6POS: X -3171.694, Y 5198.1, Z 1170.14, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 1170.14, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3269.441, Y 3673.201, Z 517.752, A -60.589, B 0, C 180, E1 3673.201, E2 0, E3 0, E4 0} C_DIS
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LIN {E6POS: X -3269.441, Y 3673.201, Z 357.752, A -60.589, B 0, C 180, E1 3673.201, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3269.441, Y 3673.201, Z 217.752, A -60.589, B 0, C 180, E1 3673.201, E2 0, E3 0, E4 0} C_DIS
WAIT SEC 1
$OUT[3]=FALSE
WAIT SEC 1
LIN {E6POS: X -3269.441, Y 3673.201, Z 267.752, A -60.589, B 0, C 180, E1 3673.201, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3159.457, Y 3654.97, Z 267.752, A -61.847, B 0, C 180, E1 3654.97, E2 0, E3 0, E4 0} C_VEL
$VEL.CP=0.02
$OUT[8]=TRUE
WAIT SEC 0.5
LIN {E6POS: X -3211.761, Y 3625.526, Z 267.752, A -61.847, B 0, C 180, E1 3625.526, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3180.927, Y 3574.03, Z 267.752, A -61.847, B 0, C 180, E1 3574.03, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3128.624, Y 3603.474, Z 267.752, A -61.847, B 0, C 180, E1 3603.474, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3159.457, Y 3654.97, Z 267.752, A -61.847, B 0, C 180, E1 3654.97, E2 0, E3 0, E4 0} C_VEL
$OUT[8]=FALSE
$VEL.CP=2
WAIT SEC 0.5
LIN {E6POS: X -3366.366, Y 3538.773, Z 267.752, A -63.256, B 0, C 180, E1 3538.773, E2 0, E3 0, E4 0} C_VEL
$VEL.CP=0.02
$OUT[8]=TRUE
WAIT SEC 0.5
LIN {E6POS: X -3418.674, Y 3509.327, Z 267.752, A -63.256, B 0, C 180, E1 3509.327, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3387.687, Y 3457.917, Z 267.752, A -63.256, B 0, C 180, E1 3457.917, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3335.379, Y 3487.363, Z 267.752, A -63.256, B 0, C 180, E1 3487.363, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3366.366, Y 3538.773, Z 267.752, A -63.256, B 0, C 180, E1 3538.773, E2 0, E3 0, E4 0} C_VEL
$OUT[8]=FALSE
$VEL.CP=2
WAIT SEC 0.5
LIN {E6POS: X -3316.136, Y 3646.914, Z 267.752, A -60.589, B 0, C 180, E1 3646.914, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3269.441, Y 3673.201, Z 357.752, A -60.589, B 0, C 180, E1 3673.201, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3269.441, Y 3673.201, Z 517.752, A -60.589, B 0, C 180, E1 3673.201, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -4224.04, Y 6040.07, Z 1331.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -4224.04, Y 6040.07, Z 1137.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -4224.04, Y 6040.07, Z 997.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
WAIT SEC 1
$OUT[3]=TRUE
```

```
WAIT SEC 0.5
LIN {E6POS: X -4224.04, Y 6040.07, Z 1331.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 1407.14, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 604.14, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 604.14, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 509.14, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
WAIT SEC 1
$OUT[3]=FALSE
LIN {E6POS: X -3171.694, Y 5268.811, Z 564.851, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 494.14, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
WAIT SEC 4
$OUT[3]=TRUE
WAIT SEC 0.5
LIN {E6POS: X -3171.694, Y 5198.1, Z 1170.14, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 1170.14, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3288.888, Y 3250.71, Z 517.752, A -61.847, B 0, C 180, E1 3250.71, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3288.888, Y 3250.71, Z 357.752, A -61.847, B 0, C 180, E1 3250.71, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3288.888, Y 3250.71, Z 217.752, A -61.847, B 0, C 180, E1 3250.71, E2 0, E3 0, E4 0} C_DIS
WAIT SEC 1
$OUT[3]=FALSE
WAIT SEC 1
LIN {E6POS: X -3288.888, Y 3250.71, Z 267.752, A -61.847, B 0, C 180, E1 3250.71, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3183.994, Y 3228.125, Z 267.752, A -64.921, B 0, C 180, E1 3228.125, E2 0, E3 0, E4 0} C_VEL
$VEL.CP=0.02
$OUT[8]=TRUE
WAIT SEC 0.5
LIN {E6POS: X -3236.971, Y 3199.789, Z 267.752, A -64.921, B 0, C 180, E1 3199.789, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3205.957, Y 3148.335, Z 267.752, A -64.921, B 0, C 180, E1 3148.335, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3152.98, Y 3176.67, Z 267.752, A -64.921, B 0, C 180, E1 3176.67, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3183.994, Y 3228.125, Z 267.752, A -64.921, B 0, C 180, E1 3228.125, E2 0, E3 0, E4 0} C_VEL
$OUT[8]=FALSE
$VEL.CP=2
WAIT SEC 0.5
LIN {E6POS: X -3431.236, Y 3094.887, Z 267.752, A -57.867, B 0, C 180, E1 3094.887, E2 0, E3 0, E4 0} C_VEL
$VEL.CP=0.02
$OUT[8]=TRUE
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WAIT SEC 0.5
LIN {E6POS: X -3400.244, Y 3043.774, Z 267.752, A -57.867, B 0, C 180, E1 3043.774, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3347.259, Y 3072.113, Z 267.752, A -57.867, B 0, C 180, E1 3072.113, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3378.414, Y 3123.493, Z 267.752, A -57.867, B 0, C 180, E1 3123.493, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3426.282, Y 3097.89, Z 267.752, A -57.867, B 0, C 180, E1 3097.89, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3431.236, Y 3094.887, Z 267.752, A -57.867, B 0, C 180, E1 3094.887, E2 0, E3 0, E4 0} C_VEL
$OUT[8]=FALSE
$VEL.CP=2
WAIT SEC 0.5
LIN {E6POS: X -3335.67, Y 3225.681, Z 267.752, A -61.847, B 0, C 180, E1 3225.681, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3288.888, Y 3250.71, Z 357.752, A -61.847, B 0, C 180, E1 3250.71, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3288.888, Y 3250.71, Z 517.752, A -61.847, B 0, C 180, E1 3250.71, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -4224.04, Y 6140.07, Z 1331.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -4224.04, Y 6140.07, Z 1137.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -4224.04, Y 6140.07, Z 997.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
WAIT SEC 1
$OUT[3]=TRUE
WAIT SEC 0.5
LIN {E6POS: X -4224.04, Y 6140.07, Z 1331.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 1407.14, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 604.14, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 604.14, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 509.14, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
WAIT SEC 1
$OUT[3]=FALSE
LIN {E6POS: X -3171.694, Y 5268.811, Z 564.851, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 494.14, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
WAIT SEC 4
$OUT[3]=TRUE
WAIT SEC 0.5
LIN {E6POS: X -3171.694, Y 5198.1, Z 1170.14, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 1170.14, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3308.589, Y 2828.967, Z 517.752, A -63.256, B 0, C 180, E1 2828.967, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3308.589, Y 2828.967, Z 357.752, A -63.256, B 0, C 180, E1 2828.967, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3308.589, Y 2828.967, Z 217.752, A -63.256, B 0, C 180, E1 2828.967, E2 0, E3 0, E4 0} C_DIS
WAIT SEC 1
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$OUT[3]=FALSE
WAIT SEC 1
LIN {E6POS: X -3308.589, Y 2828.967, Z 267.752, A -63.256, B 0, C 180, E1 2828.967, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3190.628, Y 2810.058, Z 267.752, A -58.869, B 0, C 180, E1 2810.058, E2 0, E3 0, E4 0} C_VEL
$VEL.CP=0.02
$OUT[8]=TRUE
WAIT SEC 0.5
LIN {E6POS: X -3244.387, Y 2782.994, Z 267.752, A -58.869, B 0, C 180, E1 2782.994, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3213.181, Y 2731.53, Z 267.752, A -58.869, B 0, C 180, E1 2731.53, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3159.423, Y 2758.593, Z 267.752, A -58.869, B 0, C 180, E1 2758.593, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3190.628, Y 2810.058, Z 267.752, A -58.869, B 0, C 180, E1 2810.058, E2 0, E3 0, E4 0} C_VEL
$OUT[8]=FALSE
$VEL.CP=2
WAIT SEC 0.5
LIN {E6POS: X -3454.407, Y 2671.642, Z 267.752, A -59.921, B 0, C 180, E1 2671.642, E2 0, E3 0, E4 0} C_VEL
$VEL.CP=0.02
$OUT[8]=TRUE
WAIT SEC 0.5
LIN {E6POS: X -3425.338, Y 2623.95, Z 267.752, A -59.921, B 0, C 180, E1 2623.95, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3371.57, Y 2651.019, Z 267.752, A -59.921, B 0, C 180, E1 2651.019, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3402.9, Y 2702.42, Z 267.752, A -59.921, B 0, C 180, E1 2702.42, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3408.707, Y 2699.497, Z 267.752, A -59.921, B 0, C 180, E1 2699.497, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -3454.407, Y 2671.642, Z 267.752, A -59.921, B 0, C 180, E1 2671.642, E2 0, E3 0, E4 0} C_VEL
$OUT[8]=FALSE
$VEL.CP=2
WAIT SEC 0.5
LIN {E6POS: X -3354.801, Y 2804.816, Z 267.752, A -63.256, B 0, C 180, E1 2804.816, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3308.589, Y 2828.967, Z 357.752, A -63.256, B 0, C 180, E1 2828.967, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3308.589, Y 2828.967, Z 517.752, A -63.256, B 0, C 180, E1 2828.967, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -4224.04, Y 6240.07, Z 1331.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_VEL
LIN {E6POS: X -4224.04, Y 6240.07, Z 1137.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -4224.04, Y 6240.07, Z 997.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
WAIT SEC 1
$OUT[3]=TRUE
WAIT SEC 0.5
LIN {E6POS: X -4224.04, Y 6240.07, Z 1331.78, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
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LIN {E6POS: X -3171.694, Y 5198.1, Z 1407.14, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 604.14, A -90, B 0, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 604.14, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
LIN {E6POS: X -3171.694, Y 5198.1, Z 509.14, A -90, B -45, C 180, E1 4400, E2 0, E3 0, E4 0} C_DIS
WAIT SEC 1
$OUT[3]=FALSE
```