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Study on the structural influence mechanism of robot construction on real estate project costs: Moderating effect of management change

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Study on the Structural Influence Mechanism of Robot Construction on Real Estate Project Costs: Moderating Effect of Management Change

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SINGAPORE MANAGEMENT UNIVERSITY

2024

Study on the Structural Influence Mechanism of Robot Construction on Real Estate Project Costs: Moderating Effect of Management Change

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July 2024

Statement

I hereby declare that this PhD dissertation is my original work
and it has been written by me in its entirety.
I have duly acknowledged all the sources of information
which have been used in this dissertation.

This PhD dissertation has also not been submitted for any degree
in any university previously.

Wei Xiujuan

Wei Xiujuan
July 2024

Abstract

Cost control in construction is crucial for the survival of real estate enterprises. Especially in the context of cyclical downturns in the real estate industry, it is essential to achieve cost reduction and efficiency improvement in real estate projects. Currently, the widespread application of robotics technology may hold the key to achieving this goal. Robotics technology is widely recognized for its ability to automate tasks and reduce labor costs. However, it also brings about transformative impacts on management, organization, production, and processes, which can paradoxically increase project costs. Unfortunately, there is a lack of research focusing on the impact of robot construction—a new production model—on real estate project costs. Therefore, it is worth considering the following questions. How does robot construction specifically affect real estate project costs? What are the structural characteristics of the impact? What is the role of management change in this process?

To address the aforementioned questions, leveraging my human capital strength, this study conducted a questionnaire survey focusing on real estate projects using robot construction within Group B I work for. A total of 162 respondent samples were collected from Group B across 31 cities in 13 provinces, including Guangdong in China. Additionally, the survey included 100 other real estate projects both domestically and internationally, such as the China Resources Center. Based on the internal questionnaire survey data from Group B, statistical analysis revealed that robot construction projects, on average, can reduce unit area

costs by approximately 5%. Notably, labor costs showed a significant decrease, with the construction team size decreasing by around 20% on average, resulting in a reduction of approximately 10% in construction personnel costs. Furthermore, a scale system for robot construction was established to empirically analyze its impact on the cost of real estate projects. The study found that robot construction significantly suppresses average costs and redundancy costs. The mechanism test revealed that robot construction can leverage technological advantages like shortened production cycles and demonstrate superior adaptability in flexible resource allocation. The tension of technological advantages and the enhancement of adaptability can suppress the average costs and redundancy costs of real estate projects. Additionally, technological advantages and adaptability can mediate the relationship between robot construction and the cost of real estate projects. The heterogeneity analysis revealed that the cost-reducing effect of robot construction on real estate projects is more pronounced in scenarios with higher local wage levels and larger construction scales for the project. According to the moderating effect test, management change is a key mechanism by which robot construction suppresses the cost of real estate projects. It is within the context of organizational consensus cohesion, reinforced organizational learning, and human-robot collaborative operations that the expected efficiency of robot construction in reducing the cost of real estate projects can be fully realized and even strengthened. Finally, the extended test demonstrated that while robot construction reduces costs,

it also optimizes organizational performance, thereby achieving the dual benefits of cost reduction and efficiency improvement.

Based on the analysis of the external questionnaire survey, it was found that the willingness of real estate enterprises to adopt robot construction is generally weak. This phenomenon is closely related to factors such as competitive pressures, government support, organizational consensus, technological advantages, resource readiness, perceived usefulness, and perceived ease of use. According to the PSM survey on respondents' willingness to pay (WTP), the willingness cost for real estate projects constructed with robots varies from RMB 1,970.49 to 2,074.84, surpassing Group B's cost of robot construction projects. Therefore, there is significant potential for the application and promotion of robot construction projects, and possibilities for collaboration between Group B and external enterprises can be further explored. The study's findings offer a consistent and scientifically quantified evaluation of robot construction adoption in the real estate industry. They provide precise reference guidelines for advancing intelligent real estate construction, upgrading practices, and addressing cyclic downturns. Additionally, the conclusions present empirical support for the adoption and utilization of specialized construction robots, akin to those employed by Group B.

Keywords: robot construction, cost of real estate projects, management change, structural effect

Contents

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Chapter I Introduction

1.1 Research Background

Currently, the fourth wave of technological revolution is sweeping the globe, characterized by big data, cloud technology, automation technology, robots, and AI. This revolution has accelerated the transformative development of various industries toward the “4.0” era. In particular, robots, known as the “crown jewel of the manufacturing industry” in the fourth technological revolution, have experienced rapid growth and extensive application in enterprise production and operations. According to data published by the International Federation of Robotics (IFR), the global installation of robots increased from 53,000 units in 1993 to 553,000 units in 2022, with an average annual growth rate of 8.4%. In the world’s trend of the new technological revolution, the Chinese robotics market has seen rapid development, injecting new momentum into nurturing new economic growth points and upgrading industrial transformation (Acemoglu & Restrepo, 2016, 2019; Cao & Y. Zhou, 2018; Li Lei et al., 2021). In 2016, China overtook Japan as the country with the highest number of robots. Starting from 2017, China has sustained an annual growth rate of 13% in robot installations. In 2022, China’s robot installations rose to a remarkable 290,000 units, representing a substantial share of global new installations. The real estate industry stands as a fundamental sector within China’s national economy. Leveraging the profound amalgamation of digital technologies like AI, sensor technology, and Building Information Modeling (BIM) alongside the use of construction robots, the industry is currently undergoing a transformation and upgrade to a “4.0” version (G. Han & Li Wenrui, 2021; M. Huang & Li Lin, 2020). During this process, the Party and the government have successively introduced policies to promote the R&D and application of robots in the real estate industry. In 2017, the General Office of the State Council issued the *Opinions on Promoting the Sustainable and Healthy Development of the Construction Industry*. In 2020, the Ministry of Housing and Urban-Rural Development issued the *Guiding Opinions on Promoting the Coordinated Development of Intelligent Construction and Building Industrialization*. In 2022, the Ministry of Housing and Urban-Rural Development released the *14th Five-Year Plan for the Development of the Construction Industry,* and the Ministry of Industry and Information Technology, along with other 14 departments, jointly issued the *14th Five-Year Plan for the Development of the Robotics Industry*. In 2023, the Ministry of Industry and Information Technology, along with other 16 departments, jointly issued the *Action Plan for the Application of “Robotics+.”* These critical documents lay out the roadmap for the future of intelligent construction in the real estate industry. Robot construction has been assigned the significant historical role of catalyzing the transformation and advancement of China’s real estate sector.

In contrast to typical enterprise activities, real estate construction represents a sizable endeavor that heavily relies on capital and labor, encompassing intricate business networks like supply chains, labor pools, and various departments. Consequently, the real estate construction sector inherently requires efficient cost management and control mechanisms (C. Chen et al., 2022; H. Zeng & Cheng Hu, 2014). In particular, real estate construction is facing more severe challenges than ever before. According to data from the National Bureau of Statistics, the added value of the construction industry in 2022 was RMB 8.3383 trillion, a 5.5% increase compared to that in the previous year. However, the profits of construction enterprises with qualification levels amounted to RMB 836.9 billion, a 1.2% decrease compared to that in the previous year. Against the backdrop of frequent “black swan” events and cyclical adjustments in the industry, the need for cost reduction and efficiency improvement in real estate construction has become extremely urgent (H. Zeng & Cheng Hu, 2014). However, reality contradicts this notion as real estate construction has long been trapped in a low-level balance characterized by high energy consumption, high pollution, high risks, low productivity, and low profits. This crude production approach has led to resource waste and efficiency losses, hindering adjustments for corporate costs (Duan et al., 2022a; C. Mao & Peng, 2020). As a new production method driven by technological progress, robot construction possesses both capital and labor attributes (Acemoglu & Restrepo, 2018a; Brynjolfsson et al., 2014) and can reduce production costs and improve production efficiency (Graetz & Michaels, 2018). Therefore, it has the potential to become a key breakthrough in cost management for real estate construction (Z. Liu et al., 2019; C. Mao & Peng, 2020). However, existing research on the impact of robot construction on the cost of real estate construction is mainly limited to normative and theoretical perspectives (Braganza et al., 2017; G. Han & Li Wenrui, 2021; C. Mao & Peng, 2020), lacking clear and credible empirical evidence. In the context of substantial shifts in real estate construction and industry cycles, it holds immense significance to analyze the impact of robot adoption on the costs of real estate construction. Addressing this issue can, on one hand, provide companies with practical approaches to robot adoption for corporate cost management and financial decision-making. On the other hand, it can theoretically identify the economic management effects of robot construction and formulate appropriate policies for the construction robot industry, which is also insightful for other types of robot adoption, thereby responding to significant theoretical and practical concerns.

Some existing literature has explored whether the application of robots reduces production costs and how it affects the share of labor wages, capital returns, and production performance to evaluate the potential benefits of cost reduction and efficiency improvement (Acemoglu & Restrepo, 2018a; Agrawal et al., 2018; Autor et al., 2003; Bresnahan et al., 2002; DeCanio, 2016; Destefano & Timmis, 2021; Graetz & Michaels, 2018; W. Lyu et al., 2019; J. Qi & Z. Zhang, 2022; C. Yuan et al., 2021) and the ability to enhance cost management (Li Wanhong & F. Wang, 2022; Quan & C. Li, 2022; Yue Yujun & Gu, 2021). Due to the limited availability of enterprise-level data on robots, most of the literature relies on indirect and relatively vague measurement methods to assess the application of robots. Consequently, discussions at the macro and enterprise levels may not accurately capture the cost management clues within the internal operations of the organizations. More importantly, the limitations of the data restrict the impact of robot adoption on corporate costs to general patterns. On one hand, few empirical deductive paradigms demonstrate the effect of robot adoption (robot construction) on corporate costs and management accounting, lacking evidence of heterogeneous robot adoption. Applying generalized patterns to specific robot adoption contexts may likely result in empirical biases. On the other hand, by placing corporate costs under the homogeneity assumption of new technology adoption, there has been limited discussion on the decomposition of the structural effects of costs. This makes it challenging to provide empirical evidence of the impact of robot adoption on heterogeneous cost management within enterprises. In contrast to existing research, this study adopts a questionnaire survey that investigates multiple real estate projects of Group B and the construction of external enterprises with robots procured from Group B. Based on the compiled statistical data, this study conducts empirical research from a more fundamental perspective of internal operational management in real estate construction projects. It explores the structural effects of robot construction on the cost of real estate projects and identifies the pathways for achieving such effects, thereby providing evidence of the effect of robot construction on the cost of real estate projects through a more precise, micro-level, and concrete dimension. This study represents a breakthrough in the research on the relationship between robot adoption and corporate costs.

In the context of reality, with the application of robots, significant changes occur in enterprises’ production methods, production processes, organizational structures, and business models (D. Chen et al., 2020; Liu Yang et al., 2020; P. Xu

& X. Xu, 2020). These changes also bring about systemic transformations in the management objects, management attributes, management decisions, and management ethics (P. Xu & X. Xu, 2020). However, implementing corresponding corporate systems such as risk management and internal controls cannot be accomplished overnight. The awareness and capability of management change within enterprises may struggle to match the pace of advancements in robot adoption. In this context, when organizational structures, business operations, and other management models do not align with the application of robots, enterprises may find it difficult to adapt to rapidly changing market environments and fleeting development opportunities. Consequently, they may become trapped in a "transformation dilemma" vortex, leading to increased corporate costs (Goles et al., 2019; G. Huang et al., 2022; Y. Qi & X. Xiao, 2020; J. Xiao, 2020). From this perspective, in the practice of cost control in real estate projects, relying solely on the innovative driving force of robot construction may lead to a situation where efforts do not yield proportional results. This necessitates a substantial change in enterprise management to offer essential backing. Considering this, implementing an effective system of management reform to strengthen the synergy and impetus behind the "robot construction—real estate project cost" nexus not only promotes the integration of robots for industry empowerment across systems but also assists microeconomic entities in cutting costs and enhancing efficiency. Therefore, this study incorporates management change into the analytical framework of "robot construction—real estate project cost" to uncover the key mechanisms through which robot construction impacts the cost of real estate projects and elucidate the practical path for management change in enterprise transformation and upgrading.

1.2 Research Significance

1.2.2 Practical significance

This study demonstrates the following practical significance.

First, there is currently a lack of clear empirical evidence and industry experience to guide the cost effect of robot construction. This may be one of the reasons for the significant lag in adopting robot construction methods in the construction industry, including the real estate sector. This study represents the inaugural large-scale exploration of robot construction within the real estate sector, assessing the economic management effects of implementing robot construction methods. The research results suggest that embracing robot construction techniques may lead to a reduction in production costs by around 5%, replacement of roughly 30% of construction teams, and a decrease in labor costs by approximately 10%. This empirical evidence adds scientific consistency to the promotion of robot construction, offering a clear practical significance for the intelligent upgrading of the construction industry.

Second, the adoption of robot construction highlights a common feature where large enterprises lead in R&D and implementation, while small and medium-sized enterprises (SMEs) exhibit lower implementation rates and limited willingness, **thus accentuating the "intelligence gap."** This study explores the influence of robot construction on the cost of real estate projects across diverse markets and offers insights into this matter. The research findings reveal that in contexts with high regional wage levels and large-scale construction projects, the cost-reduction effect of robot construction on real estate projects is more prominent. Therefore, when promoting the application of robot construction, leading enterprises should consider the construction enterprises, construction project scale, and labor market supply-demand relationship comprehensively and adopt a differentiated strategy to provide detailed insights into the strategy for enterprises adopting robot construction.

Moreover, the real estate sector is currently undergoing industry challenges. Transitioning the production model towards the “4.0” version, focusing on construction costs, presents an opportunity to decrease expenses and enhance efficiency within the real estate industry. This avenue offers a viable strategy for real estate enterprises to facilitate transformation and upgrade operations amidst cyclical downturns. As a pillar industry, the real estate industry grapples with challenges such as outdated production methods, inadequate labor efficiency, high consumption of energy and resources, and a lack of scientific and technological innovation. These factors have resulted in a persistent delay in the evolution of production and management models within real estate construction. The current industry downturn further highlights the need for cost reduction. This study finds that the robot construction model can significantly reduce average costs and redundancy costs in real estate projects, providing clear evidence for implementing the strategic decision of intelligent construction in the real estate industry as determined by relevant authorities.

Lastly, **in the new wave of robot adoption transformation and innovative development, enterprises need to embrace new technologies for self-production mode innovation and actively address the management model impacts brought about by the transformation, including organizational structure, management processes, and business models.** Building a systematic management optimization system is of vital significance in enhancing the fitness and driving force of the "robot adoption—enterprise transformation and upgrading" relationship. This study integrates management change into the analytical framework regarding the impact of robot construction on the cost of real estate projects. It concludes that to maximize the cost reduction and efficiency enhancement benefits of robot construction, corresponding management changes are essential. This conclusion indicates that the process of intelligent construction upgrading in the construction industry relies on the alignment of new production models with matching management models. The research conclusions provide clear insights for many enterprises and offer detailed reference significance for the strategy of industry-leading enterprises in promoting construction robots.

1.2.1 Theoretical significance

This study highlights the following theoretical significance.

First, in theoretical research on robot adoption, robots are often treated as homogeneous entities. Empirical research specifically focused on construction robots within a particular niche is almost non-existent. This is mainly due to the lack of detailed data on robot adoption, making it difficult to fill the gap in theoretical research on heterogeneous robots within the field of economic management. Drawing from nearly a year of research and questionnaire surveys conducted among leading construction robot enterprises and real estate projects spanning different organizations and locations, this study has gathered comprehensive data regarding the application and micro-characteristics of construction robots within various entities. The findings offer an outstanding analytical simple that serves to bridge this existing gap and enhance the theoretical research outlook on robot adoption. Currently, the literature has used alternative approaches to identify robot adoption, such as the IFR Global Industrial Robot Database which has been converted by weights for specific manufacturing sectors (Acemoglu & Restrepo, 2017; 2020; X. Dong et al., 2022; Li Lei & H. Ma, 2023; Y. Wang & W. Dong, 2020), robot import data from the China Customs Database (L. Feng et al., 2023; X. He & K. Liu, 2023), and text recognition (Quan & C. Li, 2022; Yue Yujun & Gu, 2021). However, these approaches are unable to provide a deeper understanding of the true nature of robot construction. Recently, there has been a growing trend in the literature to explore robot adoption using survey questionnaires (L. Chen et al., 2023; Cheng Hong & L. Yuan, 2020; Deng Yue & Jiang Wanyi, 2022; Deng Yunxue & Liu Xiao, 2022; C. Fan & Deng Yunxue, 2022). However, these discussions have not yet touched upon the application of robots in diverse industries, as they have mainly focused on analyzing global issues.

Generalized patterns may not be applicable when extended to specific robot construction scenarios. Moreover, due to the lack of enterprise-level data on robot adoption in current research, studies on the cost and management accounting of micro-level robot adoption (robot construction) have mostly remained in normative reasoning and qualitative paradigms (G. Han & Li Wenrui, 2021; C. Mao & Peng, 2020).

Second, empirical research focusing on robot adoption has mainly concentrated on perspectives such as economic growth, production efficiency, technological progress, production reshoring, industry chain, labor mobility, employment, trade, income distribution, and environmental pollution (Acemoglu & Restrepo, 2016, 2019; Aghion et al., 2017; Cao & Y. Zhou, 2018; Li Lei et al., 2021). However, these studies have not delved deeply into the internal operational management of enterprises, thus failing to effectively address the cost management effects and underlying logic of robot adoption. As a result, there is a lack of assessment regarding the true effect of robot adoption on cost reduction and efficiency improvement. Moreover, numerous domestic and international studies have failed to reach consistent conclusions regarding the cost effects generated by robot adoption (Acemoglu & Restrepo, 2018c; Graetz & Michaels, 2018; Yu et al., 2019). This lack of knowledge is particularly true for robot construction in specific contexts, leading to policy recommendations that often fall into a state of inertia. General Secretary Xi Jinping has advocated for “in-depth research on the application and impact of new technologies and serious exploration of cooperation ideas and measures.” In this context, the assessment of cost effect based on robot construction is a research topic of great theoretical value. This study effectively supplements the existing research in the field of robot adoption and cost management.

Moreover, within the deductive framework concerning robot adoption, a shared consensus exists among government bodies, enterprises, and research institutions that enterprises need profound changes in their organizational structure, decision-making processes, models, systems, and strategies to enhance their fitness to transformation and upgrading, including the application of robots (H. Guo et al., 2019; Liu Yang et al., 2020; Y. Qi & X. Xiao, 2020; J. Xiao, 2020). Many studies have followed this logic and discussed specific restructured pathways, underlying mechanisms, and consequences of enterprise management through case studies in areas such as supply chains, human-robot collaboration, and AI application (J. He & S. Yan, 2023; Y. Jiang et al., 2023; S. Li et al., 2023; T. Meng et al., 2021; X. Wu et al., 2022; Y. Zheng & J. Liu, 2019). The aforementioned literature provides valuable insights for this study. In assessing the cost effect of robot construction in real estate projects, focusing solely on robot implementation could lead to a substantial loss of information. It is necessary to integrate the level of alignment between robot adoption and management change into the analytical framework. This approach helps pinpoint the management models that empower enterprises to attain substantial cost savings and efficiency enhancements through the integration of construction robots. Unfortunately, there is a scarcity of literature that adopts an empirical deductive research paradigm to incorporate management change into the analytical framework concerning the economic management effects of robot construction. This study incorporates the management change factor into the analytical framework of “robot construction—real estate project cost” to offer a detailed explanation at the micro-level regarding the underlying mechanisms of management change in the transformation and upgrading of economic organizations.

1.3 Research Content

This study consists of seven chapters, and the main research content is as follows:

The first chapter is Introduction. This chapter focuses on elaborating on the research background and significance, discussing robot construction change in the construction industry under the digital technology revolution, including AI, and the transformative impact of this change on the construction of real estate projects. The economic and management effects triggered by robot transformation may impact the cost of real estate projects, leading to the core theme of this paper. This chapter introduces the main research content and methods, focusing on providing a technology roadmap and deconstructing the framework of ideas.

The second chapter is Literature Review. This chapter focuses on summarizing and organizing the literature related to robot construction, management change, and corporate costs. Firstly, it delineates the concept of robot construction and assesses the existing technical methodologies for its measurement. Subsequently, it delves into the literature on the driving forces behind robot construction, specifically scrutinizing the economic management impacts of robot construction and the transformative influence it exerts on enterprise behavior at the micro level. Next, it reviews the literature on management change, defines its concept and measurement methods, and explains the current driving forces behind management change, with a focus on the impact of robot construction on management change. Furthermore, it delves into the literature on corporate costs, summarizing the research findings of previous studies on the antecedents of corporate costs. It also reviews existing research on the interaction between management change and corporate costs, with a particular emphasis on the potential impact of robot construction on corporate costs. Lastly, it encapsulates the principal perspectives of existing research and identifies the areas in existing literature where research findings may appear inadequate or insufficient. This establishes a literature and theoretical groundwork for subsequent theoretical and empirical analysis.

The third chapter is Research Hypotheses. Firstly, this chapter derives the impact of robot construction on the cost of real estate projects through theoretical deduction and examines the structural effect of driven costs of robot construction after cost breakdown, leading to the formulation of basic research hypotheses. Secondly, it theoretically deduces the mechanism path through which robot construction influences the cost of real estate projects, leading to the formulation of research hypotheses for the mechanism path. Thirdly, it incorporates the management change factor to establish differentiated effects of robot construction on the cost of real estate projects. Lastly, it establishes a unified theoretical framework to establish the theoretical foundation and theoretical clues for this study.

The fourth chapter is Design and Analysis of Questionnaire for Robot Construction and External Application in Group B. This chapter first introduces the questionnaire design process and the main sources of questionnaire survey data, summarizing the results of interviews and expert opinions. It then outlines the main content of the questionnaire, drawing on existing research and incorporating interview content to design a questionnaire on the structural effect and management change of the cost of real estate projects. Furthermore, it revises the questionnaire items based on the pre-survey data analysis to finalize the formal questionnaire items. Finally, it analyzes the results of the questionnaire survey. This includes an analysis of the distribution and collection of the questionnaires, describing the demographic and enterprise features of the sample surveyed. It focuses on the current state of robot construction adoption, the cost of real estate projects, and management change, and extracts these variables for normal distribution testing.

The fifth chapter is Empirical Analysis of the Structural Impact of Robot Construction on the Cost of Real Estate Projects. First, this chapter establishes a research design for empirical tests and explains the distribution of relevant core and control variables. Second, it conducts a comprehensive regression analysis of the impact of robot construction on the cost of real estate projects. Third, it deconstructs the cost of real estate projects into multiple dimensions, including material costs, labor costs, measure costs, and expenditure, to examine the influence of robot adoption on these factors empirically. Fourth, it employs endogeneity tests such as propensity score matching, placebo tests, and instrumental variable regression to address potential endogeneity issues and validate the reliability of the research conclusions. Fifth, it utilizes a mediating effect model to explore the underlying logic between robot construction and the cost of real estate projects from the perspective of logical consistency, including information channels such as information construction and cost budgeting, and efficiency channels such as production cycles and production quality. Lastly, it examines the performance evaluation after cost reduction through performance change, social support, and customer feedback.

The sixth chapter is Empirical Analysis of the Structural Effect of Robot Construction on the Cost of Real Estate Projects from the Perspective of Management Change. This chapter first establishes a research design for empirical tests and explains the distribution of relevant core variables and control variables. Secondly, it incorporates the management change factor into the analytical framework of “robot construction—cost of real estate projects” and evaluates their moderating effects on the relationship between the two through sub-sample analysis. Lastly, it examines the mechanism through which robot construction affects the cost of real estate projects under the influence of the management change factor.

The seventh chapter is Research Conclusions and Contributions. This chapter summarizes the main conclusions obtained from the study and provides a categorization of the findings. It clarifies the research innovations and presents policy recommendations for enterprises, markets, and government levels to promote the process of intelligent manufacturing in the construction industry. It also addresses the limitations and provides future research prospects.

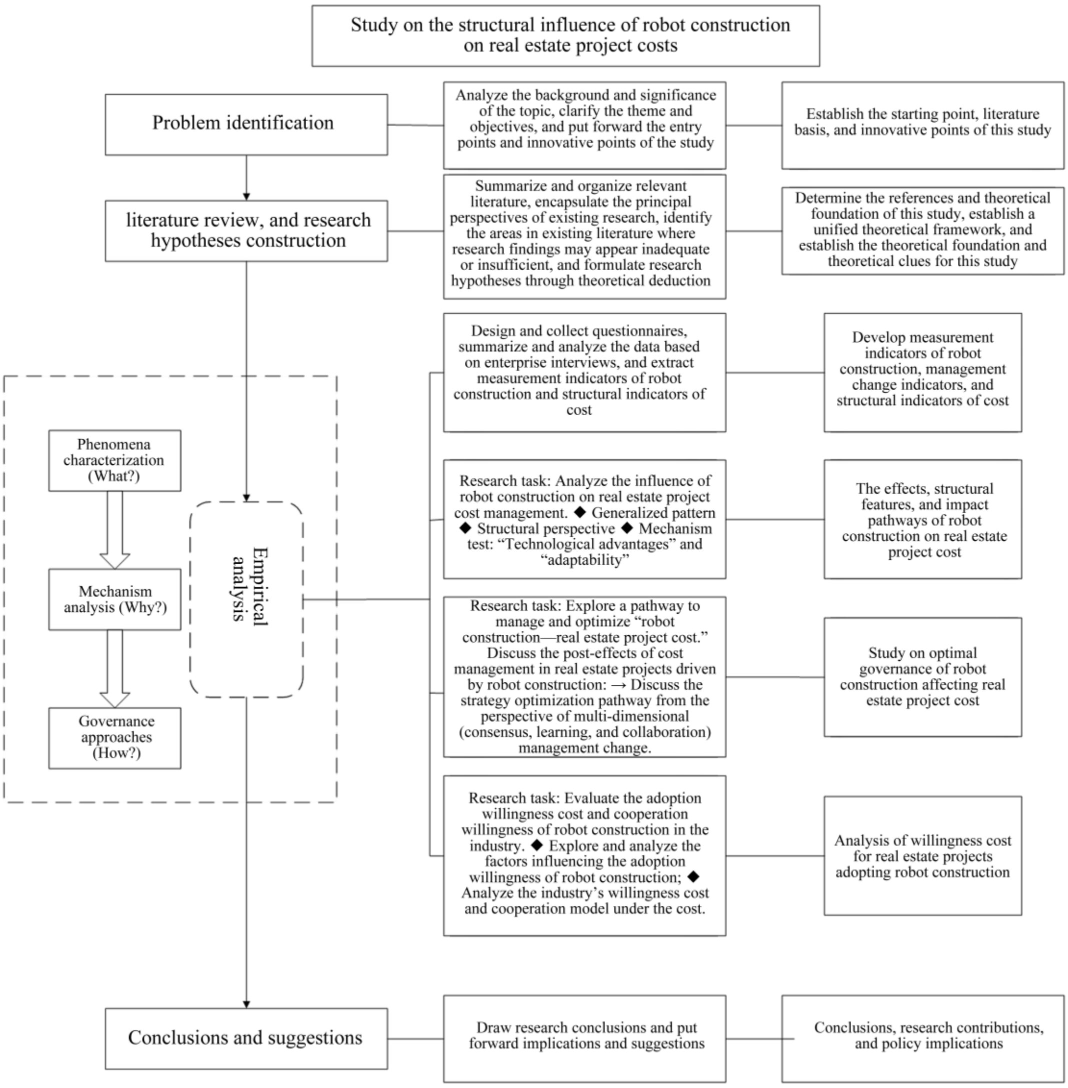

Figure 3-1 Main Research Contents

1.4 Technical Route

To delve deeper into the structural effects of robot construction on the cost of real estate projects and the role of management change in this process, this study follows a problem-solving approach consisting of phenomena characterization, problem identification, problem analysis, and problem resolution. In other words, it unfolds the analysis along the route of “What” → “Why” →

"How," aiming to achieve logical progression and interconnection between chapters as much as possible. Firstly, based on the literature review, theoretical reasoning, and solid data, this study first identifies the paradigm of "robot construction—real estate project cost" and further examines the structural characteristics of how robot construction influences the cost of real estate projects. Secondly, it dissects the intrinsic mechanism between "robot construction—real estate project cost" from the perspectives of efficiency mechanism and information mechanism. Thirdly, it investigates the post-effects of cost management in real estate projects driven by robot construction. Lastly, by incorporating the management change factor into the analysis framework of "robot construction—real estate project cost," the study analyzes the combined impact of management change and robot construction on cost management in real estate projects from four dimensions: management decisions, organizational learning, workforce adjustment, and human-robot collaboration. Thus, for the first time, this study approaches the perspective of heterogeneous robot adoption (robot construction) and adopts an empirical deduction under the organization to fill a gap in the research landscape of robots and cost management decisions. This study provides detailed empirical evidence to understand the intrinsic logic behind the transformative and upgrading role of robot construction in real estate development. It offers a practical pathway for the promotion and application of high-end and refined robots while providing clear policy and practical insights for the implementation of robot adoption in China's policies and enterprises.

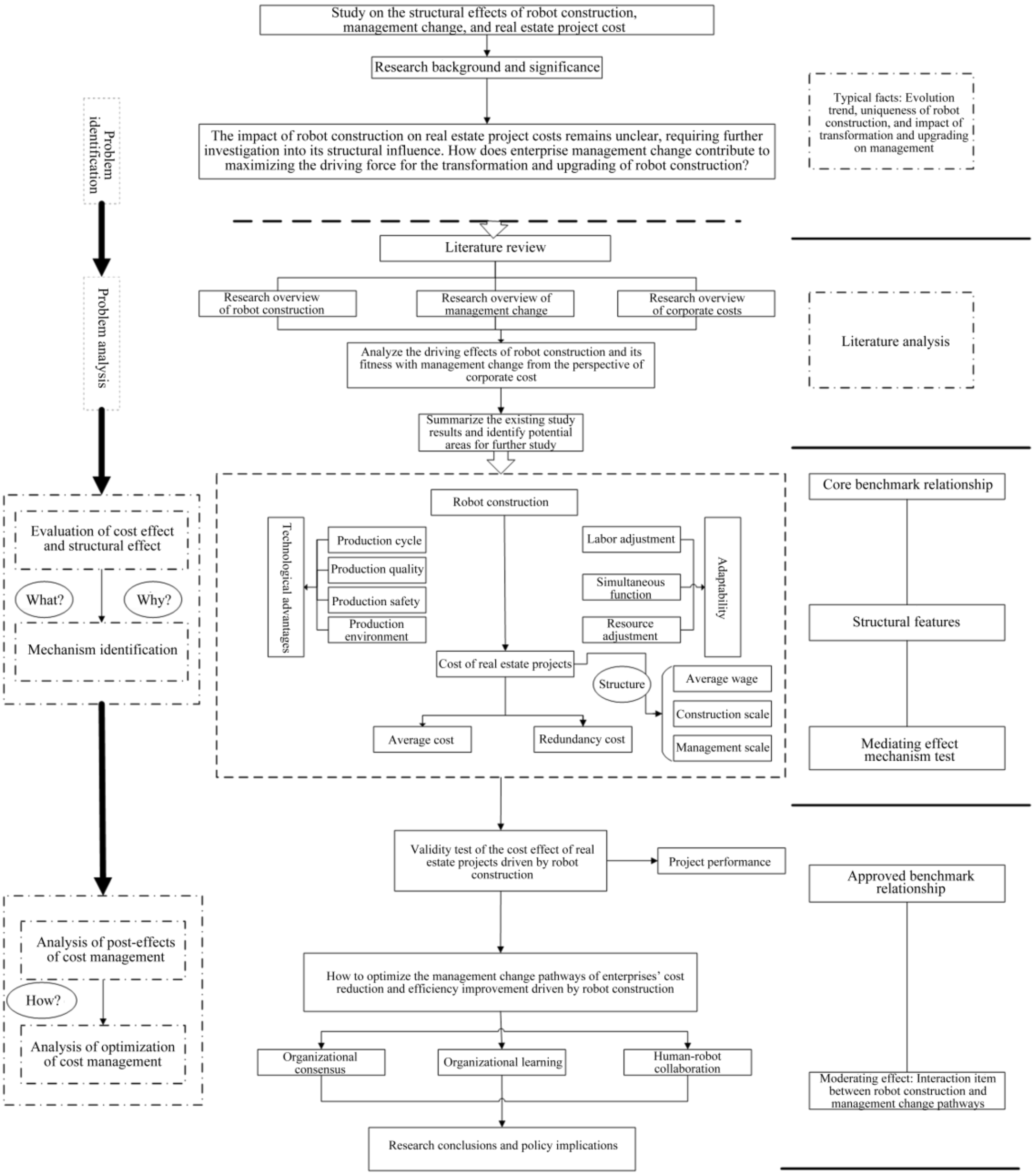

Figure 3-2 Technical Route

Chapter II Literature Review

This chapter primarily reviews and summarizes relevant literature on the topic to establish the starting point for this study. Building upon existing studies, it identifies the potential areas for further study. The literature review in this chapter focuses on three dimensions: robot construction, organizational change, and cost. It clarifies the concepts and stylized facts of these dimensions, summarizes the measurement methods for robot construction, examines the antecedents and consequences of these dimensions, and compiles relevant literature about the impact of robot construction on the cost of real estate projects, thereby providing a solid research foundation for the subsequent empirical research.

2.1 Research Overview of Robot Construction

In this section, this study begins by defining the concept of robot construction. Subsequently, it summarizes and reviews the measurement methods of robot construction. Furthermore, it focuses on summarizing the impacts of robot construction on various aspects such as economic behavior and performance.

2.1.1 Concept and stylized facts of robot construction

(1) Concept of robot construction

The thriving development of information technology, sci-tech innovation, and the digital economy has propelled the self-renewal of the construction industry. Robot construction, or “intelligent construction,” has emerged as an undeniable direction for the future. In April 2013, the German government introduced “Industry 4.0,” emphasizing the use of innovative information technology and other means to promote the intelligent upgrading of the manufacturing industry and achieve the goal of intelligent manufacturing. On the other hand, the UK government directly put forward “Construction 2025,” which highlights the need for the construction industry to develop toward intelligence and sustainability. The Ministry of Housing and Urban-Rural Development of the People’s Republic of China and 12 other authorities issued the *Guidance on Promoting Coordinated Development of Intelligent Construction and Construction Industrialization*. It emphasizes the need for the construction industry to upgrade toward industrialization, digitization, and intelligence. The aim is to accelerate the transformation of construction methods, promote high-quality development in the construction industry, and build the brand of “Chinese Construction.” Robot construction in the construction industry is already an unstoppable trend and plays a significant historical role in the era of Construction Industry 4.0. As the fourth industrial revolution in the construction industry, “Construction Industry 4.0” aims to utilize new information and digital technologies to empower the entire construction process, enabling the transformation from traditional to intelligent construction methods.

With the increasing demands for efficient, energy-saving, environmentally friendly, and safe production of engineering construction, as well as the rising construction costs, the exclusive dependence on conventional construction methods has emerged as a hindrance to enterprise growth. Consequently, integrating robots into the construction sector is vital for attaining substantial advancements in construction quality. Štefanič and Stankovski (2018) explored robot construction in the housing construction phase. F. Yuan and Y. Hu (2017) applied machine learning and algorithmic thinking to the design and construction phases, specifically examining the automated design and construction process of brick structures in housing. Duan et al. (2022a, 2022b) took robot construction projects as an example to analyze the practice of construction robot adoption, explore the digitization process of enterprises during the robot construction process, and examine the specific construction methods. Robots have already been widely adopted in manufacturing production, with industrial robots among the most prominent. However, the overall development of robot construction in the construction industry is still in its infancy. In particular, in contrast to the advancements in promoting robots in manufacturing, there remains substantial untapped potential for the implementation of construction robots. Before understanding the effects of robot construction on the construction industry, it is necessary to determine the focal point of this study—the starting point for research on robot construction. By summarizing relevant research on robot construction, this study has identified existing research on the understanding and definition of robot construction, as shown in Table 2-1.

Table 2-1 Definition of Robot Construction by Domestic and Foreign Scholars

	Author	Definition of robot construction
Foreign literature	Kong et al. (2020)	Robot construction involves the integration of intelligent computers, information and communication technologies, and other integrated technologies to merge the entire construction process with physical systems. This enables the implementation of management and control over various elements such as personnel, machinery, and facilities involved in the construction process.
	Chen & Liu (2013)	Robot construction is the integration and application of advanced technologies such as control, information, and communication in the design and construction phases.
	Song & Yang (2020)	Robot construction involves the application of computer information technology and other advancements in architectural design, project management, construction, and economic accounting to promote the intelligent and automated upgrade of the construction. It aims to enhance management capabilities, improve building quality, and ultimately achieve increased economic benefits in construction projects.
	Wang et al. (2012)	Robot construction is an innovative construction concept that adapts to the development of the new era. It involves the use of new technologies to revolutionize the construction processes and methods in traditional construction. Ultimately, the goal of robot construction is to achieve resource conservation, cost optimization, pollution reduction, and efficiency improvement for project construction.
	Dewit (2015)	Robot construction transforms the construction industry through the use of new technologies like robots to reduce the excessive reliance on manual labor, thereby improving construction accuracy, minimizing resource waste, and achieving the goal of enhancing construction quality and efficiency.
Domestic literature	L. Ding (2019)	Robot construction is an innovative construction model formed through the deep integration of new information technology and engineering construction processes. Specifically, it realizes the integration and collaboration of project decision-making, planning and design, construction, and operation and maintenance processes with the support of new information technology, thereby promoting the extension of the construction value chain and optimization of the industry structure.
	Z. Mao (2018)	Robot construction is a more advanced production method that integrates advanced technologies into design and construction to achieve interaction, coordination, decision-making, execution, and feedback between humans and robots, thereby enhancing the quality and efficiency of engineering construction activities.
	Y. Cai (2021)	Robot construction is an innovative construction model that involves the integration and application of various new technologies throughout the entire lifecycle of construction. It utilizes data to drive the connection and coordination of the entire construction process and all production elements, improving and updating existing construction technologies, construction processes, and management methods. The goal is to achieve safe, environmentally friendly, high-quality, and efficient construction and ultimately provide users with intelligent engineering products and services.
	Z. Liu et al. (2019)	Robot construction is an innovative construction method that highly integrates informatization, intelligence, and the engineering construction process. It establishes intelligent construction sites based on physical information technology and combines design and management to achieve a dynamically configured production method, thereby transforming and upgrading construction methods.
	C. Mao & Peng (2020)	Robot construction is an innovative production method that empowers the entire construction process with new technologies, connects the entire process with data, and facilitates the upgrading of construction productivity, relationships, and elements based on the high integration of informatization and industrialization to achieve information integration, business collaboration, resource value maximization, and construction process efficiency improvement across the entire industry chain.

There is a noticeable rise in the academic community's focus on robot construction, leading to the development of a fairly diverse and not completely unified definition. In 2014, the International Organization for Standardization (ISO) defined the industrial robot as a robot with multi-jointed mechanical hands or multi-degree-of-freedom designed for industrial applications. It is an automated machine that carries out tasks and performs various manufacturing functions through the pre-programming of computer programs or AI technology. Based on the insights shared by multiple scholars, this study views robot construction as a pioneering manufacturing approach that enhances the entire construction process through the incorporation of advanced technologies. It facilitates the seamless implementation and coordination of the "replacement of human labor with machine" concept across the complete lifecycle of engineering construction. This includes decision-making, planning and design, construction, and operation and maintenance stages to promote information integration, foster collaborative business practices, optimize resource utilization, and enhance efficiency throughout the industry value chain. This transformative approach is underpinned by key digital technologies like Building Information Modeling (BIM), the Internet of Things (IoT), big data analytics, cloud computing, and AI.

Robot construction is transforming and upgrading traditional construction methods that heavily rely on human labor. Scholars have summarized the characteristics of robot construction from various perspectives, including key elements and processes. Li Xiaojun (2020) summarized the characteristics of robot construction in the construction industry from five aspects: interconnection, data, logic, integration, and innovation. Based on recent practices and explorations in infrastructure robot construction, Fan et al. (2020) summarized the characteristics of robot construction, including closed-loop control, cognitive response, data-driven operations, online connectivity, collaborative sharing, and continuous optimization. C. Mao and Peng (2020) introduced the concept of robot construction and identified four major characteristics: flexible construction, continuous optimization, data-driven operations, and service upgrading.

(2) Stylized facts of robot construction

Since the successful development of the first robot by American George Devol in the 1950s, the evolution of robotics technology can be summarized into four stages (C. Chen et al., 2022). In the first stage, spanning from 1958 to 1970, characterized as the playback robot phase, robots executed predefined instructions to carry out designated tasks. These machines found utility in industrial manufacturing, engaging in activities like casting, forging, stamping, welding, and various other production processes (T. Yang et al., 2020). Transitioning to the second stage, covering the period from 1970 to 1984, robotics technology witnessed a notable evolution as machines with perceptual capabilities and adaptive functionalities emerged. These robots could adjust their operations based on offline programming and the objects they interacted with (Niu et al., 2022). During this stage, robots acquired the ability to perceive their surroundings using vision, tactile senses, force feedback, and various other sensory capabilities. They were primarily used for assembly, forging, painting, welding, and maintenance (C. Chen et al., 2022). Simultaneously, the concept of specialized construction robots was first introduced in the 1970s. After numerous experiments, the first construction robot (SSR-1) was successfully applied to fireproof coating operations in 1982. Following this milestone, countries such as the United States, developed European nations, and Australia invested in construction robot research, aiming to replace human labor in hazardous and physically demanding construction tasks. The third stage, from 1985 to 2014, marked the era of intelligent robots. In this stage, robots were equipped with diverse sensors enabling them to amalgamate data from various sources and adeptly adjust to dynamic environments. These robots demonstrated the ability to function akin to human thought processes, showcasing robust adaptability, learning capabilities, and autonomous functions (T. Yang et al., 2020). The fourth stage, from 2015 to the present, signifies the onset of the Construction Industry 4.0 era. During this phase, robot construction technology has advanced to a heightened level of intelligent construction. Data-centric intelligent construction has emerged as a pivotal trend, with robots serving as a central element in intelligent construction frameworks. The fusion of robots with digital technologies is fundamentally reshaping the landscape of the construction industry. (C. Mao & Peng, 2020).

From the standpoint of robot development, robotics technology has consistently been prioritized in industries characterized by challenging and demanding working conditions (N. Meng et al., 2021). The construction industry is widely recognized as the second most hazardous industry after mining. The construction industry in China is prone to frequent safety accidents, and construction workers face extremely high labor intensity. Compared to industries such as automotive and electronics, the construction industry still heavily relies on manual labor, resulting in low productivity (Zhang Haohan, 2021). Therefore, the introduction of robotics technology in the construction industry is a necessity and an inevitable trend of the times. Currently, with the expansion of human construction activities, construction robot adoption can be further extended to high-risk environments that are unsuitable for humans, such as nuclear radiation contamination, high temperatures, high pressures, and underwater operations. Additionally, construction robots can liberate humans from repetitive, simple, and heavy traditional construction tasks, further promoting social progress and civilization (F. Lin et al., 2021).

Although China is a latecomer in construction robots, it has shown remarkable advantages and achieved certain results. In recent years, Chinese enterprises have begun to develop construction robots, such as Bright Dream Robotics under the Country Garden, WEIBUILD, and Smart Construction. Some traditional construction enterprises have also established their robotics departments in response to this trend. Currently, automated or semi-automated robot equipment capable of specific construction tasks is emerging. According to the consulting firm Guidehouse Insights, the global market for construction robots is projected to reach USD 11 billion by 2030, with an annual growth rate of 29%. For the future market for construction robots in China, authoritative data indicates a market size of RMB 2 trillion. However, due to the complexity, harshness, and diversity of construction environments, the workload that construction robots can handle is still far from meeting the actual needs of engineering projects. This indicates that the global market for construction robot adoption is still in its nascent stage of development.

2.1.2 Measurement indicators of robot construction

There is limited literature focusing on the economic management of construction robots, with most available literature being technology or introductory research. This study examines the impact of robot construction on the cost of real estate projects. One of the key issues is the need to adopt appropriate scientific methods to measure robot construction. In this regard, this section will review existing literature on measurement techniques for robot construction to establish the basis for quantitative analysis in this study.

As mentioned earlier, quantitative studies specifically focused on construction robots are scarce. Existing research mostly discusses the quantitative aspects of overall industrial robots, focusing on macro-level or industry characteristics aspects to establish the indicator of robot adoption. In this regard, Acemoglu and Restrepo (2017, 2020) are pioneers in this field. They used the IFR Global Industrial Robot Database, which provides industrial robot data of more than 70 countries and regions across 17 industrial categories. The database reveals country-specific industrial robot stock data by sector, and based on the conversion of the weight ratio between industrial robots and labor, constructs an indicator of "robot penetration" at the regional level in the United States. Many subsequent researchers have adopted a similar approach for measurement. For example, Jiang Wei et al. (2022) constructed weights based on the proportion of employment in each province's subdivided industries relative to the total national employment in that industry, aggregating industrial robots to the provincial level to measure the indicator of the impact of robots in China. The measurement of robot penetration at the regional level can also be found in other literature (X. Dong et al., 2022; Ming & Hu Jiaqi, 2022; X. Wang et al., 2022; W. Yuan et al., 2022). As research progresses into the enterprise behavior at the micro level, researchers have utilized this weight measurement method to quantify the indicator of robot adoption at the enterprise level (Sheng & Bu, 2022; Y. Wang & W. Dong, 2020).

Undoubtedly, measuring robots at a micro level can present challenges as it may yield ambiguous, rudimentary, and indirect outcomes. To counter this, researchers have turned to sources like the China Industrial Enterprise Database and China Customs Database to glean insights into the utilization of robots within enterprises at the micro level. As per data from the IFR, before 2013, more than 70% of China's industrial robot demand was met through imports. Based on this, they used the import of industrial robots as a proxy variable for robot utilization by Chinese enterprises. This data is the trade data for enterprise products sourced from the China Customs Trade Database of the General Administration of Customs of the People's Republic of China (Fan et al., 2021; L. Feng et al., 2023; X. He et al., 2023; X. He & K. Liu, 2023; Li Lei et al., 2021). This indicator presents a more precise gauge of robot deployment within enterprises at the micro level compared to the previous weighted conversion approach. Nevertheless, it is crucial to underscore that this data has its constraints. The data derived from the China Customs Database only reveals the quantity of robots imported by individual enterprises. Should these imported robots be sold to other entities subsequently, the utilization by those businesses may go undocumented, possibly resulting in an underestimation of the extent of robot implementation across enterprises. Furthermore, the data showcases a limited perspective, primarily focusing on enterprise robot adoption trends based on robot stock and whether robots are integrated. Hence, there is a necessity to enhance the informational content.

To more accurately measure the use of robots in enterprises at the micro level, researchers have recently turned their attention to survey data. By utilizing survey questionnaires and interviews, it is possible to delve into the frontline of enterprises and obtain direct information on the use of robots. Deng Yue and Jiang Wanyi (2022) utilized the China Employer-Employee Survey (CEES) to empirically examine the impact of industrial robot adoption on enterprise technological innovation. This database provides information on whether enterprises use robots, making it an excellent sample for researching this topic. C. Fan and Deng Yunxue (2022) utilized the “Survey on Labor Employment in Manufacturing Enterprises for Advancing Intelligent Manufacturing” organized by the Human Resources and Social Security Department of Guangdong Province to collect data on the adoption of automation technologies in enterprises. The study also analyzed labor-related data and investigated the effects of the “replacement of human labor with robots” on unemployment concerns. Deng Yunxue and Liu Xiao (2022) analyzed the impact of the “replacement of human labor with robots” on women’s employment based on the GDEES survey (“Guangdong Employer-Employee Survey Data”) organized by researchers from South China Normal University and other units. L. Chen et al. (2023) discussed the impact of robot adoption on enterprise employment decisions based on survey data from 800 Guangdong-based enterprises in 2019. The survey data was collected through a sampling survey conducted in November 2019, jointly organized by the Human Resources and Social Security Department of Guangdong Province, Nanfang Daily, and Sun Yat-sen University. The sample covered 21 prefecture-level cities in Guangdong Province, with a total of 800 valid questionnaires. The questionnaire covered detailed information such as whether the enterprise utilized robots.

In comparison to the indirect measurement techniques used to assess robot adoption by enterprises, utilizing robot variables derived from micro-level research data offers a more accurate measurement. This approach unveils detailed dimensions like the composition of the enterprise workforce and its performance, thus establishing a robust groundwork for in-depth analysis. However, it is also important to emphasize that the aforementioned survey questionnaires, as a measurement technique, mostly focus on the binary question of whether or not robots are adopted. They rarely discuss the breadth and depth of robot adoption by enterprises and organizations or delve into the resistance and willingness to adopt robots within them. Additionally, these questionnaires tend to homogenize robots and categorize them under the general label of “industrial robots,” lacking characterization of the adaptive robot features specific to different enterprises. As a result, they lack more detailed evidence on industrial robots.

This study focuses on the economic evaluation of robot adoption in the construction industry. Unlike existing research highlighting a general characterization of robot adoption, it is necessary to extract robot adoption conditions in a specific industry. Therefore, as mentioned earlier, using the IFR Global Industrial Robot Database or China Customs Database to indirectly measure robot adoption may result in imprecise and rudimentary assessments. The robot adoption evaluated using existing survey questionnaire data offers valuable insights into measuring robot utilization in the construction industry. However, these surveys currently lack enterprise-specific data for the construction industry. Furthermore, the characterization of robot adoption is deemed too simplistic, thereby necessitating further research advancement.

2.1.3 Influence of robot construction

There is an absence of direct exploration regarding the impact of robot adoption in construction within the existing literature. Given the substantial uptake of industrial robots, this discussion could be incorporated into the broader literature on overall robot adoption. Currently, robots as a new factor input in technological progress have profoundly reshaped the production models of enterprises, garnering extensive attention from government, enterprises, and research institutes. There exists a substantial volume of research on the economic effects of robots, with a focus on aspects like economic growth, production efficiency, technological advancements, industry chains, employment, trade, income distribution, and green economy (Acemoglu & Restrepo, 2016, 2019; Aghion et al., 2017; Cao & Y. Zhou, 2018; Li Lei et al., 2021). However, a consensus viewpoint has yet to be formed in the academic community regarding these various topics.

Among these topics, a significant amount of research has focused on the impact of robot adoption on the labor market. Robots are often considered a prime example of technological progress. From this perspective, robots can have both replacement effects and potential incentive effects on labor market demand (Aghion & Howitt, 1994). The employment equilibrium effect driven by both only requires an assessment of the magnitude of their effects (Li Lei et al., 2021). Acemoglu and Restrepo (2018a) conducted a foundational theoretical analysis of the employment implications of robots. Their study revealed that robot adoption results in a combination of replacement and complementarity effects. They observed that automation technologies can result in "technological unemployment," displacing labor in conventional production settings. However, these new technologies can create new employment opportunities. Expanding on their earlier work, Acemoglu and Restrepo (2020) carried out a study focusing on the U.S. labor market. Their findings indicated that the adoption of robots from 1990 to 2007 indeed resulted in a decline in employment across the United States. Specifically, for every additional robot per thousand workers added, there was a reduction in the share of employment by an estimated range of 0.18% to 0.34%. Furthermore, wages were observed to decrease by approximately 0.25% to 0.5%. Kong et al. (2020) explored the labor market dynamics in China and discovered that the adoption of robots led to a significant decrease in local labor employment in the subsequent year. This underscores the substitution effect of robots on traditional labor practices. Nevertheless, over the long term, it was observed that robot adoption contributed to an increase in employment opportunities. For the examination of the impact effects on China's manufacturing industry and urban labor market, the evidence is similar (M. Han et al., 2020; X. Song & M. Zuo, 2022; X. Wang et al., 2022; Y. Wang & W. Dong, 2020). However, the effects of robots on production efficiency improvement and cost reduction (Graetz & Michaels, 2018) can give rise to new production models and new positions (Gregory et al., 2018; Wang Wen et al., 2020). As a result, the impact of robots on total employment is not solely characterized by a simple "replacement of human labor with robots" outcome (L. Zheng & D. Liu, 2023). In the long term, the scale effects brought about by robot adoption can lead to an expansion in labor demand and drive employment growth (Autor & Salomons, 2018; L. Chen et al., 2023; Gaggl & Wright, 2017; Kong et al., 2020; Li Lei et al., 2021). Due to the divergent effects of the two mentioned above, the equilibrium impact on employment is likely to be uncertain (Dauth et al., 2018; Graetz & Michaels, 2018; L. Zheng & D. Liu, 2023).

Substantial evidence indicates that evaluating robots' effect on aggregate labor employment is a controversial issue. This controversy arises primarily from the structural characteristics of the workforce, which determine which roles robots will substitute for or work alongside and the nature of the new jobs that develop as a result. There seems to be a consensus in the academic community. Employment polarization is a significant trend driven by robot adoption (Acemoglu & Autor, 2011; Autor, 2015; F. Cai, 2019; Goos et al., 2014; Graetz & Michaels, 2018). The polarization is characterized by the replacement of middle-skilled workers. However, there is a trend of scale expansion in low-skilled and high-skilled employment. X. He and K. Liu (2023) deconstructed the robot industry from the dimension of work tasks, finding that robots promote unconventional task employment but may replace jobs involving conventional tasks. X. Song and M. Zuo (2022) examined the structural attributes of the industry chain and human capital. They found that robot adoption has particularly prominent replacement effects on labor employment in upstream enterprises with a high proportion of production personnel and a low proportion of employees with a high school degree. Polarization is also manifested in labor mobility. Increased robot density is expected to create more jobs, attracting a larger labor force and significantly boosting employment for unconventional tasks (X. Wei et al., 2020). In addition, the structural characteristics of employment driven by robot adoption are also reflected in job positions. Autor and Dorn (2013) established an unbalanced productivity growth model and analyzed the low elasticity in product substitution between the service and the manufacturing industries. They observed that when computer technology reduces the production cost of stylized tasks, the replacement of low-skilled labor by machines may increase the employment share within low-skilled service industries. J. Qi and Fu (2022) highlighted that robot adoption reduces the number of jobs in the secondary industry, leading a portion of the low-skilled labor force to flow into the service industry. The robot adoption also compels individuals to join the ranks of informal employees (Chen Jiaying et al., 2022). Fan and Deng Yunxue (2022) analyzed the distribution of workers' concerns about unemployment under "replacement of human labor with robots" based on the data from the "enterprise-employee" matching survey conducted in the Guangdong manufacturing industry. They found that nearly 30% of workers are worried about technological unemployment. The workers in easily replaceable positions are significantly more concerned about technological unemployment compared to those in positions that are difficult to replace. Additionally, workers with fewer years of education are more likely to worry about technological unemployment.

It is easy to understand that robot adoption naturally affects the income distribution among labor factors while impacting the labor market. Robots, considered as capital goods, exhibit increasing marginal returns (Karabarbounis & Neiman, 2014), thus incentivizing enterprises to increase the capital factor share of robots. More importantly, robots possess comparative advantages over low-skilled labor and ordinary capital and thus can replace more types of labor, resulting in an increase in capital share and a decrease in labor income share (Brynjolfsson et al. 2014). Dinlersoz and Wolf (2018) utilized survey data from the manufacturing industry in the United States to verify their findings. They found that in enterprises with a higher degree of automation, the proportion of labor income is lower in production, while the proportion of capital income is higher. Additionally, a smaller proportion of production workers can gain high wages. DeCanio (2016) also found that this decline in labor income share even causes the crowding-out effect of capital goods input on the wage rate, aggravating the unequal income distribution. Yu et al. (2019) found based on the survey data from enterprises in Guangdong that the use of robots promotes both wage rate and labor productivity growth. However, the increase in labor productivity is more significant, which generally leads to a reduction in enterprises' labor income share. Based on the survey data from Chinese enterprises in 2018, Cheng Hong et al. (2021) found that the use of robots leads to approximately a 4% decline in labor income share. G. Zhou and Ding Xiangyuan (2022), using data from a survey on income disparity among urban residents in China, discovered that the widespread use of industrial robots notably expanded the income gap among urban residents. The literature that challenges these studies highlights that the impact of robots on labor income share is similar to their impact on employment polarization. It cannot be simply identified as a reduction in employment (Acemoglu & Auto, 2011), and only middle-skilled workers suffer greater income losses (Dauth et al., 2017). Acemoglu and Restrepo (2017b) conducted a deeper analysis based on the findings of previous studies. The traditional view holds that high-skilled workers may not be vulnerable to declining wage rates because they are difficult to replace. However, robots may also replace high-skilled workers over time, leading to a reduction in their wages. It is concluded that the total effect of robot adoption on wages remains uncertain. Nevertheless, automation invariably exacerbates wage inequality among low-skilled workers, while it tends to reduce wage inequality among high-skilled workers.

Another mainstream of literature directly assesses the effect of robot construction at the macro level such as economic growth. In terms of economic growth, robots, as a typical carrier under AI and digital transformation, have sparked a second wave of machine revolution and driven unprecedented technological progress (Brynjolfsson & McAfee, 2014). The endogenous economic growth model exactly defines technological progress as the only eternal driving force for economic growth (Solow, 1956). The application of robots to fuel economic growth has gained widespread consensus in many studies (Acemoglu & Restrepo, 2018a; Hanson, 2001; Yang Guang & Hou Yu, 2020). The mechanisms include the new automated production models created by robots (Acemoglu & Restrepo, 2018a), productivity improvements (Acemoglu& Restrepo, 2018c; Graetz & Michaels, 2018; Kromann et al., 2011; Qu & J. Lyu, 2022), technological innovation (Deng Yue & Jiang Wanyi, 2022; L. Feng et al., 2023), and value chain advancements (Huang Liangxiong et al., 2023; B. Liu & T. Pan, 2020). However, Acemoglu and Restrepo (2018c) highlighted a mismatch between the skills required for new technologies and those provided by the workforce, exacerbated by the rapid introduction of automation. New tasks require new skills and economic transformation will be hampered if the education system does not promptly provide these skills. In addition, the current tax system tends to subsidize capital rather than labor. This, combined with the friction and imperfection of the labor market, results in an equilibrium wage higher than the social opportunity cost of labor. Consequently, there is an over-adoption of automation technology and a misallocation of capital and labor, hindering labor productivity improvement.

Additionally, there is literature that focuses on the impact of robot adoption on economic externality. Green production is considered to be a major contribution of robot adoption (Li & Lin, 2018). This, together with the improvement in unit energy efficiency arising from technological progress, will reduce carbon emissions (X. Pan et al., 2017). The improvement in energy efficiency brought by robot adoption primarily stems from increased output, rather than the reduction in energy consumption during production (Huang et al., 2022). Robot adoption mainly relies on the effects of R&D growth and labor substitution to reduce pollutant emissions and bolster the environmental performance of enterprises by boosting front-end productivity and end pollution control capabilities (H. Chen et al., 2021; Sheng & Bu, 2022). Jiang Wei et al. (2022) introduced robots and carbon emissions into the monopoly competition model of heterogeneous products, building a theoretical basis for the application of robots to affect carbon emissions. They analyzed the scale emission increase effect and technical emission reduction effect of robots through capital-embodied technological progress. Leveraging China’s panel data, it is found that the average technical emission reduction effect of robots is higher than the scale emission increase effect. This net effect reflects a remarkable reduction in carbon emissions. Moreover, the use of robots has driven process innovation, that is, the implementation of new processing methods, production processes, and testing methods has enhanced the quality within enterprises (Cheng Hong & L. Yuan, 2020). By inspecting the adjustment to the scope of export products, J. Qi and Z. Zhang (2022) found that robot adoption can enhance product quality and contribute to green emission reduction. The United States Census Bureau's Annual Business Survey (ABS) 2019 statistics revealed that among enterprises adopting robots, approximately 80% (weighted by the number of employees) reported using robots to enhance the quality of their products or services, 65% to upgrade existing processes, and 54% to automate existing processes.

In recent years, robot construction has garnered wide attention from researchers, leading to a wealth of research findings that offer valuable insights for the development of this study. The above literature employs theoretical or empirical models to evaluate the economic effects of robot construction from multiple dimensions such as labor impact and economic growth. From the perspective of situational research in China, most studies utilize macro-level data to analyze robot adoption. A small amount of literature captures the situation of robot adoption through questionnaires, highlighting the need to improve the accuracy of robot identification further. In terms of research content, most studies focus on the impact of robots on the labor market (including wages). However, there is a notable scarcity of detailed discussions on the impact of robots on enterprise costs. The limited literature available makes hypothetical presumptions about the cost impact in the analysis (reducing production costs), lacking corresponding empirical evidence.

2.2 Research Overview of Management Change

This section first defines the concept of management change and then summarizes and reviews the measurement methods of management change. Furthermore, it delves into the driving factors of management change, focusing on the interactive relationship between robot construction and management change in the context of digitalization and AI.

2.2.1 Concept of management change

(1) Definition of management change

The term “change” usually refers to alterations in the nature of things, and scholars have different understandings of this concept. Some scholars view change as a process of transforming things entirely from one state to another. Others define “change” as an alteration in the development mode of affairs, often representing a directional transition from the initial state to an advanced state. Additionally, some scholars interpret “change” as a transformation in the structure of things. Management change is a broad concept, with scholars both domestic and international putting forth diverse definitions for it.

Management change refers to the process in which enterprises introduce new management modes to address environmental changes, replacing outdated management practices with modern management approaches (Chen Yu, 2006; Wang Zhongtuo, 2000). In the knowledge economy era, enterprises’ management change is mainly reflected in the change in business processes, organizational structures, management philosophies, management technologies, institutional innovation, and corporate culture (Yin Jidong, 1998; Yue Yihong & W. Han, 2002). Therefore, management change mainly includes changes in management concepts, organizational structures, management systems, and management techniques and methods (Yin Jianfeng & Long, 2017). Z. Zeng and Yu (2011) focused on analyzing the change characteristics of management philosophies, organizational structure, and management technologies under the impact of information technology, emphasizing that learning organizations, flat organizations, and manufacturing models are new characteristics of management change.

As the information technology revolution advances into the 4.0 era, digital technologies represented by AI and big data have emerged, greatly impacting traditional management theories. The dimensions and focus of management change have become more targeted. Xiao Jinghua (2020) emphasized the management adaptive change path under the cross-system digital transformation in enterprises. Management adaptability refers to an organization’s ability to appropriately respond to environmental changes through management (Stieglitz et al., 2016). In this framework, adaptive organizational learning plays a crucial role in facilitating management adaptive change. Management adaptability primarily addresses organizations’ complex feedback and nonlinear problems arising from uncertain expected results, rather than simply pursuing management efficiency (Ostrom, 2009). P. Xu and X. Xu (2020) divided management change into five dimensions:

management objects, management attributes, management decisions, and management ethics to explore the path of enterprise management change in the context of AI. Y. Qi and X. Xiao (2020) analyzed the dimensions of management change in the digital economy era. They explored the characteristics of management change from six dimensions, i.e. organizational structure, marketing model, production model, product design, R&D model, and employment model. Xiao Jinghua and Li Wentao (2020) explored enterprise strategic management change in the context of intelligent manufacturing, making analysis from the perspectives of Internet value, open innovation, and platform ecology. D. Chen et al. (2020) examined the impact of digitalization on the original ecology of enterprises, resulting in major challenges to their organizational structures. Organizational structures, platform-based governance, and human-robot interaction have emerged as important aspects of management change. X. Wu et al. (2022) used a new organizational learning model based on AI-human collaboration as an example to explore the specific path of management change and analyze the change form of organizational learning under the human-robot interaction model.

To sum up, domestic and international scholars have offered various explanations for enterprise management change based on different theories and research perspectives. This concept can be interpreted in both broad and narrow senses. Management change in the narrow sense refers to adjustments and innovation in the management structure or form, while in the broad sense, it encompasses innovation across all aspects of enterprises, such as strategy, process, production management, and product and service quality. The management change studied in this paper is a broad concept, meaning that enterprises adjust or renovate the internal factors related to organizational structure locally or wholly to adapt to the changes in the internal and external environment, thereby enhancing their competitive advantages.

2.2.2 Research on robot construction and management change

In recent years, the academic community has initiated research on management change in the digital era (D. Chen et al., 2020), with a focus on robot construction. However, existing studies seldom directly discuss and analyze the interaction between robot construction and management change. Most of these studies incorporate the two concepts in the digitization research field.

Specifically, digital application has a significant impact on human resource management (X. Xie et al., 2021). Gao and Liu Jiahui (2018) argued that AI significantly impacts traditional management theories that originated in the industrial age and bureaucratic management may struggle to adapt to changes in the internal and external environment of enterprises (P. Xu & X. Xu, 2020). Additionally, precise performance evaluation and changes in the demand for employees and job competencies may trigger the update of the performance management process. Leveraging the big data management model, enterprises have an increased preference for human capital structures such as inter-disciplinary talent and cross-department data analysis centers. Concurrently, organizational structures rely on interconnected data information platforms to drive management change (K. Yao & Gui, 2018).

From the perspective of management decisions, digitalization-driven management change can optimize enterprises' logistics, capital flow, and information flow, allowing decision-makers to allocate resources more effectively in their development strategies (Xiao Jinghua & Li Wentao, 2020; X. Xie et al., 2021). Duan et al. (2019) underscored the rapid development of AI amidst the emergence of supercomputing and big data technology and explored the impact of AI on management decisions and the possibility of replacing human decision-makers. AI assists managers by alleviating constraints related to knowledge, energy, and time and can create a range of alternatives based on previous case records, thereby aiding decision-makers in making more scientific and rational decisions (Edwards et al., 2000). AI cannot completely replace humans in decision-making due to the division of responsibilities. Instead, it primarily assists in the decision-making process. Shrestha et al. (2019) compared and analyzed the similarities and differences between manual decision-making and AI decision-making from five dimensions, finding that for most managers, the algorithmic decision-making process remains a black box. Managers need to bear responsibility for the results of algorithmic decisions, which has become a significant concern preventing them from authorizing algorithms. Consequently, most managers prefer to make decisions themselves.

From the perspective of management strategy, Xiao Jinghua and Li Wentao (2020) examined the reform of enterprise strategic management in the context of intelligent manufacturing. They highlighted that intelligent manufacturing can reshape original attribute resources and induce changes in resource forms and properties. Furthermore, they proposed that intelligent manufacturing fosters enterprise management strategies that emphasize interconnected value strategies, open innovation strategies, and platform-based ecological strategies. Similarly, the utilization of big data can make long-term decisions on how enterprises integrate resources and capabilities while also aiding in future predictions (Hitt et al., 2012). Big data can display information flow across a broader spectrum, comprehensively reflecting potential changes in business operations in real time (Bhimani, 2015). It can help enterprise managers broaden their business knowledge and make business decisions efficiently and flexibly (Brynjolfsson et al., 2011). Additionally, big data can drive innovation in business models through data monetization and digital transformation (Woerner et al., 2015). The application of big data enables enterprise managers to make decisions based on factual evidence instead of relying on experience and intuition as before, with a more holistic view. Managers must accurately understand the value of big data and make scientific decisions based on data analysis to propel enterprises forward in innovation (Ding Xuechen & Liu Xielin, 2018)

From the perspective of organizational change, Mosmann et al. (2019) examined how organizations in a community coordinate their members' activities and cultivate their sense of community through effective governance. By comparing 13 organizations operating under the sharing economy model, they identified three levels of governance models for platforms: Adventuring, Harmonization, and Gamification. Studies have indicated that the previously adopted bureaucratic system in organizations is no longer applicable under the impact of AI. Instead, the grid system has emerged as a crucial approach to management change (Gao & Liu Jiahui, 2018; Xiao Jinghua, 2020). AI drives enterprises to transform into an ecosystem, where value co-creation and value synergy have emerged as new business philosophies (Y. Qi & X. Xiao, 2020). Digital intelligence also reshapes the supply chain ecosystem (Chen Jian & Liu Yunhui, 2021), with platformization becoming a trend (Xiao Jinghua & Li Wentao, 2020).

It is not difficult to find that the advent of the digital era has fundamentally transformed the traditional management models concerning management concepts, management strategies, management decisions, business models, organizational structures, and human capital (Ding Xuechen & Liu Xielin, 2018; B. He et al., 2022). A major obstacle to the digital transformation of enterprises, leading them into crises, is their failure to carry out adaptive management change. This inability hinders organizational structures and business operations from adapting to the rapidly changing market environment and fleeting development opportunities (Goles et al., 2019), consequently making digitalization challenging. Many studies have highlighted the importance of digitalization for the future of enterprises, emphasizing that the key to achieving this leapfrog development lies in adaptive management change (Chen Jian et al., 2020; Y. Qi & X. Xiao, 2020; X. Xie et al., 2021). The digital transformation of enterprises is not merely a technical or management problem. It involves a comprehensive reconstruction of the operation model and value creation methods through digital technology. It represents an adaptive change in digital management (Xiao Jinghua, 2020; K. Xie et al., 2020). The transformation from the industrial economy to the digital economy has significantly influenced the adaptive change of enterprises, propelling them to gradually shift from the bureaucratic model to the grid system model. Thus, they can present some new characteristics such as high adaptability to rapid environmental changes and diversity in organizational innovation (B. He et al., 2022; K. Xie et al., 2020). Existing studies highlight that enterprises must break through the original pathway of industrialization adaptation, implement adaptive management change, and develop innovative adaptive responses to management in the era of the digital economy. This approach is essential to achieve cross-system digitization advancements (Goles et al., 2019; F. Wu et al., 2021; K. Xie et al., 2020).

Research on the interaction between robot construction and management change is still in its early stages (G. Han & Li Wenrui, 2021; M. Huang & Li Lin, 2020), with only a few studies addressing the topic. The wide application and rapid commercialization of technologies such as robot adoption, AI, big data, and cloud computing have significantly impacted and challenged the theoretical knowledge basis, cost management process, quality risk prevention, organizational management, talent management, and evaluation system standards of traditional project management (G. Han & Li Wenrui, 2021). Intelligent construction effectively builds a project management system model of diversified big data integrating data analysis, knowledge structure, and function model, transforming the enterprise project management system at the physical layer, data layer, knowledge layer, exchange layer, and application layer of the data analysis platform system (M. Huang & Li Lin, 2020). Duan et al. (2022a) highlighted in their research that robot construction can advance the informatization development of project management within construction enterprises. This approach can realize the organizational optimization of project management and enhance the control of project quality through collaborative construction with the BIM system. Taking the ST project adopting robot construction in Guangzhou as an example, Duan et al. (2022b) further highlighted that robot construction has realized full digitalization of the project. They also noted that the project has received positive feedback regarding construction standardization and management refinement. The introduction of robot construction in the construction industry also presents new challenges to the construction environment. It necessitates changes in site layout and management mode transformation for project management operation and maintenance. Implementing digital management methods and promoting digital management technologies such as BIM and FMS are essential to enhance management efficiency (C. Chen et al., 2022; Z. Liu & J. Shen, 2021).

Based on the above literature, it is widely agreed that the management model evolves over time and continually adapts to changes. In the digital age, the demand for management change intensifies. Existing studies have constructed the theoretical framework and model of management change in the context of digitalization from multiple dimensions. These studies predominantly explore digital technologies, such as big data, AI, and cloud computing, as well as the interaction between digital applications and management change. Robot construction is a concentrated representation of digitalization in the specific construction industry. Unfortunately, the academic community has not yet focused on the detailed deconstruction of its relationship with real estate project management change. Some literature on this topic is largely empirical and lacks theoretical construction. More importantly, there remains a significant gap in the quantitative identification of the interaction between robot construction and management change. Unveiling this black box through unique data and technical means is crucial for making breakthroughs in in-depth research in this field.

2.3 Research Overview of Corporate Costs

Cost is a term originating from the field of economic research, which is generally regarded as an expression of resource and labor expenditure in money terms. This section first summarizes the influencing factors of costs, specifically focusing on the influencing factors of construction costs of real estate projects (excluding the land acquisition cost). Secondly, it analyzes the interaction between organizational change within enterprises and costs. Thirdly, it focuses on discussing the impact of robot adoption in the real estate project construction process on the costs of real estate projects.

2.3.1 Concept and measurement of corporate costs

Classical economics analyzes enterprise behaviors according to cost changes and simplifies costs into fixed costs and variable costs. It is generally believed that when an enterprise’s operating revenue decreases, its costs will proportionally decrease as well. The equilibrium point, where changes in the enterprise’s scale stabilize, is reached when average costs equal marginal returns. In this context, it examines the rational behaviors of enterprises leveraging the interrelationship between cost changes and revenue changes. Cost primarily represents the economic benefits and profitability of an enterprise. Especially in the era of fierce competition and slim profits, “cost reduction” has become an ideal way for enterprises to establish their core competitiveness (L. Guo & M. Wu, 2020).

In the development of modern enterprises, all aspects incur costs. **From an accounting perspective,** costs comprise operating expenses directly related to business activities and fall under the broader category of corporate expenses. Under the increasingly complex market economy, enterprises also incur other expenditures to generate revenue. These expenses ensure the smooth execution of all supporting activities involved in the whole process of production, management, and sales, such as administrative expenses, sales expenses, taxes, and other costs closely associated with production. According to the essential requirements for high-quality accounting information (Zhang Lu et al., 2014), all indicators for enterprise performance evaluation in the profit statement are based on the matching results of operating revenue and structural costs. Therefore, this study suggests that some expense items should be included in the cost analysis. To define the research scope, this study focuses on the operating costs and some expenses of enterprises, excluding financial expenses that are not part of direct costs and related to financing activities. **From the perspective of cost nature,** costs can be categorized into explicit and implicit costs. Explicit costs are visible in the financial accounting data of enterprises as elaborated above, while implicit costs encompass more costs that adhere to conventional “rules.” From the perspective of information flow, costs are associated with information, including those arising from asymmetric information and reputation damage. Representing this cost with data is challenging, but the influence remains continuous, stable, and strong. Accordingly, this study analyzes both explicit financial costs and implicit costs.

Under the above-defined concept, it is important to emphasize that the costs of real estate projects differ from those of general enterprises. The construction and operation of real estate projects have their unique characteristics, often involving a substantial scale of expenditures. The costs of real estate projects are the monetary sum of resources and labor consumed in the whole life cycle, primarily including the expenditure on labor, materials, and machinery at each stage of the life cycle. Therefore, the costs of real estate projects encompass the total expenditures incurred in the whole life cycle from preliminary project approval, feasibility study, scheme decision-making, drawing functional design, housing entity construction, purchase and supply of building materials, real estate sales, human resource coordination, and operation and use. It needs to be emphasized that this study excludes the land acquisition costs of real estate projects. The rationality for this decision is twofold. First, due to the particularity of land policies, land price is largely determined by policies and local governments rather than by enterprises. Therefore, land costs should be addressed as a separate topic, which is not the subject of this study. Second, this study focuses on the construction costs of real estate projects, thus only considering the real estate construction cost after the acquisition of land resources and excluding factors related to land acquisition.

In the following sections, this study will review the literature on costs within the established cost framework.

2.3.2 Influencing factors of corporate costs

Institutional design is regarded as a crucial factor influencing corporate costs. The transaction costs proposed by Coase (1937) epitomize this explanation. Coase highlighted that enterprises and markets are two alternative mechanisms for resource allocation. Market transaction costs are substantial due to bounded rationality, opportunism, uncertainty, and small-numbers conditions. To save these transaction costs, enterprises emerge as a new form of transaction to replace markets. Following this logic, researchers focus on the institutional design with the primary goal of reducing corporate costs (transaction costs). Property rights design represents a classic approach to institutional design. Transactions are the way through which property rights arrangements for research expenditures influence resource allocation, and transaction costs determine the viability of enterprises. The ultimate purpose for enterprises to adopt various organizational modes is to save transaction costs (Furubotn & Rudolf, 1998). W. Zhang (2002) defined transaction costs as “a series of institutional costs, including information costs, negotiation costs, contract drafting and implementation costs, property right definition and enforcement costs, supervision and management costs, and costs associated with changing institutional arrangements. According to different stages of cooperation, transaction costs can be categorized into search and communication costs, negotiation and contract signing costs, and performance costs.” The institutional analysis of changes in rural management rights emerges as a typical example of property right design aimed at cost reduction (K. Cheng & Y. Lu, 2011; Q. Cheng & Xiong, 2016; L. Xie & B. Luo, 2017). S. Wei (2001) estimated the economic costs associated with opacity based on research samples from 35 countries and concluded that “opacity” significantly inhibits a country’s FDI inflow while additionally increasing the operating costs of enterprises. Notably, this opacity does not generate any revenue for governments. His study underscores the systematic impact of robust institutions on enterprise cost reduction.

Externalities are also widely regarded as a systemic solution to reduce costs. Yang Guochao et al. (2021) found in their research that high-speed railway infrastructure construction breaks the geographical segmentation, facilitates the flow of factors, and optimizes the external environment of enterprises, thereby improving their cost management efficiency. Infrastructure construction has been widely recognized for its role in reducing transportation costs and enterprise inventory (H. Li & Tang, 2015; M. Xu & Y. Feng, 2021; Shirley & Winston, 2004).

Policies designed to optimize externalities are often viewed as desirable means to reduce corporate costs. Some studies have found that environmental protection policies, industrial policies, tax reduction policies, and industrial agglomeration can all reduce corporate costs in the long run (Chen, 2021; Hu Jun et al., 2020; Ni & B. Yan, 2021; Shen Hong & Xiang, 2017).

There has been rich and well-established literature on the cost decision factors for individual enterprises. Classical economics places economic subjects in a complete and perfect information environment, but the real world is full of extensive information asymmetry. This discrepancy leads to complex cost decision-making challenges in the context of imperfect information. Cost stickiness, an anomaly in accounting management, has become the focus of cost research. Cost cannot be discussed separately as it is intrinsically linked to enterprise size. The effectiveness of corporate cost management can only be accurately gauged by relating the growth in size to the relative speed of cost growth. In this context, the concept of “cost stickiness” proposed by Anderson et al. (2003) is centrally characterized by the phenomenon where corporate costs do not decrease as much when revenue falls as they increase when revenue rises by the same amount. Undoubtedly, the tendency for costs to rise easily but be difficult to decline places a significant burden on enterprises when revenue falls, thus further deteriorating enterprise performance and threatening enterprise survival. It is a manifestation of inefficient resource allocation. The cause of this anomaly can be roughly attributed to adjustment costs, agency problems, and the management’s optimistic expectations (Banker et al., 2010a). **Adjustment costs** refer to the expenses incurred by an enterprise when its business volume increases or decreases (Liang, 2016; Yang Guochao et al., 2021). These costs include the costs associated with the disposal of idle assets, possible losses from discount sales and severance expenses incurred by dismissing redundant employees when the business volume declines. Conversely, when business volume increases, these costs encompass additional procurement costs for replacing assets, the potential opportunity costs of delays in resource replenishment, recruitment and training costs for re-employed employees, and the opportunity costs of failing to recruit employees promptly. It is generally believed that employee-intensive, capital-intensive, and some resource-dependent enterprises fall into the trap of high-cost stickiness due to significant adjustment costs (Anderson et al., 2003; Balakrishnan & Gruca, 2008; Banker & Chen, 2006a; Stickney & Brown, 1999).

Agency conflict is recognized as a major contributor to the relative increase in corporate costs. In actual operations, even two enterprises in the same industry and of the same business scale may incur greatly different corporate costs. This is because, in addition to business scale, corporate governance (the key mechanism for mitigating agency conflicts) also affects costs. Anderson et al. (2003) highlighted that cost stickiness is a typical consequence of agency problems in case of interest conflicts between the management and shareholders. The above-mentioned agency problems can be attributed to the inconsistency between managers' self-interested behaviors and shareholders' interests (Jensen & Meckling, 1976), referred to by researchers as the first type of agency conflict. Managers try to establish an "enterprise empire," making costs rise easily but difficult to decline. Typically, these managers do not focus on achieving the optimal enterprise size but prioritize large-scale expansion. Their motivation lies in enjoying the associated status, power, compensation (including in-service consumption), and prestige associated with scale expansion, ultimately increasing personal utility (Hope & Thomas, 2008; Jensen, 1986; Masulis et al., 2007; Stulz, 1990). However, such inefficient scale expansion, such as serial M&A and low investment efficiency (Dittmar & MahrtSmith, 2007; Masulis et al.; 2007; Titman et al., 2004), has become chronic issues of modern corporate governance, threatening the survival of enterprises. Taking excessive employee expansion as an example, Williamson (1963) found that the management has too much discretion, resulting in a deviation from the optimal level of staffing. The reasons behind this lie in that the management can increase their self-interest income by expanding the size of employees. Additionally, the costs associated with making decisions and efforts around layoffs can be high, making shirking responsibility an optimal choice (Bertrand & Mullainathan, 2003). Unlike the relatively dispersed equity in mature markets, cost stickiness under agency conflicts in China exhibits new features. Firstly, agency conflict is predominantly reflected in that major shareholders encroach on the interests of minor shareholders (the second type of agency conflict). To conceal their behaviors such as illegal related party transactions, over-investment, and illegal misappropriation of assets of "hollowing out" enterprises, controlling shareholders may disguise various illegal expenses as costs. These illegal expenses are inflexible and difficult to fluctuate with enterprise revenue, thus increasing cost stickiness (Chen et al., 2012; Luan et al., 2022). Secondly, the unique characteristics of state-owned enterprises further amplify cost stickiness. For example, China’s state-owned enterprises bear the policy burden of employment, with CEO promotions being closely related to this responsibility. This leads to excessive labor costs in the CEO cost decision-making process (Liao & Shen Hongbo, 2014; Q. Zeng & X. Chen, 2006). Therefore, it is essential to improve the corporate governance mechanism to mitigate agency problems and reduce the cost stickiness of enterprises (Chen et al., 2012). Numerous studies have found that internal and external governance measures are conducive to alleviating corporate cost stickiness. These measures include enhancing board independence, introducing institutional investors, adopting state-owned enterprise reform, implementing equity incentives, strengthening media supervision, improving external audit supervision, and enhancing internal control quality (Chung et al., 2019; Y. Geng & Y. Ma, 2020; Liang, 2016; Yang et al., 2020).

The management’s optimistic expectations are viewed as another driver influencing corporate costs. Supporters of the management’s optimistic expectations hold that the long-term trend of business volume, such as sales volume, tends to increase gradually. As a result, managers are more likely to estimate the future sales growth of a company optimistically rather than pessimistically, leading them to expect higher future sales volume compared to current sales volume.

Managers may be more reluctant to reduce committed resources in response to a decline in current sales volume because doing so may lead to increased adjustment costs. On the one hand, reducing these committed resources incurs corresponding costs. On the other hand, when future demand for enterprises' products or services recovers, they need to reinvest in these resources. Managers are more willing to add various committed resources if there is an increase in current sales volume, because enterprises will need them more in the future. Managers' optimistic expectations of future sales volume also lead to asymmetric cost fluctuations as business volume rises and falls, leading to cost stickiness. Liang (2015) found that the overconfidence of the management may increase the cost stickiness of enterprises. Y. Song et al. (2019) also found evidence that a CEO's excessive optimism results in a high level of cost stickiness.

2.3.3 Research on the impact of robot construction on corporate costs

Currently, there is limited literature directly discussing the relationship between robot construction and corporate costs. However, the concept of robot construction aligns with the concept of AI regarding robot adoption, industrial robots, and intelligent manufacturing. This clue is hinted at indirectly or directly in many pieces of literature.

Intuitively, **robot adoption impacts enterprises' explicit costs.** The most direct impact is on labor costs. Acemoglu and Restrepo (2018) highlighted that the replacement of human labor with robots increases the competition with low-skilled workers. However, the introduction of robots reduces the variable costs of enterprises. Additionally, robots can realize synergy with high-skilled workers, leading to a long-term reduction in corporate costs (Autor et al., 2003; Bresnahan et al. 2002). This, in turn, boosts the productivity of enterprises and lowers their product prices (Graetz & Michaels, 2018). L. Feng et al. (2023) examined the use of industrial robots in China's manufacturing industry and found that robot adoption offers significant cost-saving advantages by reducing the marginal production costs of enterprises and increasing the marginal benefits from innovation. Dinlersoz and Wolf (2018) analyzed the survey data from the manufacturing industry in the United States, discovering that in enterprises with a higher degree of automation, the proportion of labor income is lower in production, while the proportion of capital income is higher. Additionally, a smaller proportion of production workers can gain high wages. DeCanio (2016) found that capital owners obtain higher returns by squeezing labor remuneration, and that robot adoption can reduce workers' wages, thus reducing labor costs of enterprises. Similar evidence can also be found in the samples from industrial enterprises in China. X. He et al. (2023) found that enterprises adopting robots incur a lower proportion of wage costs. Based on micro-survey data, it is also found that robot adoption reduces workers' income share (Cheng Hong et al., 2021; Yu et al., 2019). Based on the situational research of developed countries, it is found that robot adoption is effective in reducing labor costs and serves as an important tool to attract enterprises in developed countries. Adding one robot to every 100 workers in the manufacturing industry can lead to a 3.5% increase in enterprises returning to their home country (Krenz et al., 2021).

Furthermore, Li Lei and H. Ma (2023) examined the impact of robot adoption in developed countries on the withdrawal of foreign-funded enterprises from China. They found that a 0.1% increase in the penetration rate of robots leads to approximately 7% and 13.6% increase in the number of withdrawn foreign-funded enterprises and foreign capital, illustrating the trend of foreign-funded enterprises "returning production to their home country." Although the purchase of robots may incur significant fixed costs in this process, it can also encourage enterprises to dynamically adjust production decisions, simplify non-value-added activities, enhance supply chain management efficiency, and effectively reduce their production and operating costs (Agrawal et al., 2018). In this context, J. Qi and Z. Zhang (2022) found that robot adoption can reduce average costs, thus encouraging enterprises to expand their export product range. The cost reduction and scale effect arising from robot adoption are conducive to enhancing the operational efficiency of enterprises (Liu Jun et al., 2023) and fostering the growth of new enterprises (S. Chen et al., 2023).

In terms of implicit costs, it is widely believed that robot adoption can reduce internal and external information asymmetry within enterprises (Balakrishnan et al., 2014; Matarazzo et al., 2021), thus reducing corporate costs. Robot adoption is often accompanied by the digital transformation of enterprises, enhancing the information integration capabilities across the whole process. This is especially true in the context of intelligent construction in the construction industry. H. Duan et al. (2022b) took the Fengtong Garden Project in Foshan as a case study to explain the digital transformation process in robot construction, BIM system construction, and data platform construction. The rapid flow of data elements can enhance the efficiency of enterprise management decisions (Sadeghi et al., 2021; Z. Zhao, 2015) while reducing the material costs associated with enterprise project construction through lower information search costs and negotiation costs (C. Yuan et al., 2021). Moreover, the rapid improvement of information transmission speed and the alleviation of information asymmetry enable managers to fully and promptly access and master the latest dynamic information of projects (F. Wu et al., 2021) and base their decisions more on data information rather than on experience, thereby diminishing irrational biases such as overconfidence and optimistic expectations of managers (Ye et al., 2023).

Additionally, enterprises' implicit costs can be reflected in their social responsibility. Studies have indicated that robot adoption can also reduce environmental pollution (C. Han & Li Xinping, 2023; Jiang Wei et al., 2022; X. Lin et al., 2023; Nie et al., 2022; Sheng & Bu, 2022). This pollution reduction can decrease enterprises' expenditure on environmental protection. Moreover, the improvement in product quality brought about by robot adoption is mainly reflected in their performance in a series of repetitive and high-precision tasks (Destefano & Timmis, 2021). Robot adoption can realize the integration and hierarchization of production links, reduce product loss, and ensure quality and accuracy in production (B. Liu & T. Pan, 2020; J. Qi & Z. Zhang, 2022). From the perspective of cost stickiness, Quan and C. Li (2022) found that robot adoption can optimize the efficiency of resource allocation and enhance enterprises' information processing capabilities, thus reducing their cost stickiness.

Although a substantial body of literature affirms the "cost reduction" effect of robot adoption, some studies highlight that robot adoption can cause wage polarization (Acemoglu & Auto, 2011). When it is challenging for robots to replace high-skilled jobs, the wage rate may increase (Yu et al., 2019; Graetz & Michaels, 2018; Cheng Hong et al., 2020). Moreover, Acemoglu and Restrepo (2018c) emphasized the mismatch between the skills required for emerging technologies and those provided by the labor force, the introduction of automation at an excessive speed, and the misalignment between the education system and robot application technology, which will hinder economic transformation and thereby increase the operating costs of enterprises. Furthermore, excessive government subsidies for capital goods can result in an imbalanced capital-labor ratio and redundancy costs. Additionally, robot adoption impacts traditional production and management modes, which may adversely affect the operational stability of enterprises, creating an inhibitory effect in the short term (F. Wu et al., 2021). Moreover, transfer costs arise as individuals transfer from one industry to another or from one place to another, which means that a seamless transition cannot be achieved simply by relying on the market itself (Stiglitz, 2017). Studies have indicated short-term and long-term heterogeneity in the economic effects of robots. Only effective matching can create a sustained incentive effect (Acemoglu & Restrepo, 2018a).

According to the literature in this section, corporate costs are integrated into the discussion of enterprise performance. The literature primarily focuses on the field of cost stickiness, with limited literature systematically analyzing the structural characteristics of costs or giving clear evidence from the perspective of robot adoption. However, the current literature concerning robot adoption in the construction industry primarily introduces the cost-reduction effect of robot construction but lacks evidence and theoretical support.

2.4 Research Review

Current literature research on robot adoption mainly focuses on the labor market, economic growth, green environment, the increasing value of the industry chains, and production efficiency. Especially in the field of labor economics, extensive research has shown that robot adoption has a replacement effect, a complementary effect, and a creation effect. These effects significantly reshape traditional production modes and, as a result, affect the behaviors of individual microeconomic units. However, due to challenges in achieving precise robot measurements and data limitations, many studies rely on macro panel data, which can only indirectly measure robot indicators. Consequently, the topics discussed lack detailed micro-survey data for accurate matching. Additionally, most researchers follow the dichotomy of classical economics for general summarization of costs. The research on costs primarily examines cost stickiness and driving factors of cost elements. The existing literature offers limited structural analysis of costs and differentiation outcomes. Moreover, there is a lack of detailed data on the cost-driving effect of robot construction applications. The economic impact brought by robot construction on enterprise ecology has not yet reached a consensus. Moreover, the existing literature on the economic effects of robots has assumed that enterprises possess corresponding management capabilities, management levels, and decision-making capacities. This literature downplays the critical role of organizations and management in the adoption and promotion of robots, making it challenging to evaluate the role of management change. The above literature provides valuable insights for this study. This study posits that there is still significant potential for breakthroughs in this field. Firstly, the research on corporate costs remains insufficient. Existing studies tend to evaluate costs holistically or integrate them into the discussion on enterprise performance, without delving into the structural differences of costs. Secondly, the existing research focuses more on the far-reaching impact of robot adoption on the labor force, with limited literature examining other structural costs. Thirdly, the key mechanism regarding the impact of robot adoption on corporate costs has not been adequately explored. This study incorporates management change into the same framework and investigates its impact on the "replacement of human labor with robots" and corporate costs. In addition, different from robot usage in conventional construction and the cost accounting of general enterprises, this study focuses on the effectiveness of robot construction in the construction industry. Projects with a high capital-labor ratio provide highly informative evidence for the cost effect of robot construction and management change.

Chapter III Theoretical Model Building and Research Hypotheses

3.1 Theoretical Model Building

While China vigorously promotes the development and transformation of robot construction within real estate construction enterprises, the current adoption rate of construction robots in real estate projects remains low. Against this backdrop, this study aims to examine the factors restricting the adoption of robot construction technology by real estate construction enterprises, evaluate the cost effect of robot construction adoption on real estate projects, promote the adoption of robot construction technology in real estate construction enterprises, and accelerate the intelligent transformation and development of real estate construction.

The overview of theories related to robot construction and corporate costs in Chapter II indicates that existing theories concerning the adoption of robot construction primarily examine its impacts on economic performance, such as labor force and employment. However, few theories focus on the impact of robot construction on real estate project costs. While some theories assess the influencing factors of robot construction adoption on individuals and analyze the factors affecting construction enterprises’ willingness to adopt robots, they seldom delve into the impact of robot construction on real estate project costs, the impact pathways, the difference in cost effect of robot construction on real estate projects under different conditions, and the external conditions necessary to achieve cost reduction and efficiency improvement in robot construction.

In this regard, this study takes real estate construction enterprises as the research object and explores the effect of organization-level robot construction on real estate project costs based on real estate projects of organizations. Drawing from real estate projects of organizations, this study considers two key aspects. First, it gathers specific data concerning the financial costs of project operations and the adoption of robot construction. Second, while organizational costs are typically observed through financial statements, organization members are the primary drivers of cost management implementation. H. Mao et al. (2012) extensively discussed organizational behaviors such as internal coordination, budget mechanisms, accounting practices, monitoring measures, analysis methods, assessment strategies, material cost management, and project manager management, as well as analyzed the perceptions and behaviors of organization members based on exploratory cases. It is necessary to analyze individual-level insights for a profound understanding of the cost effect of robot construction on real estate projects. This study focused on an investigation and analysis of individual members within the organizations. Therefore, this study was conducted from the perspectives of organizations and their members. The members were regarded as the smallest study unit, with their subjective perceptions serving as the primary focus, complemented by the objective real estate project costs of organizations. These elements were integrated to establish a cohesive framework.

The empirical tests were conducted to explore the influence mechanism and structural changes brought about by robot construction on real estate project costs, treating robot construction as the antecedent variable, project costs (including average costs and redundancy costs) as the outcome variable, production efficiency (including adaptability and technological advantages) as the mediating variable, and management change (comprising organizational consensus, organizational learning, and human-robot collaboration) as the moderating variable. This study delved into the mediating roles of adaptability and technological advantages, analyzing the key mechanisms behind cost reduction and efficiency improvement in robot construction from the perspectives of organizational consensus, organizational learning, and human-robot collaboration. Furthermore, we investigated the project performance effect of cost reduction in robot construction. This study aims to evaluate the cost effect of robot construction on real estate projects and provide a theoretical basis and guidance suggestions that promote the efficient adoption of robot construction technology and its wider adoption to facilitate the transformation towards intelligent construction in the real estate industry. The theoretical framework of this study is shown in Figure 3-1.

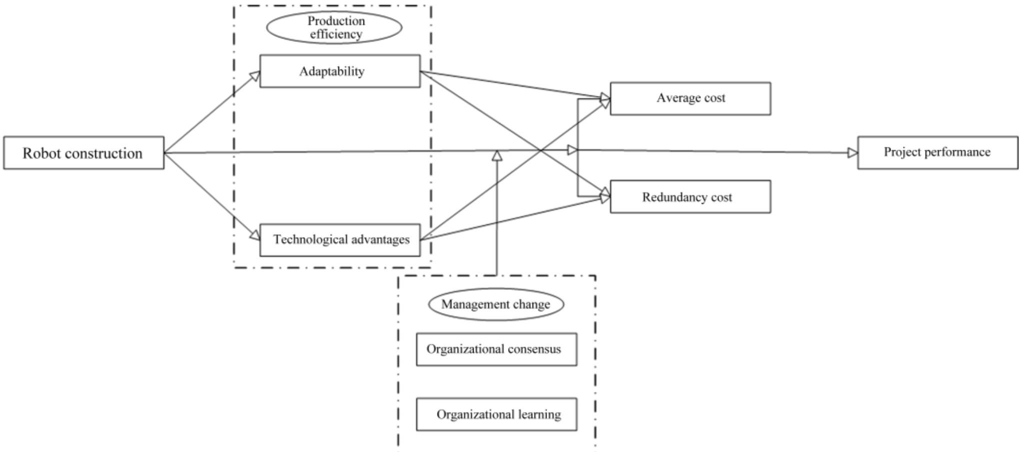

Figure 3-1 Theoretical Framework

3.2 Research Hypotheses

3.2.1 Robot construction and real estate project costs

Robot construction can reduce asset adjustment costs, improve asset utilization efficiency, and lower the average costs of real estate projects. First, robot construction changes the way assets are used, enhancing resource utilization efficiency. Traditionally, enterprise assets incur high adjustment costs and are challenging to be used for other purposes (Anderson et al., 2003). However, adopting new-generation information technology in the robot construction model allows real estate projects to employ construction robots across multiple scenarios. Some robots can even be repurposed for other tasks simply by changing their parts, which significantly reduces asset specificity. This reduction in asset specificity enables enterprises to pursue large-scale production and customization (Y. Wu et al., 2016). Consequently, enterprises can quickly respond to market changes, fully utilize or promptly dispose of idle resources, and cut costs.

Second, robot construction can transform the asset structure of enterprises, reduce the labor force scale, and improve human resource utilization efficiency (Sun & Hou Yulin, 2019). With the adoption of construction robots, the marginal output of labor is replaced, leading to lower average costs. In the context of robot construction, numerous real estate project scenarios can now be efficiently completed by construction robots. For instance, measuring robots can obtain highly accurate data and ground-leveling robots have largely replaced traditional labor over extensive areas. As a result, the replacement of labor with construction robots is becoming increasingly common (Chen Yanbin et al., 2019). The replacement of human labor with robots reduces the labor force scale and alleviates the constraints traditional labor imposes on enterprises' production factors (Acemoglu & Restrepo, 2018). The high adjustment cost of human capital is a significant factor in the elevated construction costs of real estate projects (Anderson et al., 2003). This issue is exacerbated by the gradual disappearance of the demographic dividend and the rapid rise in labor costs. Robot construction overcomes the reliance on proprietary technology and labor in real estate project construction. This breakthrough is significant not only in terms of scale but also in addressing the physiological and operational limitations associated with manual construction. Traditional manual labor is constrained by time and space, whereas construction robots can theoretically operate 24 hours a day and function simultaneously in multiple positions across different scenarios. This capability significantly surpasses the limitations of human labor. By using construction robots to replace manual labor, real estate projects can reduce the labor force scale, enhance labor use efficiency, and consequently lower average costs.

Based on this, this study proposes the following basic hypothesis:

H1a: Robot construction reduces the average costs of real estate projects.

Robot construction can improve the quality of project construction information and enhance the ability to flexibly adjust project input factors, thus lowering the redundancy costs of real estate projects. Construction robots have transformed the way real estate projects manage resources and improved resource utilization efficiency (C. Zhao et al., 2020). In traditional real estate construction, the extensive production mode often results in huge resource waste. This includes material waste during construction and the necessary yet repetitive construction of temporary facilities, both of which increase project redundancy costs. Additionally, the project manager-based management and control model frequently leads to principal-agent problems in cost control, where actual costs deviate significantly from budgeted costs, resulting in inefficient resource allocation and high project costs. The robot construction model can effectively address these issues.

First, robot construction involves not only the use of construction robots but also the enhancement of information integration systems such as BIM and big data processing systems, which can significantly improve project cost control and reduce redundancy costs. Before the introduction of robot construction, differences in information technology, systems, and business processes across various stages of project construction led to “information islands,” resulting in low internal information utilization efficiency. By incorporating BIM systems, wireless communication technology, 3D printing technology, and cloud technology, real estate projects can connect procurement, transportation, production, inventory, and other stages intelligently and in real time. This integration facilitates the collaboration and sharing of information resources across all construction stages, reducing the cost of obtaining production information and helping enterprises accurately assess their cost-control capabilities. Additionally, after adopting robot construction, construction enterprises can leverage new-generation information technology to enhance traditional market analysis tools, improve material usage forecasts, and better predict construction timelines, thus reducing the investment in and arrangement of slack resources. Moreover, robot construction can minimize man-made material loss. In traditional construction environments, principal-agent problems are prevalent, where project managers may form insider groups, leading to inefficient resource investment and increased cost control challenges. Robot construction adoption, enterprises' digitization and cloud platform development, and UAV technology utilization enhance the ability of enterprises to supervise project construction. Through real-time information transmitted during on-site construction, enterprises can monitor material usage and other stages effectively to address internal information asymmetry and keep costs within budgeted limits to reduce redundancy costs. Furthermore, enterprises can make precise decisions on project costs by incorporating factors such as robot construction adoption and data flows from different production scenarios into big data prediction models (McGuire et al., 2012). This approach reduces uncertainty and lowers corporate costs.

Second, due to varying business volumes at different construction stages of real estate projects, idle resources on construction sites may increase. If not promptly managed, these idle resources can lead to slack resources and higher redundancy costs. The robot construction model changes how enterprises control resources, reduces on-site input factors, promotes project construction management and general contracting, as well as enhances idle resource allocation. On the one hand, construction robots can minimize investment in temporary works and other sunk costs. For example, exterior wall climbing robots significantly reduce the need for temporary structures like lifting frames/scaffolding for aerial tasks, cut down on auxiliary works that were necessary for traditional construction models but were ultimately redundant after use, and greatly save redundancy costs. On the other hand, construction robots can be purchased or produced by enterprises, or adopted by enterprises through leasing or even construction management and general contracting by construction robot enterprises. Besides, information cloud services are often shared, allowing enterprises to flexibly adjust resource investment according to project needs. When construction robots are no longer needed, they can be subleased to other project sites—a challenging task in traditional production models. Project construction used to rely heavily on contracting, with direct yet crude cost accounting and sunk investment in surplus labor and materials. Robot construction differs by offering diversified production models and resource sharing, which effectively enhances the ability of construction enterprises to control resources, reduces unnecessary input factors, and lowers redundancy costs in real estate projects.

Based on this, this study proposes the following basic hypothesis:

H1b: Robot construction reduces the redundancy costs of real estate projects.

3.2.2 Robot construction and production efficiency

Robot construction can enhance the production efficiency of construction projects, impacting the production cycle, quality, safety, and environment. Regarding the production cycle, robot construction overcomes human physiological limitations and the exclusivity of human capital. The traditional production model relies heavily on manual labor, requiring huge human involvement and being restricted by the need to allocate work and leisure time, thus imposing time constraints on project implementation. Additionally, the proprietary nature of technological expertise often necessitates diverse manpower allocations and increases friction with project construction enterprises, as reflected in high contract costs. Construction robots effectively eliminate these limitations. They can operate 24 hours a day, bypassing the information search and transaction costs related to human exclusivity. Their emotionless operation avoids the impact of human emotional fluctuations, significantly improving the project's construction efficiency and shortening its production cycle.

In terms of production quality, the construction process involves many complex stages, and the quality and technical proficiency of construction teams can vary widely. This variability often leads to issues in knowledge imparting and reliance on manual experience, resulting in deviations and errors. For instance, engineering leveling is a common stage for quality complaints, posing challenges for traditional models to overcome. Construction robots, equipped with precision instruments such as advanced measurement technology, laser technology, sensing technology, and radar technology, can enhance construction accuracy across various stages. This precision ensures that project quality remains within limited error margins. More importantly, construction robots follow fixed construction procedures, which reduces the production quality issues caused by the uncertainties of human involvement. Moreover, construction robots can perform real-time quantitative inspections on finished surfaces, enabling more precise quality control.

In terms of safety, traditional construction often involves dangerous environments such as aerial work, where safety accidents are prone to occur. Unlike traditional construction models, construction robots can replace human workers in high-risk scenarios, such as exterior wall painting at heights, tasks at edges and openings, formwork operations, lifting frames/scaffolding works, and vertical transportation. By adopting construction robots in these scenarios, the exposure of workers to dangerous environments is significantly reduced, thus greatly enhancing the safety of construction projects.

Regarding the production environment, traditional construction models lead to resource waste and severe environmental pollution. Construction teams often work in polluted environments for a long time, causing occupational diseases. As mentioned above, the high precision of robot construction helps reduce resource waste and lower pollution emissions to some extent. Furthermore, the extensive replacement of traditional labor with construction robots reduces the size of construction teams and the environmental pollution exposure for workers. In addition, construction robots require better on-site construction environments, which encourages timely cleanliness and reduces construction waste on-site for higher environmental quality. Therefore, construction robots improve the project production environment by mitigating pollutant discharge and reducing personnel exposure to pollutants.

Based on this, this study proposes the following hypothesis.

H2a: **Robot construction can enhance the technological advantages of project construction.**

The robot construction model changes the input structure of construction enterprises, facilitating the replacement of human labor and reducing asset exclusivity. This transformation enhances the adaptability of project construction. In the context of diminishing demographic dividends, labor shortages, and rising labor costs, construction enterprises often struggle to manage labor costs. Due to this uncertainty, project costs remain high. However, investing in construction robots can mitigate construction enterprises' reliance on human labor, overcome the constraints of manpower, and enable large-scale substitution. Moreover, the robot construction model significantly advances the informatization of project construction and improves the prediction of factor inputs. Enterprises can dynamically adjust the input of materials, construction robots, and labor as needed, avoiding slack resources. Additionally, the sharing of construction robots allows construction enterprises to utilize these resources flexibly, increase investment when necessary, and shift to a sharing model when the resources lie idle. Therefore, robot construction can enhance the adaptability of project construction.

Based on this, this study proposes the following hypothesis.

H2b: **Robot construction can enhance the adaptability of project construction.**

3.2.3 Production efficiency and real estate project costs

Several critical factors influence project costs, including the production cycle, quality, safety, and environment. Efficient production and a shortened project construction period can significantly enhance project output and accelerate the discounting of future cash flows, which in turn reduces average and redundancy costs. Production quality is a critical factor affecting short-term and long-term project costs. In the short term, poor flatness performance requires rework, while long-term quality issues can damage an enterprise’s reputation and cause irreversible harm. Production safety is also essential, as safety incidents can lead to shutdowns and compensation and litigation costs of construction enterprises, increasing project costs. Additionally, compliance with regulatory requirements regarding the production environment is mandatory, adding to the cost burden. The high-tech advantages of modern production models offer more efficient production cycles, higher production quality, improved production safety, and better production environments. These improvements positively impact the reduction of average and redundancy costs in real estate projects.

Based on this, this study proposes the following hypothesis.

H3a: **Technological advantages can reduce the average costs of real estate projects**

H3b: **Technological advantages can reduce the redundancy costs of real estate projects**

A major contributor to the high costs of real estate projects is the insufficient ability to adjust resources effectively. Flexible resource adjustment is critical for cost reduction. Ideally, if the exact output value, required labor, and capital investment are known, enterprises could achieve efficient resource allocation, lower real estate project costs, and eliminate redundancy costs. However, due to uncertainties, it is challenging for enterprises to predict outcomes accurately across different environments. Therefore, reducing uncertainty and enhancing adaptability to environments is crucial. By responding promptly, flexibly, and accurately to project progress and site conditions, construction enterprises can improve resource utilization efficiency and lower the average and redundancy costs of real estate projects.

Based on this, this study proposes the following hypothesis.

H4a: **Adaptability can reduce the average costs of real estate projects.**

H4b: **Adaptability can reduce the redundancy costs of real estate projects.**

3.2.4 Mediating effect based on production efficiency

On the one hand, compared to traditional extensive construction models, robot construction offers significant advantages in shortening production cycles, enhancing production quality, ensuring production safety, and improving the production environment. These advancements enhance resource utilization efficiency and enable large-scale production, ultimately reducing the average costs of real estate projects.

On the other hand, the technological advantages of robot construction facilitate the full utilization of resource inputs, reduce losses and the need for repeated construction, and lower the redundancy costs of real estate projects.

Based on this, this study proposes the following hypothesis.

H5a: **Technological advantages play a mediating role between robot construction and the average costs of real estate projects.**

H5b: **Technological advantages play a mediating role between robot construction and the redundancy costs of real estate projects.**

For one thing, compared with traditional extensive construction models, the shift in factor input structure and the substitution of labor with construction robots address the difficulty of adjusting labor factors in real estate project construction. Besides, the asset-sharing nature of construction robots mitigates the law of diminishing marginal returns on capital and reduces the average costs of real estate projects.

For another, improved informatization in the construction environment reflects robot construction’s strong adaptability. Enhanced information flow reduces internal and external uncertainties, making cost control easier compared to the traditional principal-agent production model. This improvement increases the accuracy of project cost budgeting and enhances cost management control, reducing deviations caused by human factors and improving resource utilization. Consequently, enterprises can lower the redundancy costs of real estate projects.

Based on this, this study proposes the following hypothesis.

H6a: **Adaptability plays a mediating role between robot construction and the average costs of real estate projects.**

H6b: **Adaptability plays a mediating role between robot construction and the redundancy costs of real estate projects.**

3.2.5 Moderating effects of management change

Theoretically, the robot construction model is conducive to reducing real estate project costs. However, in reality, unlike the widely adopted robot production model in the manufacturing industry, robot construction has a low adoption rate in the real estate industry. Additionally, many real estate projects have experienced increased costs rather than cost reductions after implementing robot construction. This discrepancy raises the question of whether construction enterprises adopting robot construction have overlooked key environmental variables that could cause large deviations from the expected cost reduction and efficiency improvement outcomes. This study believes that the state of management change in construction projects is a critical mechanism affecting cost reduction and efficiency improvement in robot construction.

Under the trend of intelligent construction, production activities are increasingly driven by data resources instead of physical resources, and the role of human workers has changed significantly. The adoption of construction robots inevitably impacts traditional management modes. One major reason hindering the upgrade and transformation towards intelligent construction, or even leading to crises due to transformation, is the failure to implement adaptive management changes. This failure makes it difficult for organizational structures and business operations to adapt to rapidly changing market environments and fleeting development opportunities (Goles et al., 2019). The wide application and rapid commercialization of technologies such as robot adoption, AI, big data, and cloud computing have significantly impacted and challenged the theoretical knowledge basis, cost management process, quality risk prevention, organizational management, talent management, and evaluation system standards of traditional project management (G. Han & Li Wenrui, 2021). Therefore, simply investing in robot construction without addressing the management changes brought about by the production model transformation may lead to a failure in achieving cost reduction and efficiency improvement.

According to organizational conflict theory, the introduction of construction robots creates a game-like relationship in the organization. If organization members adopt resistance strategies such as non-cooperation and slack in work, there will be huge challenges in adopting construction robots. Since construction robots cannot entirely replace human workers, establishing a harmonious cooperative relationship is essential to cultivate strong adaptability and reduce internal resistance. It is crucial for organizations to develop a consensus on construction robot adoption. Senior executives should foster a strong consensus on prioritizing construction robots as a strategic development goal. Building organizational consensus and investing substantial resources in robot construction and upgrading can alter the benefit-cost function of resistance strategies, thus reducing internal conflicts caused by construction robot adoption and enhancing robot construction’s positive impact on real estate project costs.

Organizational learning theory suggests that organizational learning is a process through which enterprises change their actions based on accumulated knowledge. From the perspective of information flow, organizational learning is a process where an enterprise obtains useful information from different sources and makes informed decisions on its production and operation activities to adapt to the environment. Organizational learning is a process of knowledge flow. Knowledge flow’s key elements include the sources, content, and acceptors of knowledge, as well as the transmission medium. Tidd and Besssant (2011) highlighted that enterprises primarily obtain knowledge from innovation networks, including customers, suppliers, competitors, strategic alliances, and professional knowledge production units. The transition from traditional construction to robot construction in the real estate industry requires building a robust information cloud platform and investing in new technologies. For construction enterprises, it is crucial to obtain information from professional knowledge production units (market participants such as construction robot solution providers, cloud service software vendors, and technological practitioners). Besides, improving the knowledge structure of existing construction teams and encouraging acceptance of new production technologies is essential. The information content acquired by construction enterprises greatly impacts the subsequent knowledge flow process, which directly affects the efficiency of the organization's knowledge value chain. Common knowledge facilitates the enhancement of knowledge aggregation. Transforming information into common knowledge in an organization is influenced by personal factors such as individual attitudes and education levels, as well as cultural factors. Building an incentive compatibility system for learning robot construction technology can guide organization members to actively learn this technology. Offering more training courses on construction robot adoption can expand the scope of knowledge transfer and improve members' ability to learn and absorb information. When members can transform information into common knowledge, the adoption of robot construction can better collaborate with them, which is crucial for achieving cost reduction and efficiency improvement in robot construction.

Human-robot collaboration emphasizes the interaction and cooperation between construction robots and operators in robot construction. When operators find the process easy to learn, controllable, practical, interesting, responsive, and interactive, they experience higher satisfaction with adopting construction robots. Effective interaction and cooperation between personnel and construction robots are fundamental in project construction. When managers perceive accurate and timely information feedback from construction robots, they are more likely to accept data-driven construction modes. Similarly, when operators experience the convenience and efficiency of robot operations, they are more likely to collaborate effectively with construction robots. Therefore, building a good collaboration relationship between project construction workers and construction robots is essential for reducing costs and improving efficiency in robot construction.

Based on this, this study proposes the following hypothesis.

H7a: **Management change plays a moderating role between robot construction and the average costs of real estate projects.**

H7b: **Management change plays a moderating role between robot construction and the redundancy costs of real estate projects.**

3.2.6 Organizational performance effect of robot construction

As discussed above, the robot construction model can transform traditional extensive operations, effectively improve the efficiency of project resource input, and reduce resource waste, thus lowering project costs. This effect extends to project performance in several key ways. On the one hand, robot construction's advantage in production efficiency can scale the operations of construction enterprises and improve project performance. On the other hand, the higher production quality achieved by robot construction can increase the trust of real estate developers, enhance brand value, achieve positive customer feedback, and improve project performance in the long run. Additionally, the robot construction model reduces internal and external information asymmetry in project construction. Enhanced information flow allows for a more accurate reflection of the project value, which is conducive to improving the performance of real estate projects.

Based on this, this study proposes the following hypothesis.

H8: **Robot construction positively affects the performance of real estate projects.**

In conclusion, the hypotheses proposed in this study are summarized in Table 3-1.

Table 3-1 Summary of Research Hypotheses

S/N	Research hypothesis
H1a	Robot construction reduces the average costs of real estate projects
H1b	Robot construction reduces the redundancy costs of real estate projects
H2a	Robot construction can enhance the technological advantages of project construction
H2b	Robot construction can enhance the adaptability of project construction
H3a	Technological advantages can reduce the average costs of real estate projects
H3b	Technological advantages can reduce the redundancy costs of real estate projects
H4a	Adaptability can reduce the average costs of real estate projects
H4b	Adaptability can reduce the redundancy costs of real estate projects
H5a	Technological advantages play a mediating role between robot construction and the average costs of real estate projects
H5b	Technological advantages play a mediating role between robot construction and the redundancy costs of real estate projects
H6a	Adaptability plays a mediating role between robot construction and the average costs of real estate projects
H6b	Adaptability plays a mediating role between robot construction and the redundancy costs of real estate projects
H7a	Management change plays a moderating role between robot construction and the average costs of real estate projects
H7b	Management change plays a moderating role between robot construction and the redundancy costs of real estate projects
H8	Robot construction positively affects the performance of real estate projects

Chapter IV Research Design

The previous chapters have summarized and reviewed the literature related to robot construction and corporate costs, as well as the theoretical pathways through which robot construction affects corporate costs. Undoubtedly, in the current wave of global intelligence, intelligent construction represents a significant evolution. Robot adoption is the most typical feature of this trend. Unfortunately, few studies have scientifically evaluated the effects of construction robots. In other words, there is a lack of clear empirical evidence regarding the impact of construction robots. The progress of this research lags far behind the urgent need for intelligent construction, which is largely due to the lack of data on traits. Given this context, this study investigated the current state of robot construction in real estate projects using surveys and questionnaires for the first time. Leveraging my human capital advantages, work experience, and field surveys and interviews with front-line real estate project personnel, we developed questionnaires for Group B and external enterprises. We collected robot adoption questionnaires from 262 real estate projects, including those across China and some overseas ones. These survey samples and questionnaires provide a solid foundation for this study to capture the current state of robot construction in organizations and analyze its impact on real estate project costs.

This chapter first elaborates on the questionnaire design process and the main sources of questionnaire survey data, summarizing the interview results and expert opinions. It then outlines the main content of the questionnaire, drawing on existing research and incorporating interview content to design a questionnaire on the structural effect of real estate project costs and the role of management change. Furthermore, it revises the questionnaire items based on the analysis of pre-survey data to finalize the items for the formal questionnaire. Finally, it analyzes the questionnaire survey results. This includes an analysis of the distribution and collection of the questionnaires, describing the demographic and enterprise features of the sample surveyed. It focuses on the current state of robot construction adoption, the cost of real estate projects, and management change, and extracts these variables for normal distribution testing.

4.1 Questionnaire Design and Data Source

4.1.1 Questionnaire design

Questionnaire design is a critical component of the survey process, and its rationality and reliability will directly impact the survey data. Drawing on the questionnaire design process and principles outlined by Churchill (1979), this study determined the formal questionnaire items and conducted a formal questionnaire survey based on initial questionnaire items, expert input in interviews, and a small-scale pre-survey, to ensure the rationality of the questionnaire and the reliability of the results. There are two types of questionnaires in this study: (1) Internal questionnaire that focuses on the adoption of construction robots by Group B in real estate projects. (2) External questionnaire that addresses robot adoption by non-Group B enterprises.

First, we interviewed experts and scholars in robot construction, as well as managers, technicians, business development personnel, and other front-line department members from real estate project construction enterprises. The contents of these interviews were analyzed to determine the accounting and structure of real estate construction costs, the factors affecting these costs, and any significant differences from those identified in the literature. This ensured that the structural features of robot construction impacting costs in real estate construction enterprises align with industry realities.

Second, well-established scales suitable for this study were identified by referencing existing relevant research. Using this foundation, the influencing factor scale and items for accounting were selected based on the research objects and the characteristics of each influencing factor to be measured. Subsequently, the initial questionnaire items were finalized by assessing the clarity of language expression and the rationality of the elaborated content of each item and making necessary adjustments.

Third, we analyzed the small-scale pre-survey data to modify the initial questionnaire items. Based on this analysis and expert interviews, necessary corrections were made to finalize the formal version.

Following the research objectives, existing literature, and the above procedures, we developed the formal questionnaire for research on robot construction and real estate project costs. The internal questionnaire consists of eight parts: (1) Basic information such as gender, age, educational background, and enterprise location of the respondents; (2) Robot construction adoption in real estate projects, including the number of applications, years of adoption, and overall evaluation of the adoption effect; (3) Conditions such as quality, safety, construction period, and environment of projects constructed with robots; (4) Organizational structure, organization system, and management decisions applied in projects constructed with robots; (5) Human resource investment and human-robot collaboration in projects constructed with robots; (6) Costs and expenses of real estate projects constructed with robots; (7) Evaluation of performance in customer satisfaction and output value of real estate projects constructed with robots; (8) Respondents' evaluation of the prosperity and policy support for the adoption of robot construction. Notably, Likert scale measurement variables were used to ensure a more precise quantification of cost accounting, improve the identification ability of questionnaire respondents, and effectively capture their moderate attitudes. The internal questionnaire comprises 53 items and 101 sub-items.

The external questionnaire consists of three parts: (1) Basic information, including gender, age, educational background, enterprise location, nature, and size, and project construction method; (2) Enterprises' willingness to adopt robot construction and their anticipated costs; (3) Respondents' evaluation of the prosperity and policy support for the adoption of robot construction. The external questionnaire contains a total of 27 items.

4.1.2 Data source

As a regional manager of Group B, I have extensive industry experience and a strong advantage in human capital. Leveraging these advantages, I facilitated the accurate distribution of questionnaires to real estate project managers and commercial promotion personnel across China through top-down promotion within the Group. Group B is one of the top 10 real estate enterprises in China. One of its subsidiaries, founded in July 2018, is a leading intelligent construction solution provider in China, focusing on the R&D, production, and adoption of construction robots. This subsidiary has empowered several construction robot enterprises and enjoys significant influence and reputation in the industry. The Xinyi Garden Project in Foshan, managed by Group B, is among the first batch of intelligent construction pilot projects supported by the Ministry of Housing and Urban-Rural Development. As of May 2023, 28 construction robots from the robot company under Group B had been commercially adopted, serving over 650 projects across 31 provinces, municipalities, and autonomous regions. Consequently, the promotion of questionnaire interviews within Group B has the advantage of large and highly representative samples. In addition, this study evaluated the anticipated costs of robot construction by external enterprises, focusing on their willingness to adopt robot construction. This external perspective was corroborated by the internal questionnaire. Utilizing the human capital advantages of myself, my colleagues, and Group B, we obtained widely distributed and diverse samples from external enterprises.

This study's questionnaire survey centered on robot construction, aiming to discuss the structural effects of real estate project costs and the role of management changes. The respondents were primarily technicians and managers at various levels in real estate project construction enterprises. These included project managers and department managers who possess a thorough understanding of the adoption of robot construction technology, real estate project management modes, and project costs within their enterprises. The questionnaire survey aimed to identify the internal and external environments of enterprise development and the adoption of robot construction technology, providing an accurate reflection of the cost management performance of robotics technology in real estate projects. The empirical research in this study focused on various real estate projects, including those constructed with and without robots, spanning different construction areas. It encompassed projects of varying natures such as state-owned and private ones, construction modes (such as construction management and general contracting), and regions.

4.2 Interview

In this study, semi-structured interviews were conducted with experts, scholars, and managers from surveyed real estate project construction enterprises. These interviews aimed to gain a deeper understanding of the concerns of experts, scholars, and middle and senior management personnel in enterprises regarding the adoption of robots in real estate projects and the factors influencing project costs from a practical perspective. This information also served as a reference for the initial design of questionnaire items. A semi-structured interview outline prepared in advance was used for interviews. Compared with structured interviews, semi-structured interviews have the advantage of being highly targeted, allowing for collecting more relevant and valuable content in a shorter interview time. Before the interviews, we communicated with the identified respondents.

The semi-structured interviews involved 10 experts and scholars in the field and managers of surveyed construction enterprises. Specifically, the respondents included three teachers (including supervisors) engaged in research in the field, one senior executive of Group B, one middle-level manager of Group B's local real estate projects, one senior executive of state-controlled real estate projects, one technical manager of Group B's local real estate projects, one technical manager of state-controlled real estate projects, and two government leaders (the leader of the housing and urban-rural development bureau of a prefecture-level city in Guangdong Province and the director of a development zone). Through expert interviews and coding analysis, we first identified relevant factors affecting real estate project costs and key mechanisms by which robot construction impacts these costs. During the pre-survey phase of the questionnaire, expert interviews were also conducted to review and refine the questionnaire items before finalizing the formal questionnaire.

Before delving into the factors influencing real estate project costs, it was essential to define the project cost and its dimensions. As shown in Table 4-1, project costs are categorized into five dimensions: staff cost, labor cost, material cost, measure cost, and management expense. In this study, the five dimensions were used as the structure to show real estate project costs. The analysis and breakdown of them are reasonable and practically significant.

Table 4-1 Interview Results of Real Estate Project Cost and Its Dimensions

	Dimension	Description	Frequency	Adopted or not
Cost of real estate projects	Staff cost	Staff wages and personnel training expenses	10	Yes
	Labor cost	Wages of construction personnel	10	Yes
	Material cost	Usage of building materials, material cost per unit area, and material waste	10	Yes
	Measure cost	Warehousing cost, logistics cost, maintenance cost, and robot adoption cost	8	Yes
	Management expenses	Management team size and management expense per unit area	7	Yes
	Sales expenses	Business development and other expenses	3	No
	Financial expenses	Interest earned by leasing and loans	4	No

During semi-structured interviews, 10 respondents—including scholars in the field, on-the-job graduate students, and senior executives of real estate project construction enterprises—shared their insights on current project costs. They emphasized that staff costs and labor costs constitute the majority of project costs and are particularly challenging to adjust. They suggested that if a project can control these costs, the project cost decision will be greatly optimized. Furthermore, the use of building materials is a crucial component of the overall cost. All 10 respondents agreed that the quality and price of purchased materials and the efficient use of these materials are the key factors in cost control. In addition to these costs, a significant portion of real estate project costs is attributed to measure costs such as warehousing, consumables, water and electricity charges, transportation fees, and scaffolding/lifting frames used during construction. The management personnel of surveyed projects and enterprises all confirmed this. Another considerable expense is management expenses. The senior executives of surveyed enterprises agreed that effective cost control and budget adherence in a project largely depend on the management personnel, the organization's ability to strictly follow the company's system arrangements, the precision of site management, the project's implementation, and the management expense per unit area in the project.

Based on the interview content and my extensive working experience, it is evident that project costs are also influenced by project scale, regional economic development level, and project type. These factors are included in the model considerations for this study.

Moreover, in interviews regarding the technological advantages of robot construction in reducing real estate project costs, respondents highlighted that improving construction efficiency and information communication is key to achieving cost reduction and efficiency improvement in robot construction. Efficiency factors include the project production cycle, production quality, production safety, and production environment. Information factors encompass information management, cost budgeting, and knowledge structure. These two dimensions and seven perspectives outline how robot construction can impact real estate project costs. After interviews and discussions, it is reasonable and practical for this study to analyze the aforementioned factors. The details are provided in Table 4-2.

In semi-structured interviews, all 10 respondents emphasized that the construction time of a project significantly determines its overall cost, asserting that shortening the construction period often leads to cost reductions. Senior executives also pointed out that construction is susceptible to climate change. Severe weather or rainy conditions can halt construction progress, thus delaying the scheduled completion time due to these uncontrollable factors. The respondents further noted that in addition to project construction's speed, production quality and safety are crucial factors affecting project costs. Senior executives from the surveyed enterprises highlighted that their organizations have early warning systems for project quality and safety, with red-yellow-black warning boundaries. Such warnings can undoubtedly impact the normal operation of the project. Strict standards are applied to all aspects of project construction, including the completion criteria. For example, leveling and hollowing are subject to rigorous review. Rework is common, and customer satisfaction is closely tied to the project's qualification rate. Additionally, the surveyed experts pointed out the importance of considering the construction environment's impact, which may have more permanent effects beyond economic factors. The surveyed senior executives noted that pollution from building materials and construction sites has been a longstanding issue. Companies must invest significantly in environmental protection to mitigate pollution sources such as construction dust. Reducing environmental protection expenses can lower costs to some extent.

The above factors can be observed in the specific operational status of projects, and cost control methods are considered crucial in determining overall costs. The respondents highlighted that investment in information technology within the construction industry is extremely low. Beyond the hardware investments in new technologies adopted by real estate projects, the supporting information infrastructure must also advance to effectively reduce costs. They emphasized that current information technologies, such as AI and big data, present significant opportunities for cost reduction. Real estate projects' alignment with the digitization trend will greatly benefit cost reduction. The respondents also stressed the uniqueness of real estate project construction, which relies heavily on industry-specific technologies like BIM, GIS, and UAV. The technological requirements are extremely strict, making enhancements in information infrastructure particularly critical for cost reduction. Another aspect reflecting the effectiveness of a project's information infrastructure is the alignment between budgeted and actual construction costs. The respondents noted that when actual costs closely match budgeted costs, project decision-making can be effectively implemented. Furthermore, the introduction of new technologies inevitably creates a huge demand for talent. To facilitate robot adoption's impact on lowering project costs, it is crucial to have an adaptive talent structure. While the adoption of robots is one aspect, having skilled personnel to operate robots is key. The ability to manage these extensive projects with robust software and hardware support is essential. Through face-to-face communications with the respondents and subsequent analysis and summary of their insights, this study identified two dimensions and seven perspectives on the mechanism paths where robot construction impacts real estate project costs (see Table 4-2).

Table 4-2 Interview Results of Main Paths for Real Estate Project Cost Reduction by Robot Construction

	Dimension	Description	Frequency	Adopted or not
Technological advantages	Production cycle	Construction completion time and the ability to reduce the interference of factors such as climate	10	Yes
	Production quality	Project quality warning, project qualification rate, and customer feedback on quality	10	Yes
	Production safety	Casualties of construction personnel and the capacity for substituting hazardous operations	10	Yes
	Production environment	Environmental protection expenses in project construction, dust emissions at the construction site, and inspection of the project construction environment	8	Yes
Adaptability	Demand for labor	Demand for labor at the construction site and changes in resource input caused by project adjustments	10	Yes
	Flexibility	The ability to adjust materials and labor, and the flexibility to overcome time and physical constraints	9	No

In further interviews, we paid attention to the profound impact of robot construction on existing management modes. The respondents emphasized that achieving a breakthrough with robot construction depends heavily on reshaping the management mode. This transformation requires both top-down and bottom-up approaches. On the one hand, company leaders must promote the adoption of robotics technology as a major strategic change within the Group. On the other hand, employees must recognize and embrace robot adoption from a values perspective, being willing to learn new knowledge and integrate robotics technology into their daily tasks. Based on the interviews, this study identified four dimensions of management change: management decisions, organizational learning, workforce adjustment, and human-robot collaboration. The specific interview results are shown in Table 4-3.

During the interviews, six employees from the Group highlighted that the importance placed by senior executives on robot development and adoption significantly influences the extent and emphasis of robot adoption on project construction sites. When senior executives have a positive attitude towards robot adoption and its impact on traditional production processes, resistance within the organization diminishes considerably. However, three respondents pointed out that the Group has reduced its R&D and adoption of robotics technology amidst cyclic downturns in the industry. The hesitation toward robot adoption in real estate projects has hindered the promotion of robot adoption. Minor strategic changes have also resulted in insufficient drive for adopting robots in these projects. Additionally, three surveyed scholars stressed that the successful implementation of robotics technology requires more than just the robots themselves. It requires combining the physical and virtual worlds. By reshaping enterprise management modes through robot adoption and integrating management with digital governance, the full benefits of robot construction can be realized.

In further interviews, respondents emphasized the need to standardize the management system for the adoption of robotics technology and enhance its acceptance within organizations. Two senior executives from the Group highlighted that the company places great importance on establishing rules and regulations for adopting robotics technology. They actively promote robotic learning courses within the Group, incorporating these courses into the performance appraisals of senior management and employees. Furthermore, the Group has made great efforts in talent cultivation and invested a lot in recruiting robot R&D talent. Some core technical personnel have left the Group to establish their own robotics companies. Five employees stressed the Group’s dedication to training courses on robot adoption, noting that robot operation still requires human intervention and specialized training. Two senior executives from state-owned enterprises pointed out that large-scale robot adoption in their enterprises is restricted by a lack of proficiency in robot operations. Many employees are unfamiliar with robot adoption and do not know how to address faults. They expressed a desire for mentorship from the Group when adopting robots. Three experts mentioned that robot construction significantly impacts the knowledge structure of organization members, requiring training courses for employees. Respondents also highlighted that after adopting robotics technology, higher standards are required for talent cultivation and high-level talent introduction, thus improving employees’ overall education level. Five employees of the Group noted that since implementing the robot construction strategy, the Group has established a core technical talent system for robot R&D. The talent system helps the Group build industry-leading advantages and benefits other companies in the same industry, making it highly popular in the professional market.

Additionally, respondents underscored the necessity of human-robot collaboration for effective robot adoption. If the technology is easy to learn, it will facilitate the replacement of traditional production processes and improve acceptance in project construction. Two senior executives from the Group pointed out that the Group's pilot projects are running well, with employees showing a high acceptance of collaborating with robots. Technical senior executives emphasized that the complexity of human-robot operations is gradually decreasing, with ongoing efforts to improve operability and enhance human-robot collaboration. Two salespersons from the Group mentioned that in promoting robot adoption, they often encountered challenges with technical operability. We proposed helping construction enterprises by providing robot operation training and maintenance services. Two senior executives from state-owned enterprises stressed their concern about the operability of construction robots. They have high knowledge requirements for construction personnel and are not rushing to adopt robots in project construction. Instead, they anticipate that construction robots can eventually become automatic, eliminating the need for extensive training as the cost of learning raises the promotion costs.

Table 4-3 Interview Results of Key Mechanisms for Real Estate Project Cost Reduction by Robot Construction

	Dimension	Description	Frequency	Adopted or not
Management change	Organizational consensus	Senior executives' attitude, the company's strategic planning, attitude towards the adoption of new robot construction technology, and the importance attached to feedback on robot construction in the company's decision-making	10	Yes
	Organizational learning	Developing a learning manual for robot construction, establishing rules and regulations for robot construction, conducting training courses on robot construction, and recruiting talent in robot construction	9	Yes
	Human resources advantages	Cultivating talent in robot construction R&D, production, and sales, increasing the proportion of highly educated talent, and establishing the company's competitive advantage in talent resources	10	Yes
	Human-robot collaboration	Employees' willingness to adopt robot construction technology, challenges associated with the adoption, and the feasibility of using robots to replace traditional manual labor	8	Yes

Based on the results of these interviews, we developed an internal questionnaire. The respondents provided the concerns of the non-Group companies regarding the adoption of robotics technology. In response, we formulated an external questionnaire. According to semi-structured interviews, several noteworthy questions emerged: What are the concerns of these companies regarding the adoption of robot construction technology? What is their willingness to adopt robot construction? How much are they willing to invest in robot construction and collection? The external questionnaire also accounts for the varying levels of applying robotics technology understood by respondents. For example, senior management personnel of state-owned construction enterprises indicated the common use of UAVs, big data, and BIM technology and the trial adoption of significantly advanced cloud platforms for smart sites and IoT due to the impact of COVID-19. In contrast, senior management of private enterprises reported that robot construction technology is rarely used in their enterprises, with common UAVs and BIM technology only in small-scale adoption. In light of these findings, we synthesized the suggestions and opinions of multiple respondents. Before preparing the external questionnaire on the adoption of robotics technology in enterprises, an additional section was included to investigate the current adoption status of robotics technology in real estate project enterprises. This addition aims to facilitate a statistical understanding of the current adoption status of robot construction technology in real estate project construction enterprises.

4.3 Variable Measurement

Designing reasonable and scientific items for measuring the variables involved in hypothesis models is an important part of a questionnaire. In this study, based on the screening of relevant well-established scales and referencing their items, we designed the measure items for each variable according to the characteristics of the research objects and variables to be measured, combined with interview results. This process resulted in the initial measurement scale for each variable.

4.3.1 Measure of robot construction adoption

Due to limited research on robot construction technology, a reliable scale for measuring this technology has not yet been developed. The essence of robot construction technology is to simulate human capabilities, and its development level directly impacts social productivity. Construction robots are characterized by replacing human labor. However, the unique nature of the construction industry necessitates collaboration between these robots and human technicians. These robots serve as aides and extensions of human beings. Therefore, one critical indicator for measuring the intensity of human-robot collaboration is the closeness of human-robot cooperation. Additionally, the adoption of construction robots inevitably raises information requirements within the construction industry, and the degree of informatization can gauge the range of robot use. Therefore, measuring the adoption of robot construction in real estate projects can be largely assessed by the extent of construction robot participation in project construction. We drew on research scales generated by Y. Han (2020), Medcof (2011), Zhang Lei (2019), and Zhong (2023) for related technologies in construction projects to form appropriate scale items, thereby enhancing the credibility of the research and data quality, and better addressing the research questions.

The scale designed aims to evaluate the degree of adoption of robot construction technology in enterprises, including the degree to which project construction relies on feedback from robot construction, the degree to which construction robots replace traditional labor, the degree to which construction robots engage in engineering construction links, and the independent work of construction robots. Details are provided in Table 4-4.

Table 4-4 Measure Items for Robot Construction Adoption

Variable	Item No.	Item	Source
Robot construction	R-1	To what degree does the construction decision-making of project construction rely on the digital information fed back by robot construction?	Y. Han (2020), Medcof (2011), Zhang Lei (2019), Zhong (2023)
	R-2	To what degree do robots replace traditional labor in procedural processes?	
	R-3	To what degree does robot construction engage in the engineering construction links?	
	R-4	To what degree does the project require independent robot construction?	

4.3.2 Adaptability measure

If construction robots can replace traditional labor and overcome the time constraints of labor, they may offer advantages in adjusting resources. W. Wu & Tian (2022) pointed out that cost reduction partially stems from the ability to flexibly adjust resources—fully mobilizing resources during high performance and reducing input during low performance. We referenced this concept to establish an adaptability scale. Drawing on the technology acceptance model (TAM) of Davis (1989), which measures the usefulness of technology from seven aspects, including improving job performance and meeting job requirements, we combined these with the idea that construction robots can help real estate construction processes be less affected by labor supply and demand, use one device in multiple scenarios, and adjust costs flexibly. In addition, referring to the items of well-established scales by

Davis (1989) and other scholars, we set the following three items to constitute the adaptability measure scale for robot construction, as shown in Table 4-5.

Table 4-5 Measure Items for Adaptability

Variable	Item No.	Item	Source
Adaptability	AB-1	The demand for labor on the construction site is reduced after the adoption of robot construction.	Davis (1989), Venkatesh & Davis (2000), W. Wu & Tian (2022)
	AB-2	The robot construction can help constructors work on multiple construction links at the same time.	
	AB-3	Robot construction can help us adjust costs flexibly.	

4.3.3 Measure of technological advantages

The scale of technological advantages is mainly used to measure the advantages of robot construction technology versus traditional construction technology in building construction and management. S. Liu (2018) drew on the description of technological innovation characteristics by Kim et al. (2016), Moore (1991), and Rogers (1983) to measure technological advantages by assessing the technology application's role in improving production efficiency, enhancing project quality control, reducing risks, lowering costs, and shortening project duration. Oliveira et al. (2014) also measured technological advantages by identifying improvements in business productivity, operational quality, and management operation efficiency. Given that robot construction technology in this study is a technology category instead of a singular technology, we took into account both the scale proposed by S. Liu (2018) and the key advantages of robot construction technology to develop the scale of measuring technological advantages in four dimensions: enhancing production efficiency, enabling quality control, enhancing safety on construction sites, and improving the overall construction environment. Details are provided in Table 4-6.

Table 4-6 Measure Items of Technological Advantages

Variable	Item No.	Item	Source
Technological advantages	TA-1	The adoption of robot technology can improve production efficiency and shorten the construction period.	Kim et al. (2016), S. Liu (2018), Moore (1991), Rogers (1983)
	TA-2	The project work's qualification rate increases and quality warning decreases after the adoption of robot construction.	
	TA-3	The project accidents are reduced and safety is improved after the adoption of robot construction.	
	TA-4	Robot construction can reduce pollution emissions from the construction site and improve nearby environmental quality.	

4.3.4 Measure of project cost

Currently, there are relatively few well-established scales for measuring project cost. From a qualitative perspective, H. Mao et al. (2012) divided project cost management into budget mechanism, accounting mechanism, monitoring mechanism, analysis mechanism, and assessment mechanism, emphasizing material control and project manager control. We focused on explicit material control. Zhi et al. (2022) explored an ecological cost management model in the context of Haier Group's ecosystem micro-communities, classifying costs into fixed cost, variable cost, average cost, and ecological cost. This study integrated the two approaches to establish an average cost dimension. Considering that many projects in the construction industry encounter issues such as material waste, temporary construction, and safety measures, a redundant cost dimension was included to address the current situation of one-time resource use. For the average cost scale, we leveraged the organizational performance measures by Covin & Slevin (1991) and H. Xie et al. (2006) to measure the real estate project's average costs including average area cost, average area labor cost, average area material cost, and average area measure cost. Regarding the redundancy cost scale, we drew on the measures of slack resources by Bourgeois (1981), Chen Jing et al (2021), and Ji (2014) to introduce items including budget control, material waste, and ancillary works. Details are shown in Table 4-7.

Table 4-7 Measure Items of Project Cost

Variable	Dimension	Item No.	Item	Source
Project cost	Average cost	MC-1	Robot construction is adopted to reduce the average construction cost.	Covin & Slevin (1991), H. Mao et al. (2012), H. Xie et al. (2006), Zhi et al. (2022)
		MC-2	Robot construction is adopted to reduce the average labor cost.	
		MC-3	Robot construction is adopted to reduce the material cost per unit area.	
		MC-4	Robot construction is adopted to reduce the measure cost per unit area.	
	Redundancy cost	RC-1	A small gap exists between the construction cost of robot construction and the estimated construction cost, indicating better control costs than traditional construction.	Bourgeois (1981), Chen Jing et al (2021), Ji et al. (2014)
		RC-2	The material waste in construction is significantly reduced after the robot construction is adopted.	
		RC-3	The adoption of robot construction reduces the need for ancillary works.	

4.3.5 Measure of management change

In the digitization era, enterprises and organizations face significant challenges. Organizational structure, platform-based governance, and human-robot interaction have become crucial aspects of management change (D. Chen et al., 2020; X. Wu et al., 2022). P. Xu and X. Xu (2020) divided management change into five dimensions: management objects, management attributes, management decisions, and management ethics to explore the path of enterprise management change in the context of AI. Based on their approach, the scale for measuring management change within this study comprises three dimensions: organizational consensus, organizational learning, and human-robot collaboration. Organizational consensus measures strategic planning, senior management's attitude, and organizational endorsement of robot construction technology. Jarvenpaa & Ives (1991) developed a senior management attitude scale measuring senior management endorsement. P. Li (2019) drew on the well-established scales generated by Zhang Haihua (2018) and Arayici et al. (2012) to measure organizational consensus through enterprise strategy, enterprise innovation culture, and senior management's attitude. Considering interview results, this study measured organizational consensus from three aspects: senior leaders' determination for construction robot adoption, attitude toward adoption risks, and internal employees' endorsement of robot construction adoption, designing a scale for measuring organizational consensus based on well-established scales such as the one proposed by Jarvenpaa & Ives (1991).

Organizational learning measures the organization's training of employee knowledge structure and system improvement after the introduction of robot construction technology. Based on Maduku et al. (2016), Lai (2018) measured organizational learning such as enterprise manpower and capital by examining the organization's support for technology training and employment of technicians. SinKula et al. (1997) developed a scale for measuring organizational learning, focusing on learning input, organizational openness, and shared vision. Kang (2015) drew on it to measure organizational learning from learning input and organizational openness. We measured organizational learning by combining construction robots' characteristics and assessing the organization's establishment of learning performance evaluation of construction robot technology, investment in human resource training, and training of learning robot adoption.

Human-robot collaboration scales are scarcely found in existing literature. P. Shen et al. (2021) drew on scales of perception connectivity, perception controllability, and perception responsiveness proposed by Yoo et al. (2010) and Lee (2005) to measure human-robot interaction in online retail scenarios from perception connectivity, perception personalization, perception controllability, and perception responsiveness. Zhong (2023) measured the completeness of human-robot collaboration networks from the interaction and mutual influence between human and robot construction technology. Combining construction robot adoption and information-based cooperation, this study measured human-robot collaboration through four aspects: the fluency of construction robots replacing the labor force, the informatization of project construction, and the degree of man-robot cooperation.

Details are shown in Table 4-8.

Table 4-8 Measure Items of Management Change

Variable	Dimension	Item No.	Item	Source
Management change	Organizational consensus	MD-1	The company's senior leaders exhibit an active attitude toward the adoption of robotics technology, delivering long-term strategic commitment and strong support.	Arayici et al. (2012), Jarvenpaa & Ives (1991),

		MD -2	Senior leaders are willing to take on the potential risks of promoting the adoption of robotics technology.	Zhang Haihua (2018)
		MD -3	The adoption of robotics technology is highly endorsed within the company, with employees demonstrating active and voluntary engagement.	
	Organizational learning	OL-1	The company develops metrics for learning and development regarding organizational learning of robot construction and implements them accordingly.	Lai (2018), Maduku et al.(2016), SinKula et al.(1997)
		OL -2	The company has vigorously promoted training courses on robot adoption and consistently carried out robot training for employees.	
		OL -3	It is easy to understand and master robot construction technology.	
	Human-robot collaboration	LR-1	The robot construction adoption demonstrates strong compatibility with human resources and possesses sufficient adaptability to facilitate project construction.	P. Shen et al. (2021), Yoo et al.(2010), Lee (2005), Zhong (2023)
		LR-2	The project construction personnel exhibit data processing capabilities that align with robot construction, enabling prompt response to the requirements of the construction site.	
		LR-3	There are no obstacles to substituting regular employees with construction robots in the project's business operations.	
		LR-4	The interaction and collaboration between construction personnel and robotics technology adoption are highly effective.	

4.3.6 Measure of project performance

The scale for measuring project performance primarily focuses on three aspects: customer satisfaction with real estate projects adopting robot construction, output level versus traditional production, and brand reputation. Steers (1975) adopted a self-evaluation method involving multiple factors to measure organizational performance via satisfaction with market share, net profit, and new product development performance. G. Chen (2009) developed a scale for measuring organizational performance based on the balanced scorecard theory proposed by Kaplan and Norton (1992), including financial performance, operational performance, customer performance, and employee performance. Combined with the existing research with well-established scales, this study formulated a scale for measuring real estate project performance based on three dimensions: customer performance feedback, output performance, and brand performance. The details are displayed in Table 4-9.

Table 4-9 Measure Items of Project Performance

Variable	Item No.	Item	Source
Project performance	I-1	The company's construction projects adopting robot construction hold a competitive advantage in customer satisfaction.	G. Chen (2009), Kaplan & Norton (1992), Steers (1975)
	I-2	Robot construction has advantages in output scale and creates greater output value versus traditional construction within the same period.	
	I-3	Robot construction contributes to enhanced brand awareness and credibility.	

4.3.7 Selection of control variables

Consulting the studies by Anderson et al. (2003) and Liang (2018), the control variables selected in this study are economic factors, specifically management team size (MS), number of project construction personnel (WS), project output value (RETO), years of work experience of respondents (WT), gender (GEN), educational background (EDU), among others. Regional (City) fixed effects were added in the model.

Chapter V Empirical Analysis of the Impact of Robot Construction on Real Estate Project Cost—Based on Internal Questionnaire

5.1 Sample Analysis

5.1.1 Distribution and collection of questionnaire

The formal questionnaire survey was conducted from September 2023 to January 2024. Leveraging my human resources advantages within Group B, the questionnaires were distributed and collected through both online and offline methods. The primary online platform used was Wenjuanxing, and invitations were extended to relevant real estate construction project leaders, managers, technicians, and marketing personnel via enterprises' work chat groups, WeChat, QQ, email, and paper mailing. The colleagues, classmates, and friends working in real estate and construction enterprises were also asked to help disseminate the questionnaire by forwarding the link to relevant colleagues in their work chat groups. While the online method increased the convenience of completing the questionnaire, ensuring its effectiveness remained challenging. Therefore, an offline method was employed. We used relevant social network resources to contact nearby real estate construction enterprises and related construction project departments for exchange and learning and invited their management personnel to complete the questionnaire.

The offline method primarily involved the MZQYB Project and the MZQYA Project in a third-tier city of Guangdong Province. Offline completion not only improved the effectiveness of questionnaire collection but also provided an opportunity to communicate with the surveyed personnel to understand the current adoption of robot construction in their projects and its real and intuitive impact on real estate project costs.

Additionally, criteria were established to screen the collected questionnaires. For the online collected questionnaires, only one response per IP address was allowed, and questionnaires completed in less than 10 minutes were excluded. The rationality of the questionnaire was further assessed based on the responses provided. Questionnaires with uniform or patterned responses were removed, and the reliability of the questionnaire was judged based on the logical consistency of the responses. All unrealistic questionnaires were excluded to ensure valid questionnaires.

A total of 162 valid internal questionnaires were collected. Respondents reported 115 projects adopting robot construction, accounting for 76% of the total sample. Due to overlaps of some projects, the actual number of projects surveyed was 121. These projects were distributed in 31 cities including Shenzhen, Hangzhou, Dongguan, Meizhou, Foshan, Suzhou, and Ningbo in 13 provinces in China. One project was located in Vientiane, Laos.

5.1.2 Characteristic analysis of sample demographic and project statistics

Table 5-1 reports the descriptive statistics of the formal questionnaire data.

Table 5-1 Characteristic Analysis of Formal Survey Samples

Sample characteristics	Statistical criteria	Number of samples	Percentage
Gender	Male	147	90.74%
	Female	15	9.26%
Educational background	High school degree/technical secondary school degree and below	5	3.09%
	University degree/Junior college degree	137	84.57%
	Master's degree or above	20	12.35%
Working years	20+ years	8	4.94%
	15–20 years	13	8.02%
	10–14 years	51	31.48%
	5–9 years	58	35.8%
	5 years or less	32	19.75%
Position	Front-line managers/technicians	66	40.74%
	Project general managers and deputy general managers	30	18.52%
	Management personnel	6	3.70%
	Business development personnel	51	31.48%
	Others	4	2.47%
MS	1–3 persons	12	7.41%
	4–6 persons	36	22.22%
	7–9 persons	19	11.73%
	10–12 persons	43	26.54%
	Over 13 persons	52	32.10%
WS	1–20 persons	81	50.00%
	21–40 persons	41	25.31%
	41–70 persons	27	16.67%
	71–110 persons	4	2.47%
	More than 111 persons	9	5.56%
RETO	Below RMB 2,000	44	27.16%
	RMB 2,001-2,200	60	37.04%
	RMB 2,201-2,400	30	18.52%
	RMB 2,401-2,600	15	9.26%
	RMB 2,601-2,800	4	2.47%
	Above RMB 2,801	9	5.56%

The data reveal that 90.74% of the sample are males, consistent with the actual demographic of employees in construction enterprises. Additionally, 96.01% of the respondents had received junior college education or higher, indicating that most respondents are well-educated and likely knowledgeable about robot construction. Furthermore, 80.25% of the respondents had five or more years of work experience, with 49% having ten or more years of experience. This suggests that most respondents had substantial experience in real estate project construction, ensuring a relatively accurate perception of project costs and other relevant aspects. Notably, 18.52% of the respondents are project leaders, and 40.72% are front-line managers. This indicates that they possess rich experience in project management and a deep understanding of the adoption status of robot construction and the factors affecting project costs. Regarding the characteristics of the surveyed projects, management teams with fewer than 6 members, 7–12 members, and more than 13 members account for 29.63%, 38.27%, and 32.10%, respectively. The construction teams vary in size, with 50% having 1–20 members, 25.31% having 21–40 members, and 24.69% having more than 41 members. The output value per unit area of the project is primarily concentrated below RMB 2,200, with 35.8% exceeding this value. Overall, the sample data are well-representative and can meet the needs of this study.

5.1.3 Descriptive statistics of items for measuring variables

A normal distribution test was conducted on the sample data, with the results presented in Table 5-2. The absolute value of skewness for each observed variable ranges from .7 to 1.4, while the absolute value of kurtosis ranges from .5 to 3.1. The results indicate that the data adheres to a normal distribution.

Table 5-2 Descriptive Statistics of Items for Measuring Variables

	Item	Sample size	Mean ± SD	25th percentile	Median	75th percentile	Kurtosis	Skewness
Robot construction	R-1	162	4.611±1.029	4.000	5.000	5.000	2.363	-1.134
	R-2	162	4.475±1.082	4.000	5.000	5.000	.912	-.830
	R-3	162	4.556±1.142	4.000	5.000	5.000	1.639	-1.215
	R-4	162	4.747±1.029	4.000	5.000	5.000	3.034	-1.377
Adaptability	AB-1	162	4.500±1.105	4.000	5.000	5.000	1.064	-.868
	AB-2	162	4.401±1.054	4.000	5.000	5.000	1.419	-.928
	AB-3	162	4.636±1.050	4.000	5.000	5.000	2.498	-1.310
Technological advantages	TA-1	162	4.457±1.126	4.000	5.000	5.000	1.338	-1.053
	TA-2	162	4.377±1.052	4.000	5.000	5.000	1.756	-1.129
	TA-3	162	4.537±1.081	4.000	5.000	5.000	1.587	-1.022
	TA-4	162	4.623±1.052	4.000	5.000	5.000	2.485	-1.175
Average cost	MC-1	162	4.426±1.091	4.000	5.000	5.000	.888	-.738
	MC-2	162	4.309±1.053	4.000	4.000	5.000	1.141	-.744
	MC-3	162	4.358±1.118	4.000	5.000	5.000	1.543	-1.150
	MC-4	162	4.346±1.077	4.000	4.500	5.000	.556	-.697
Redundancy cost	RC-1	162	4.247±1.115	4.000	4.000	5.000	.419	-.666
	RC-2	162	4.593±1.031	4.000	5.000	5.000	1.385	-.975
	RC-3	162	4.593±.943	4.000	5.000	5.000	2.888	-1.172
Organizational consensus	MD-1	162	4.673±.945	4.000	5.000	5.000	2.964	-1.137
	MD-2	162	4.543±1.010	4.000	5.000	5.000	1.931	-1.072
	MD-3	162	4.580±1.050	4.000	5.000	5.000	2.079	-1.144
Organizational learning	OL-1	162	4.537±.985	4.000	5.000	5.000	2.441	-1.091
	OL-2	162	4.519±.998	4.000	5.000	5.000	2.467	-1.114
	OL-3	162	4.549±1.046	4.000	5.000	5.000	1.859	-1.023
Human-robot collaboration	LR-1	162	4.167±1.217	3.000	4.000	5.000	-.233	-.513
	LR-2	162	4.358±1.096	4.000	5.000	5.000	.962	-.866
	LR-3	162	4.364±1.085	4.000	5.000	5.000	1.125	-.856
	LR-4	162	4.451±1.058	4.000	5.000	5.000	1.446	-.953
Project performance	I-1	162	4.346±1.077	4.000	4.500	5.000	.556	-.697
	I-2	162	4.364±1.062	4.000	5.000	5.000	.748	-.773

Table 5-2 Descriptive Statistics of Items for Measuring Variables

Item	Sample size	Mean ± SD	25th percentile	Median	75th percentile	Kurtosis	Skewness
I-3	162	4.370±1.015	4.000	4.000	5.000	1.007	-.617

5.2 Status Quo Analysis of Robot Construction and Real Estate Project Cost

5.2.1 Adoption Status of Robot Construction

Figures 5-1 and 5-2 illustrate the adoption of robot construction in real estate projects. Respondents reported 115 projects adopting robot construction, representing 76% of the total sample size. This underscores the relevance of the sample investigation to the study's objectives regarding the adoption of robot construction. Some real estate projects statistically surveyed didn't adopt robot construction due to the absence of explicit requirements from the Group, so robot construction has not yet seen widespread adoption in such projects. Among sample projects employing robots, such as leveling robots, screeding robots, intelligent follow-up distributors, and measuring robots, most projects adopted 4–7 construction robots with different functions, and some projects adopted more than 13 robots. These robots can be applied across a wide range of construction scenarios, including concrete works in civil engineering, high-precision ground works, waterproofing, exterior wall coating, and paving works. There is also a gradual promotion of their use in interior decoration. Technologies such as leveling robots, measuring robots, and floor smoothing robots are highly mature, enabling barrier-free human-robot cooperation. However, the data indicate that the current coverage of construction robots needs expansion. On the one hand, compared to intelligent industrial manufacturing, intelligent construction is still in its nascent and promotion stages and has significant room for expansion. On the other hand, as construction robots fall under the category of special robots, many technologies require further optimization. This suggests that the adoption of construction robots in large-scale construction activities remains relatively restricted.

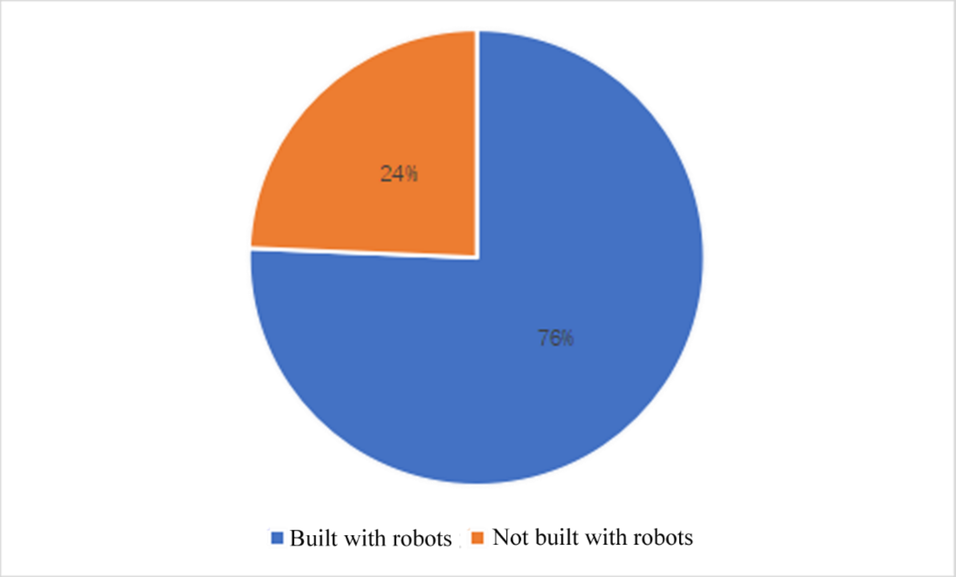

Figure 5-1 Sample Distribution of Construction Robots in Real Estate Projects

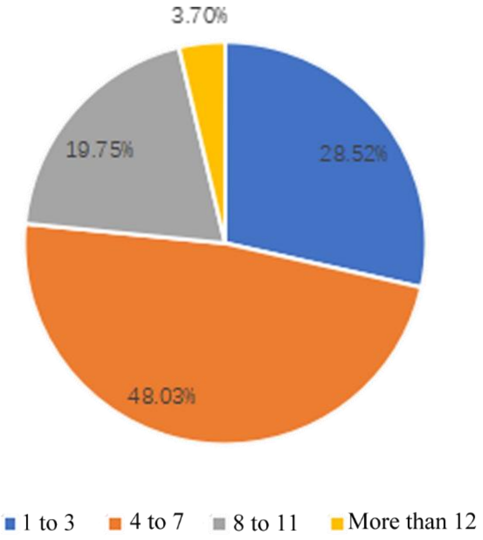

Figure 5-2 Sample Distribution of the Number of Construction Robots Adopted in Real Estate Projects

5.2.2 Analysis of robot construction experience

This study assessed respondents' perceptions of their experiences with robot construction through ranking questions, as reflected in Figure 5-3. Overall, respondents rated “saving labor costs” the highest, with a score of 5.01. This indicates that most respondents believe that the most significant benefit of robot construction is labor cost savings. This was followed by “improving project quality” (4.25), “shortening project cycle” (3.56), and “enhancing brand awareness” (3.43). In contrast, “saving material cost input,” “saving management cost,” and “improving real-time project supervision capability” received lower scores, with the last one scoring the lowest at 2.65.

Analyzing the distribution of options across different ranking positions, the selection rate for “saving labor costs” in the first place was 47.97%, substantially higher than other options, indicating that respondents predominantly viewed labor cost savings as the primary benefit of robot construction. “Improvement of project quality” had the highest selection rate (39.42%) in the second rank, signifying that respondents considered it a significant priority following labor cost savings. The low selection rate for “improving real-time project supervision capability” across different ranks suggests that this effect is relatively unimportant to the respondents.

In summary, respondents generally perceived that robot construction significantly saves labor costs, improves project quality, and shortens project cycles. However, its effects on saving material costs, saving management costs, enhancing brand awareness, and improving real-time project supervision were considered relatively minor. These experiences provide implications for further investigation into the impact of robot construction on project costs.

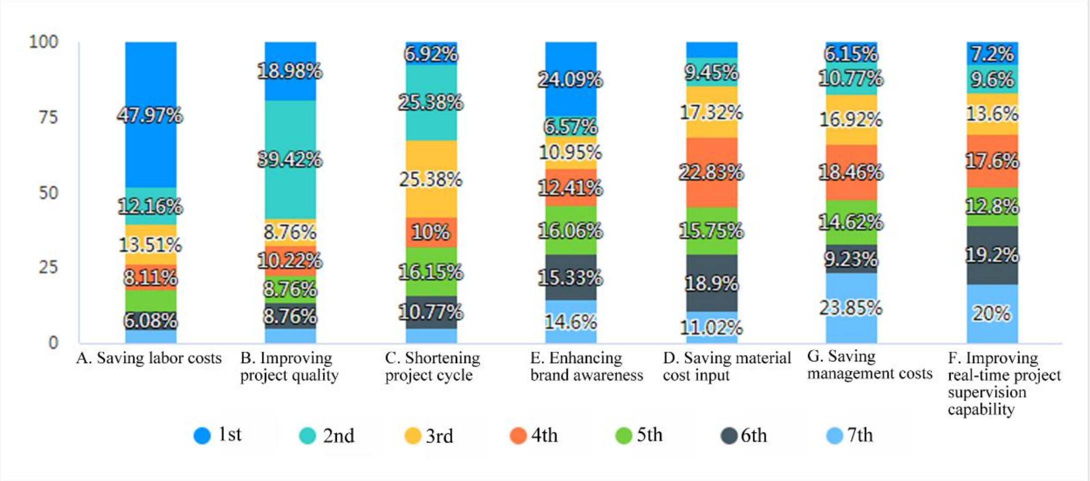

Figure 5-3 Experiences of Real Estate Project Managers in Robot Construction

This study investigated the factors limiting the adoption of construction robots, with the findings illustrated in Figure 5-4. Survey statistics show that the most significant challenge facing robot construction is the high investment cost, cited by 66.05% of respondents. The second most common challenge is the lack of skilled personnel in the field of robot construction, mentioned by 61.11% of respondents. Additional challenges include insufficient government support (30.25%), difficulties in receiving support from existing management mechanisms (46.91%), lack of collaborative innovation from external enterprises (35.8%), lack of operation resulting in poor outcomes post-construction (46.3%), inadequate after-sales service and delays in technical support (38.27%), complex operation with lengthy learning curves (31.48%), and oversized robot equipment (29.63%). Notably, the perception of insufficient support from headquarters was low, and only 5.56% of respondents cited other reasons. From the perspective of respondents' perceptions of factors limiting the adoption of construction robots, it is evident that capital investment is the most critical factor. The deployment of a diverse array of construction robots necessitates substantial financial resources for R&D, production, purchase, and leasing, which aligns with the current industry conditions. Additionally, there is a significant challenge in developing the necessary talent for robot adoption. The current mismatch between skills and robot operators hinders the effective adoption of construction robots. The investigation revealed that adopting construction robots impacts the existing management system; traditional manual operations are being replaced, which necessitates enhanced project informatization, improved site maintenance practices, and a sound construction environment for adopting construction robots. These aspects were overlooked. It is crucial to emphasize the growing importance of changing project operation management. Therefore, the above investigation and analysis results are basically consistent with real-world operation and maintenance, which highlights the research focus of this study.

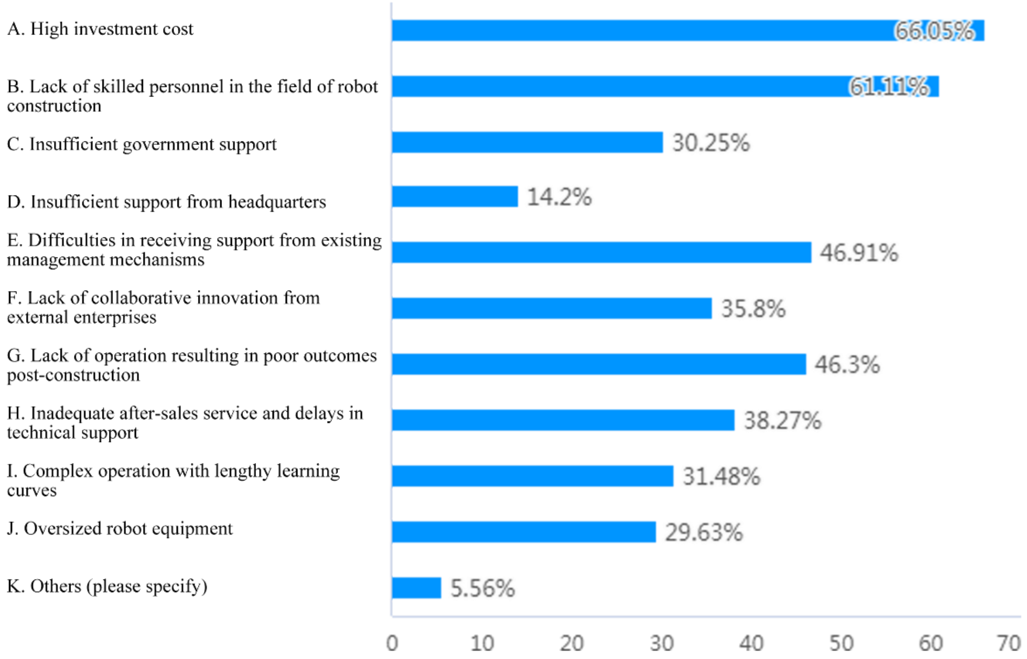

Figure 5-4 Perceptions of Difficulties in Robot Construction Adoption

5.2.3 Basic information of real estate projects

(1) Number of projects

A total of 162 respondents participated in this internal questionnaire survey. It is important to note that some respondents were associated with the same project, which resulted in an actual count of 121 surveyed projects. Notably, the Central Park project in Meizhou and the FHSC project in Longchuan were repeated, involving 42 participants collectively. These projects are typical demonstration projects for the Group's robot construction, characterized by large scales and multiple phases, thus providing highly representative samples. Leveraging my human capital advantages, it is possible to acquire firsthand information which ensure the experiential credibility of the collected samples. As a result, the questionnaires gathered were of high quality.

(2) Geographical distribution

Based on my human capital advantages, local managers from internal work groups were mobilized to collect questionnaires accurately from real estate project managers and management personnel across various locations. The projects spanned 31 cities, such as Shenzhen, Hangzhou, Dongguan, Meizhou, Foshan, Suzhou, and Ningbo, in 13 provinces including Guangdong. There was also one project located in Vientiane, Laos (see Figure 5-5). Among the projects, 134 were in Guangdong and 11 in Zhejiang. The sampled projects included piloting projects characterized by "intelligent construction" (robot construction), such as Fenghuangtai, Fenghuang Shangcheng, and Meijiang Qinyang Central Park, as well as those not adopting “intelligent construction” like Shenlan International and Nanxun Fengshun. It is noteworthy that the same project might adopt or not adopt robot construction technology across different works. For instance, the robot construction was used for the Bid B Project of Gurao Phase IV, whereas it was not employed in the Bid A Project.

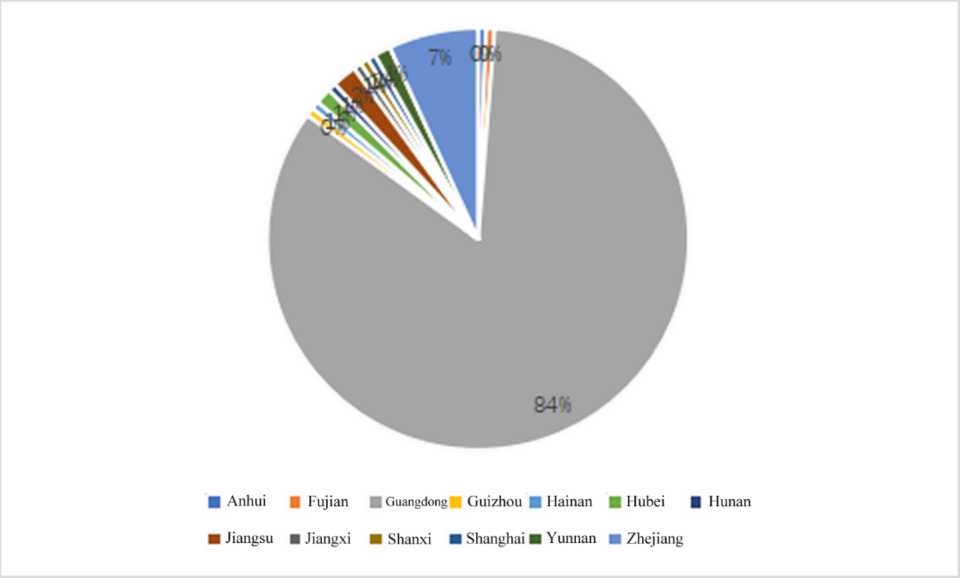

Figure 5-5 Geographical Distribution of Surveyed Real Estate Projects

(3) Project type

In addition to proprietary brand projects, Group B actively engages in general contracting and undertakes government-initiated public construction projects, thus operating diverse types of projects. As shown in Figure 5-6 (there is overlap of project nature), the surveyed real estate projects primarily include commercial housing, residential buildings, and commercial complexes, along with a proportion of public buildings, hospitals, and indemnificatory housing, indicating a diverse and representative sample set.

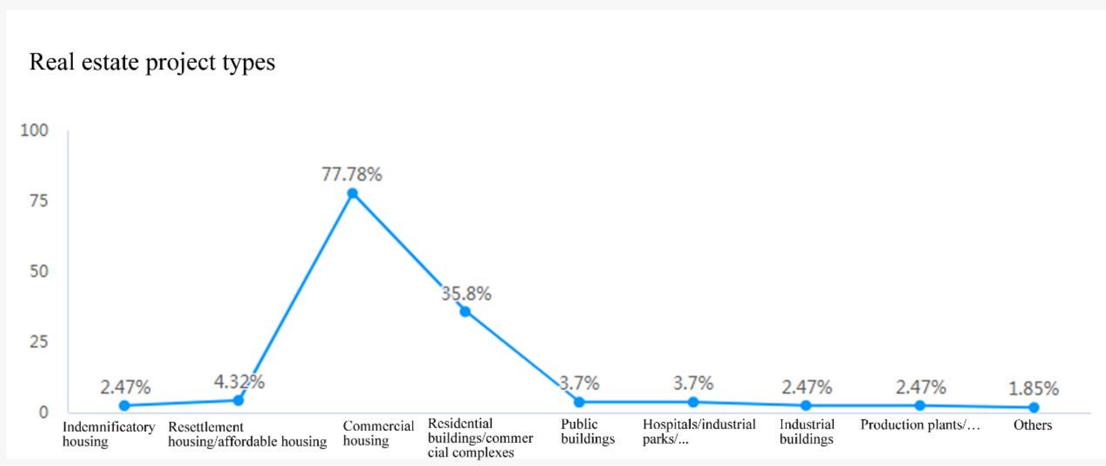

Figure 5-6 Distribution of Real Estate Projects by Type

5.2.4 Cost of real estate projects

The cost of a real estate project can be divided into four categories: material cost, labor cost, measure cost, and management expense. Material cost refers to the intermediate materials purchased during project construction, such as cement, waterproofing materials, pipelines, coatings, and other building materials. This category represents one of the primary expenses in project construction. Based on my working experience and structured interviews, material cost typically accounts for about 50% of the total project cost. Labor cost encompasses the wages of construction personnel and constitutes approximately 40% of the total project cost. It is also the main variable factor influencing the overall project cost. Reducing labor costs is a primary focus in cost management. Measure cost includes auxiliary supporting items like temporary construction works, external wall support, storage fees, transportation fees, and safety and civilization fees incurred during the construction process. Management expense primarily covers the wages of management staff of construction organizations, office allowances, travel expenses, labor protection fees, business entertainment expenses, construction site subsidies, completion acceptance fees, and other related expenditures. Theoretically, the adoption of construction robots can facilitate cost optimization, as this approach can replace numerous on-site workers, enable cross-time configuration, and surpass physiological constraints.

Figure 5-7 illustrates the unit area costs of real estate projects. The total cost per square meter selected by respondents is relatively evenly distributed, mostly ranging from RMB 1,500 to 2,000, with about 14% of costs falling below RMB 1,500 and above RMB 2,200 at both ends. The cost data conforms to a normal distribution pattern. Specifically, 59.26% of respondents estimated the material cost to be between RMB 901 and 1080, 56.91% assessed the measure cost to be between RMB 201 and 300, and 58.64% assessed the labor cost to be between RMB 501 and 780. Overall, the cost distribution in the sample survey aligns with generalized experience in real estate project costs.

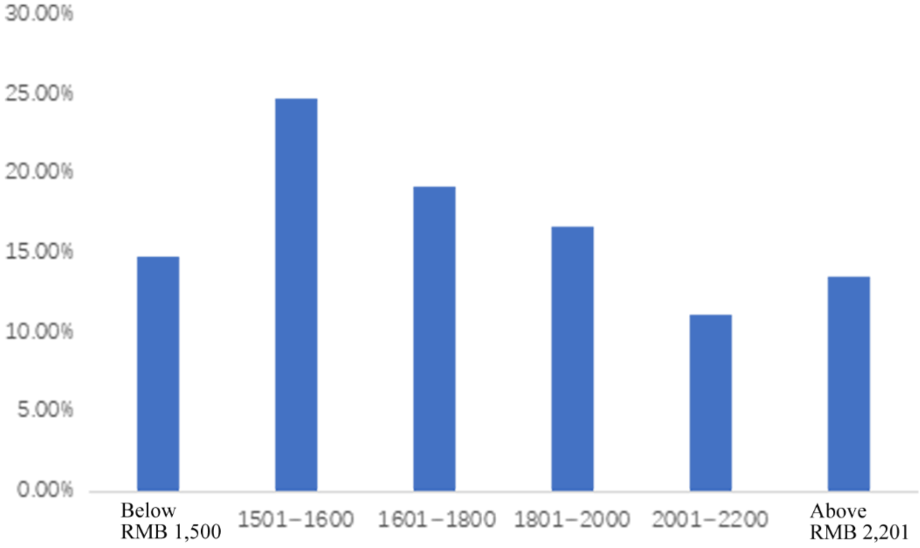

Figure 5-7 Distribution of the Total Cost of Real Estate Projects

According to the survey results, this study analyzed the cost changes in real estate projects after the adoption of construction robots. As reported in Table 5-

3, regarding the projects utilizing robot construction, half of the respondents believed that production cost, labor cost, material cost, measure cost, and management expense could be reduced by an average of 1% to 10%. Nearly 14% of respondents believed that production cost could be reduced by 21% to 30%, 16.92% thought that labor and measure costs could be optimized by about 11% to 20%, and 10.77% believed that material cost could be optimized by 21% to 30%. Additionally, more than 6% of respondents believed that production and measure costs could even be reduced by more than 31%, although almost no respondents thought that the labor cost could be reduced by more than 40%. It is important to note that not all projects adopting robot construction experienced cost reductions. At least 7% of respondents reported no effect on total cost, labor cost, material cost, measure cost, or management expanse, and 16.92% reported no effect on material cost optimization. More than 10% of respondents even reported an increase in total cost and various other costs due to robot construction.

In conclusion, the cost effects of adopting robot construction vary significantly across different projects. While there is a high probability that cost optimization falls within the 1–10% range, there is also an 18–27% possibility that costs might not be optimized. This result warrants further investigation into the factors that positively and negatively influence the cost effects of robot construction in real estate projects. These aspects deserve further investigation in this study.

Table 5-3 Cost Optimization Rate Distribution of Real Estate Projects by Robot Construction Versus Traditional Construction

Optimization rate	Cost per unit area	Labor cost per unit area	Material cost per unit area	Measure cost per unit area	Management expense per unit area
Negative rate	10.77%	10.77%	10.77%	12.31%	15.38%
0%	7.69%	9.23%	16.92%	10.77%	7.69%
1-10%	50.77%	52.31%	50.77%	47.69%	55.38%
11%-20%	9.23%	16.92%	6.15%	16.92%	9.23%
21-30%	13.85%	4.62%	10.77%	4.62%	7.69%
31-40%	3.08%	6.15%	1.54%	3.08%	3.08%
41%-50%	1.54%	0.00%	1.54%	1.54%	1.54%
Above 50%	3.08%	0.00%	1.54%	3.08%	0.00%

Furthermore, this study converted the quantitative questions from the questionnaire into numerical values and conducted *t*-tests. It is important to note that the *t*-tests assess differences in means that were obtained based on questionnaire items. As shown in Table 5-4, the average cost of real estate projects adopting robot construction is RMB 1,900/m^2, significantly lower than the average unit cost of projects not adopting robot construction. Regarding projects adopting robot construction, the main cost reduction driver is a substantial decrease in labor costs, with the unit area cost being RMB 550, much lower than that of projects not adopting robot construction. This reduction is largely attributed to a sharp decrease in the size of construction teams, with the average team size for robot construction-supported projects being 30 people, compared to 55 for projects not adopting robot construction. Nevertheless, it is pertinent to highlight that projects adopting robot construction do not especially excel in reducing material and measure costs; however, they noticeably augment the size of the management team. On average, the management team size for these projects stands at 11 members, contrasting with 8 for projects that do not adopt robot construction. Despite this, the swift impact of the new production model substantially bolsters production efficiency while curbing management costs. Specifically, the management cost per unit area in projects adopting robot construction amounts to RMB 40, noticeably less than that observed in projects not adopting robot construction.

Table 5-4 Test of Difference in Cost Effect Means for Robot Construction

	Built with robots (a)		Not built with robots (b)		*t*-test of the mean
Variable	N	Mean	N	Mean	(a)-(b)[t-value]
Average production cost	115	1900	47	2100	-.605**(-2.361)
Average material cost	115	1020	47	1120	-.025(-.117)
Average labor cost	115	550	47	650	-.301***(-3.464)
Average measure cost	115	275	47	275	-.143(-.676)
Average management expense	115	40	47	60	-.378***(3.003)
Construction team size	115	30	47	55	-.248***(-3.745)
MS	115	11	47	8	.069***(2.854)

5.3 Reliability and Validity Analyses

5.3.1 Reliability analysis

SPSS 26.0 was utilized to conduct the reliability test. The detailed reliability results are presented in Appendix 1. It was found that the standardized Cronbach's alpha (α) value exceeds .7, and the corrected item-total correlation (CITC) values for all items are greater than .5. Further analysis revealed that Cronbach's α for each variable as a whole surpassed the values when scale items were deleted, demonstrating that the formal survey data exhibited high internal consistency and successfully passed the reliability test. The reliability analysis confirmed that the data are highly reliable and suitable for further analysis.

5.3.2 Validity analysis

The scale used in this study was developed by referencing existing literature and interviewing experts and experienced practitioners in the construction industry, ensuring robust content validity. Prior to conducting the validity analysis, the Kaiser-Meyer-Olkin (KMO) measure and Bartlett's Test of Sphericity were performed. As shown in Appendix 2, whether tested individually or collectively, the KMO values for the robot construction application scale, project cost scale, production efficiency scale (adaptability and technological advantage scale), management change scale, and project performance scale were all greater than .70. Additionally, the Bartlett's Test of Sphericity was significant ($P < .001$).

(1) Convergent validity

This study includes 31 significant variables and 162 collected questionnaires, meeting the requirement that the sample size be more than five times the number of variables, thus allowing for confirmatory validity tests. The convergent validity test was conducted using Amos 23.0, with the results shown in Appendix 2. The Average Variance Extracted (AVE) values for the 9 latent variables were .725, .759, .728, .705, .696, .759, .699, .741, and .758, respectively, all exceeding .50. The composite reliability (CR) values were .913, .904, .914, .905, .873, .904, .874, .919, and .904, respectively, all surpassing .70. Additionally, the standardized factor loadings of items were greater than .50, indicating that the good convergent validity of variable measure scale in this study.

(2) Discriminant validity

Further discriminant validity tests were conducted, with results shown in Appendix 2. The absolute values of the correlation coefficients (values below the diagonal) between each variable and other variables were less than .85, and all were lower than the square root values of the AVE for the variables (values on the diagonal in bold), indicating the measure scale's good discriminant validity.

5.3.3 Test of common method bias

Common method biases, which are errors caused by factors such as the environment, measure tools, and characteristics of measure items, were controlled in this study through methods such as anonymous surveys, the use of multiple items to measure the same variable, and the collection of questionnaires both online and offline during the questionnaire design and actual survey process. Additionally, SPSS 26.0 was employed to test common method bias using Harman's single-factor test, with results shown in Appendix 3. Nine factors with eigenvalues greater than 1 were extracted without rotation, and the first factor's variance explained was less than the critical criterion of 40%, indicating no significant common method bias.

5.4 Main Effect Test

5.4.1 Robot construction and real estate project costs

According to the benchmark empirical analysis results in Table 5-5, we focused on identifying general patterns within the "robot construction—real estate project cost" paradigm. The explained variables in Models (1) to (3) are average costs, while the explained variables in Models (4) and (5) are redundancy costs.

This study employed a stepwise regression approach: initially, only core explanatory variables were included without controlling regional fixed effects; subsequently, regional control variables were added; finally, the effects of core explanatory variables were evaluated after adding control variables. In Model (1), a univariate regression of robot construction and real estate project costs was performed. The results indicate that the more extensive the adoption of robot construction technology by construction enterprises, the more beneficial it is in reducing their average costs (the regression coefficient of robot construction on average cost is - .646, significantly negative at the 1% confidence interval). In Model (2), with the inclusion of the city-specific dummy variable, which does not change over time, the result was still significantly negative (the coefficient for robot construction is - .596, passing the significance test at the 1% level). In Model (3), after adding control variables such as project output value, project construction team size, and management team size, the influence of robot construction on reducing real estate project costs remains significant (coefficient is - .572, passing the significance test at the 1% level), validating the conclusion. This study further investigated the influence of robot construction on the redundancy costs of real estate projects. The results indicate a significant inhibitory effect, with coefficient values of - .611, - .573, and - .556, all passing the significance test at the 1% level. Based on these results, it can be confirmed that robot construction effectively reduces the average cost of real estate projects. Thereby, H1a and H1b are supported.

Moreover, the control variables included in the analysis provide additional insights. As shown in Table 5-5, the expansion of operator scale in project construction significantly increases both the average and redundancy costs of real estate projects. Similarly, an increase in the proportion of management personnel among project employees also elevates these costs. These relationships align with expectations. Although other control variables are not significant, their directions are generally consistent with real-world patterns.

Table 5-5 Regression Model of Robot Construction and Real Estate Project Costs

	(1)	(2)	(3)	(4)	(5)	(6)
	Average cost	Average cost	Average cost	Redundancy cost	Redundancy cost	Redundancy cost
Robot construction	-.646***	-.596***	-.572***	-.611***	-.579***	-.556***
	(-10.86)	(-8.39)	(-7.62)	(-12.49)	(-9.63)	(-8.73)
Output value			-.076			-.055
			(-.81)			(-.70)
WS			.015**			.012**
			(2.41)			(2.23)
Proportion of management personnel			.793**			.621*
			(2.11)			(1.95)
GEN			.469			.452
			(1.18)			(1.34)
EDU			-.192			-.212
			(-.52)			(-.67)
WT			-.088			-.016
			(-.71)			(-.16)
_cons	.000	-.076	-.096	.000	-.396	-.436
	(.00)	(-.06)	(-.05)	(.00)	(-.34)	(-.28)
City	Uncontrolled	Controlled	Controlled	Uncontrolled	Controlled	Controlled
N	162	162	162	162	162	162
adj. R^2	.421	.413	.424	.491	.452	.461

Note: (1) ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. (2) Robust t statistics are in parentheses. These approaches are applied in the following sections.

5.4.2 Robot construction and production efficiency

The empirical research above confirmed that robot construction can reduce the cost of real estate projects. The focus now shifts to exploring the mechanism path. The regression results of robot construction versus production efficiency are presented in Table 5-6. The regression coefficient of robot construction on technological advantages is .689 (significant at the 1% confidence interval), and on adaptability is .607 (also significant at the 1% confidence interval).

Table 5-6 Regression Model of Robot Construction Versus Production Efficiency

	(1) Technological advantages	(2) Technological advantages	(3) Technological advantages	(4) Adaptability	(5) Adaptability	(6) Adaptability
Robot construction	$.760^{***}$	$.726^{***}$	$.689^{***}$	$.649^{***}$	$.635^{***}$	$.607^{***}$
	(14.71)	(11.46)	(10.23)	(13.47)	(10.86)	(9.75)
Output value			-.035			.070
			(-.42)			(.90)
WS			-.007			$-.011^{**}$
			(-1.19)			(-2.09)
Proportion of management personnel			-.506			-.424
			(-1.50)			(-1.36)
Gender			-.435			-.077
			(-1.22)			(-.23)
EDU			$.610^{*}$			.279
			(1.83)			(.91)
WT			.048			-.012
			(.44)			(-.12)
_cons	.000	.454	-.574	-.000	.700	.106
	(.00)	(.38)	(-.35)	(-.00)	(.63)	(.07)
City	Uncontrolled	Controlled	Controlled	Uncontrolled	Controlled	Controlled
N	162	162	162	162	162	162
adj. R^2	.572	.543	.547	.528	.507	.509

5.4.3 Production efficiency and real estate project costs

This study examined the relationship between production efficiency and real estate project costs. The specific regression results are illustrated in Table 5-7. Equations (1) and (2), and Equations (4) and (5) represent simple univariate linear regressions, with results indicating robot construction's role in improving the average costs of real estate projects through both technological advantages and adaptability. After adding control variables, as shown in Equations (3) and (6), this conclusion remains unchanged, thus supporting H3a and H4a. The regression coefficient of robot construction on technological advantages is .732 (significant at the 1% confidence interval), and on adaptability is .900 (also significant at the 1% confidence interval).

Table 5-7 Regression Model of Production Efficiency Versus Average Costs of Real Estate Projects

	(1) Average cost	(2) Average cost	(3) Average cost	(4) Average cost	(5) Average cost	(6) Average cost
Technological advantages	-.762***	-.742***	-.732***			
	(-15.24)	(-13.19)	(-12.11)			
Adaptability				-.933***	-.908***	-.900***
				(-19.35)	(-17.09)	(-15.89)
Output value			-.090			-.009
			(-1.19)			(-.14)
WS			.011**			.005
			(2.12)			(1.26)
Proportion of management personnel			.408			.405
			(1.32)			(1.55)
Gender			.176			.410
			(.54)			(1.48)
EDU			.181			.032
			(.59)			(.12)
WT			-.061			-.102
			(-.61)			(-1.19)
_cons	.000	.195	-.445	.000	.537	.027
	(.00)	(.18)	(-.30)	(.00)	(.57)	(.02)
City	Uncontrolled	Controlled	Controlled	Uncontrolled	Controlled	Controlled
N	162	162	162	162	162	162
adj. R^2	.590	.612	.612	.699	.721	.721

This study further explored the relationship between production efficiency and the redundancy cost of real estate projects, with regression results shown in Table 5-8. Equations (1) and (2), and Equations (4) and (5) involved simple univariate linear regression, with results indicating robot construction's role in improving the redundancy cost of real estate projects through both technological advantages and adaptability. After adding control variables, as shown in Equations

(3) and (6), this conclusion remains unchanged, thus supporting H3b and H4b. The regression coefficient of robot construction on technological advantages is - .738 (significant at the 1% confidence interval), and on adaptability is .900 (also significant at the 1% confidence interval). As a result, the average cost of real estate projects is significantly correlated with technological advantages and adaptability.

Table 5-8 Regression Model between Production Efficiency Versus Redundancy Cost of Real Estate Projects

	(1) Redundancy cost	(2) Redundancy cost	(3) Redundancy cost	(4) Redundancy cost	(5) Redundancy cost	(6) Redundancy cost
Technological advantages	-.751***	-.742***	-.738***			
	(-21.85)	(-18.16)	(-16.85)			
Adaptability				-.882***	-.873***	-.868***
				(-26.72)	(-23.01)	(-21.45)
Output value			-.074			.010
			(-1.33)			(.21)
WS			.007**			.003
			(1.98)			(.86)
Proportion of management personnel			.237			.246
			(1.06)			(1.32)
Gender			.148			.396**
			(.62)			(2.01)
EDU			.187			-.001
			(.84)			(-.00)
WT			.013			-.031
			(.17)			(-.50)
_cons	-.000	-.106	-.810	-.000	.187	-.313
	(-.00)	(-.13)	(-.75)	(-.00)	(.28)	(-.35)
City	Uncontrolled	Controlled	Controlled	Uncontrolled	Controlled	Controlled
N	162	162	162	162	162	162
adj. R^2	.747	.734	.735	.816	.814	.815

5.5 Mediating Effect Test Based on Production Efficiency

The empirical results presented in the previous chapters demonstrate that the adoption of robot construction contributes to reducing the costs of real estate projects and enhancing the technological advantages and adaptability in the construction of real estate projects. In turn, the enhanced technological advantages and adaptability effectively reduce the costs of real estate projects. These conclusions remain valid even after robustness testing. The subsequent inquiry investigated whether production efficiency—encompassing technological advantages and adaptability—mediates the costs of real estate projects. This section provides a detailed analysis of this aspect.

The mediating effect regression results, based on production efficiency, are displayed in Table 5-9. This study employed a progressive regression model to elucidate the mediating pathway. From the analysis of Model (1) (robot construction—average cost), Model (2) (robot construction—technological advantage), and Model (4) (robot construction—adaptability), it can be inferred that robot construction reduces average costs through mechanisms where it positively impacts technological advantages and adaptability. Model (3), which includes robot construction and technological advantage as core explanatory variables, reveals that the mediating effect is partial, with both variables being statistically significant. Similarly, Model (5) indicates that average cost and adaptability are significant at least at the 5% level, suggesting adaptability's certain mediating role. In Model (6), which incorporates both mediating variables—technological advantages and adaptability—into the analysis framework, the signs and significance of the core explanatory variables and mediating variables remain consistent for the following reasons: robot construction effectively controls the average cost of real estate projects by enhancing the technological advantages and adaptability at the construction site. Technological advantages and adaptability partially mediate the relationship between robot construction and the average cost of real estate projects. Thus H5a and H6a are supported.

Table 5-9 Robot Construction and Average Cost of Real Estate Projects: Mediating Effect Test Based on Production Efficiency

	(1) Average cost	(2) Technological advantages	(3) Average cost	(4) Adaptability	(5) Average cost	(6) Average cost
Robot construction	-.572***	.689***	-.126**	.607***	-.146**	-.108**
	(-7.62)	(10.23)	(-2.31)	(9.75)	(-2.36)	(-2.03)
Technological advantages			-.349***			-.146***
			(-7.96)			(-3.41)
Adaptability					-.468***	-.229***
					(-11.52)	(-6.77)
Output value	-.076	-.035	-.098	.070	-.015	-.020
	(-.81)	(-.42)	(-1.29)	(.90)	(-.23)	(-.30)
WS	.015**	-.007	.011**	-.011**	.006	.006
	(2.41)	(-1.19)	(2.09)	(-2.09)	(1.27)	(1.29)
Proportion of management personnel	.793**	-.506	.465	-.424	.425	.418
	(2.11)	(-1.50)	(1.50)	(-1.36)	(1.61)	(1.58)
Gender	.469	-.435	.187	-.077	.403	.386
	(1.18)	(-1.22)	(.57)	(-.23)	(1.45)	(1.37)
EDU	-.192	.610*	.204	.279	.051	.068
	(-.52)	(1.83)	(.66)	(.91)	(.20)	(.26)
WT	-.088	.048	-.056	-.012	-.098	-.095
	(-.71)	(.44)	(-.56)	(-.12)	(-1.14)	(-1.10)
_cons	-.096	-.574	-.468	.106	-.003	-.034
	(-.05)	(-.35)	(-.31)	(.07)	(-.00)	(-.03)
City	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
N	162	162	162	162	162	162
adj. R^2	.424	.547	.616	.509	.720	.728

The study examined the mechanism by which robot construction influences the redundancy costs of real estate projects. The results are reported in Table 5-10. Using a progressive regression model, the study analyzed the mechanism systematically. Model (1) (robot construction—average cost), Model (2) (robot construction—technological advantage), and Model (4) (robot construction—adaptability) suggest that robot construction reduces redundancy costs through significant positive impacts on technological advantages and adaptability. Model (3) shows that when core explanatory variables—robot construction and technological advantages—are included, the mediating effect is partial, with both variables being statistically significant. Similarly, Model (5) indicates that average cost and adaptability are significant at least at the 5% level, suggesting adaptability's certain mediating role. In Model (6), which incorporates both mediating variables—technological advantages and adaptability—into the analysis framework, the signs and significance of the core explanatory variables and mediating variables remain consistent for the following reasons: robot construction effectively reduces the redundancy costs of real estate projects by enhancing the technological advantages and adaptability at the construction site. Technological advantages and adaptability partially mediate the relationship between robot construction and the redundancy costs of real estate projects. Thus H5b and H6b are supported.

Table 5-10 Robot Construction and Redundancy Costs of Real Estate Projects: Mediating Effect Test Based on Production Efficiency

	(1) Redundancy cost	(2) Technological advantages	(3) Redundancy cost	(4) Adaptability	(5) Redundancy cost	(6) Redundancy cost
Robot construction	$-.556^{***}$	$.689^{***}$	$-.108^{**}$	$.607^{***}$	$-.112^{**}$	$-.098^{*}$
	(-8.73)	(10.23)	(-2.06)	(9.75)	(-2.05)	(-1.89)
Technological advantages			$-.380^{***}$			$-.198^{**}$
			(-11.51)			(-2.51)

Adaptability					-.531***	-.263***
					(-15.49)	(-7.78)
Output value	-.055	-.035	-.079	.070	.002	-.016
	(-.70)	(-.42)	(-1.44)	(.90)	(.05)	(-.35)
WS	.012**	-.007	.007*	-.011**	.003	.003
	(2.23)	(-1.19)	(1.95)	(-2.09)	(.88)	(1.06)
Proportion of management personnel	.621*	-.506	.277	-.424	.268	.240
	(1.95)	(-1.50)	(1.23)	(-1.36)	(1.43)	(1.30)
Gender	.452	-.435	.156	-.077	.388*	.315
	(1.34)	(-1.22)	(.66)	(-.23)	(1.97)	(1.61)
EDU	-.212	.610*	.203	.279	.021	.094
	(-.67)	(1.83)	(.91)	(.91)	(.11)	(.51)
WT	-.016	.048	.016	-.012	-.026	-.015
	(-.16)	(.44)	(.22)	(-.12)	(-.43)	(-.24)
_cons	-.436	-.574	-.826	.106	-.348	-.479
	(-.28)	(-.35)	(-.76)	(.07)	(-.38)	(-.54)
City	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
N	162	162	162	162	162	162
adj. R^2	.461	.547	.737	.509	.815	.822

5.6 Heterogeneity Test

While the previous sections have thoroughly analyzed the impact of robot construction on real estate project costs and the underlying mechanisms, the analysis assumes heterogeneity. This assumption overlooks the potential variability in the impact of robot construction on real estate project costs across different subjects and environments. In other words, such an impact is asymmetric.

To address this, a heterogeneity test was conducted. The external environment of the project and the project’s characteristics were considered to conduct a structured effect analysis. For the external environment, the study used the growth rate of the per capita wage in the cities and towns where the projects are located as a criterion. This approach investigated how the increase in per capita wage affects the impact of robot construction on real estate project costs. Figure 5-

9 illustrates this effect. It is evident that as the wage levels in the cities where construction enterprises are located increase, the ability of robot construction to reduce average project costs weakens, and the significance of this effect diminishes. A similar conclusion applies to project redundancy costs. The explanation lies in the labor replacement achieved by robot construction. While one might expect robot construction's advantages in labor cost reduction because of labor replacement to be more pronounced with rising wage levels, the opposite conclusion is observed. This may be attributed to the polarization of labor distribution in the robot construction mode. On the one hand, robot construction replaces conventional labor; on the other hand, it demands professional skilled labor. This actually expands the workforce and optimizes the employment structure, potentially increasing the input of knowledge capital. In areas with high wage levels, the increased factor input costs due to structured labor may impair robot construction's ability to reduce project costs.

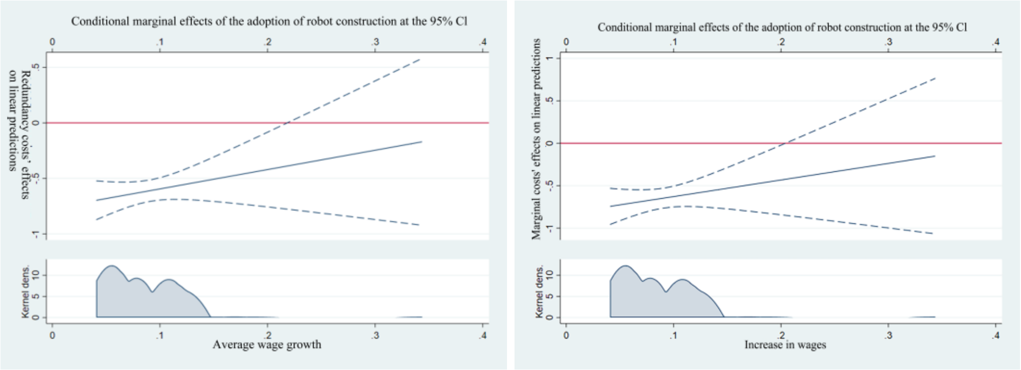

Figure 5-9 Asymmetric Effect Based on Regional Average Wage Growth Rate

For project characteristics, this study analyzed from two dimensions: construction team size and management size. Figure 5-10 illustrates the change in the impact of robot construction on projects' average and redundancy costs with rising construction team sizes. It shows that the adoption of robot construction distinctly restrains the average and redundancy costs of projects in scenarios involving larger construction teams as opposed to smaller ones. This observation underscores that the cost-saving benefits of robot construction become more pronounced with larger-scale construction projects. This phenomenon can be elucidated by two main factors. Firstly, in the context of real estate projects with sizable construction teams and extensive project scales, the increasing marginal returns derived from investments in construction robots exhibit enhanced performance advantages, thereby fostering a more robust cost containment impact. Secondly, as the construction team expands, the technological advantages and adaptability of robot construction manifest a heightened optimization effect within intricate construction environments, mitigating the challenges posed by increased project scales and thus demonstrating a more pronounced cost reduction effect.

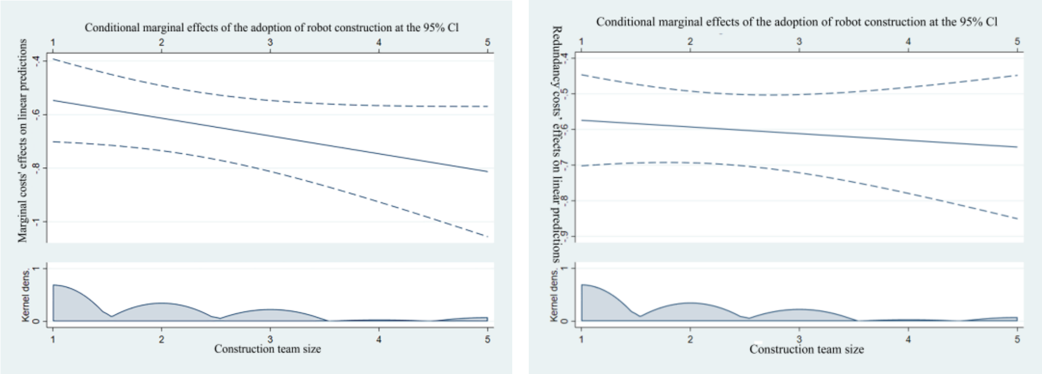

Figure 5-10 Asymmetric Effect Based on the Size of Project Construction Team

Figure 5-11 illustrates the change in the impact of robot construction on projects' average and redundancy costs with rising management sizes. It shows that the adoption of robot construction distinctly restrains the average and redundancy costs of projects in scenarios involving large-size project management as opposed to small-size project management. This observation underscores that the cost-saving benefits of robot construction become more pronounced with more complex project management. This phenomenon can be elucidated by two main factors. Firstly, heightened numbers of project management entail a propensity toward organizational decision-making reliance and an increased involvement of multiple departments regarding managed projects. Within this framework, the integration of robot construction can alleviate the adverse impacts of such intricate management, thereby exhibiting advantages in reducing average and redundancy costs. Secondly, as the management size expands, the elevation of informatization levels driven by robot construction can furnish project management teams with more precise insights, thereby augmenting collective rationality. This holds great significance for the management team, which often finds it challenging to reach a consensus. Consequently, within construction projects characterized by expanded management size, robot construction exhibits a more conspicuous inhibitory impact on the average and redundancy costs of real estate projects.

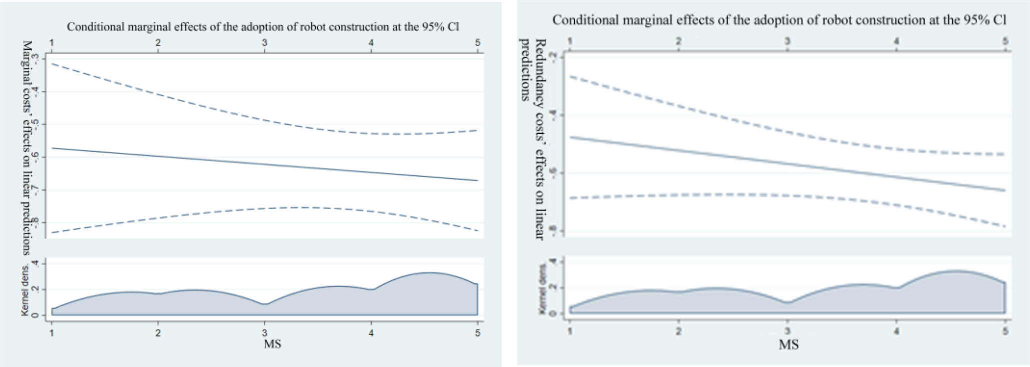

Figure 5-11 Asymmetric Effects Based on Project Management Team Size

5.7 Moderating Effect Test of Management Change

This section explores the critical mechanisms through which robot construction impacts real estate project costs. As previously discussed, the anticipated cost reduction effect of robot construction can only be achieved under certain conditions. The study posits that robot construction revolutionizes traditional management practices. If an organization cannot adapt to this change, the resulting incompatibility will increase project costs and potentially lead to the failure of the robot construction transformation. Thus, this study examined the role of external key mechanisms from three dimensions: organizational consensus, organizational learning, and human-robot collaboration. The empirical results are reported in Table 5-11. The findings indicate that organizational consensus, organizational learning, and human-robot collaboration can reduce both the average and redundancy costs of projects. This suggests that adaptive changes implemented by construction enterprises are conducive to cost reduction. Furthermore, the core variables—the interaction item of organizational consensus and robot construction, the interaction item of organizational learning and robot construction, and the interaction item of human-robot collaboration and robot construction—are all significantly negative. This indicates that as construction enterprises enhance their changes in organizational consensus, organizational learning, and human-robot collaboration, the adoption of robot construction has a stronger effect on reducing the costs of real estate projects. In other words, the effect of robot construction in reducing project costs is strengthened only when organizations implement corresponding management changes. Therefore, H7a and H7b are supported.

Table 5-11 Robot Construction and Average Cost of Real Estate Projects: Analysis of Management Change's Mediating Effect

	(1) Average cost	(2) Average cost	(3) Average cost	(4) Redundancy cost	(5) Redundancy cost	(6) Redundancy cost
Robot construction	-.147*	-.098	-.123**	-.136**	-.142**	-.178***
	(-1.85)	(-1.45)	(-2.10)	(-2.23)	(-2.51)	(-3.49)
Organizational consensus	-.786***			-.753***		
	(-8.87)			(-11.08)		
Organizational consensus × Robot construction	-.131**			-.120**		
	(-2.13)			(-2.39)		
Organizational learning		-.882***			-.751***	
		(-12.11)			(-12.23)	
Organizational learning × Robot construction		-.126**			-.133**	
		(-2.50)			(-2.39)	
Human-robot collaboration			-.776***			-.647***
			(-13.86)			(-13.30)
Human-robot collaboration × Robot construction			-.073*			-.066*
			(-1.71)			(-1.75)
Output value	-.027	-.021	-.008	-.010	-.011	.000
	(-.37)	(-.34)	(-.14)	(-.18)	(-.21)	(.01)
WS	.007	.004	-.002	.003	.002	-.003
	(1.37)	(.87)	(-.57)	(.88)	(.45)	(-.82)
Proportion of management personnel	.576*	.397	.103	.375	.253	.032
	(1.88)	(1.50)	(.42)	(1.60)	(1.14)	(.15)
Gender	.338	.112	.307	.327	.148	.317
	(1.08)	(.41)	(1.23)	(1.36)	(.64)	(1.46)
EDU	-.194	-.307	-.392*	-.186	-.288	-.370*
	(-.65)	(-1.20)	(-1.66)	(-.82)	(-1.33)	(-1.81)
WT	-.106	-.052	-.029	-.030	.018	.033
	(-1.09)	(-.61)	(-.37)	(-.40)	(.26)	(.49)
_cons	.261	.421	.269	-.175	-.054	-.150
	(.18)	(.34)	(.23)	(-.16)	(-.05)	(-.15)
City	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
N	162	162	162	162	162	162
adj. R^2	.643	.733	.772	.726	.753	.776

5.8 Robot Construction-Supported Project Performance Effect Test

The preceding sections have provided a basic identification, mechanism analyses, difference tests, and discussions of external key mechanisms concerning the cost effect of robot construction. Rich empirical evidence has been gathered. Consequently, it is pertinent to consider whether the cost reduction effect of robot construction can translate into improved project performance.

Following this rationale, the relationship between robot construction and real estate project performance was investigated, with results reported in Table 5-12. The results indicate that robot construction significantly enhances project performance, with coefficients of .596, .580, and .579, all significantly positive at the 1% level. This demonstrates that the adoption of construction robots not only improves the cost of construction projects but also enhances project performance. The validation and assessment of this issue establish a foundation for the adoption and effect evaluation of construction robots. The empirical results thus supports H8.

Table 5-12 Robot Construction and Real Estate Project Performance

	(1) Project performance	(2) Project performance	(3) Project performance
Robot construction	$.596^{***}$	$.580^{***}$	$.579^{***}$
	(11.41)	(8.92)	(8.40)
Output value			.116
			(1.37)
WS			$-.011^{*}$
			(-1.92)
Proportion of management personnel			$-.726^{**}$
			(-2.11)
Gender			-.455
			(-1.25)
EDU			.089
			(.26)
WT			.065
			(.57)
_cons	-.000	.777	.816
	(-.00)	(.62)	(.49)
City	Uncontrolled	Controlled	Controlled
N	162	162	162
adj. R^2	.445	.389	.399

Table 5.9 Summary of Hypothesis Test Results

The hypothesis tests are summarized in Table 5-13 below.

Table 5-13 Summary of Hypotheses

Variable	Research hypothesis	Test results
Robot construction and real estate project costs	H1a: Robot construction reduces the average cost of real estate projects	Supported
	H1b: Robot construction reduces the redundancy costs of real estate projects	Supported
Robot construction and production efficiency	H2a: Robot construction can enhance the technological advantages of project construction.	Supported
	H2b: Robot construction can enhance the adaptability of project construction.	Supported
Production efficiency and real estate project costs	H3a: Technological advantages can reduce the average costs of real estate projects	Supported
	H3b: Technological advantages can reduce the redundancy costs of real estate projects	Supported
	H4a: Adaptability can reduce the average costs of real estate projects.	Supported
	H4b: Adaptability can reduce the redundancy costs of real estate projects.	Supported
Mediating effect test based on production efficiency	H5a: Technological advantages play a mediating role between robot construction and the average costs of real estate projects	Supported
	H5b: Technological advantages play a mediating role between robot construction and the redundancy costs of real estate projects	Supported
	H6a: Adaptability plays a mediating role between robot construction and the average costs of real estate projects	Supported
	H6b: Adaptability plays a mediating role between robot construction and the redundancy costs of real estate projects	Supported
Moderating role of management change	H7a: Management change plays a moderating role between robot construction and the average costs of real estate projects	Supported
	H7b: Management change plays a moderating role between robot construction and the redundancy costs of real estate projects	Supported
Performance effect of robot construction	H8: Robot construction positively affects the performance of real estate projects	Supported

Chapter VI Analysis of Willingness Cost for Real Estate Projects Adopting Robot Construction—Based on the External Questionnaire Survey

The preceding chapters are grounded in internal questionnaire data from real estate projects across various locations within Group B. They investigated the cost effect stemming from the degree of robot construction utilization within the project, focusing on the outcome variables—average costs and redundancy costs. The study found that the adoption of robot construction significantly suppresses average costs and redundancy costs. The mechanism path analysis reveals that robot construction highlights several technological advantages, such as reducing production cycles, enhancing production quality, ensuring production safety, and improving the production environment. Additionally, it demonstrates exceptional adaptability, like budget cost control and flexible resource allocation. The technological advantages and adaptability can effectively reduce the average costs and redundancy costs of real estate projects. Based on the mediating effect model, it was identified that technological advantages and adaptability mediate the relationship between robot construction and the costs of real estate projects. Through heterogeneity analysis, it was discovered that the cost effect of robot construction on real estate projects presents notable non-structural features. With an increase in labor wages at project locations, the cost-reduction effect of robot construction tends to diminish. In the context of large-size project construction teams and project management teams, robot construction has a more prominent impact on reducing both the average costs and redundancy costs of real estate projects. The moderating effect analysis reveals that the key mechanism by which robot construction reduces the costs of real estate projects encompasses three dimensions of management change: organizational consensus, organizational learning, and human-robot collaboration. Within an environment of organizational consensus cohesion, knowledge dissemination and absorption through organizational learning, and effective human-robot collaborative operations, the expected effect of robot construction in lowering both the average costs and redundancy costs of real estate projects can be fully realized and even strengthened. Finally, the extended research found that robot construction can significantly improve organizational performance while reducing costs.

The aforementioned analysis has outlined the pattern, underlying logic, and optimization path of how robot construction impacts the costs of real estate projects. This offers evidence supported by empirical experience, filling the gaps in current literature research. It is important to emphasize that the empirical experience mentioned earlier is derived from the analysis of data collected through the internal questionnaire. This questionnaire was designed based on scientifically validated measurement techniques drawn from existing literature and expert input. It was tailored for individuals and projects with extensive practical experience, enabling the collection of relevant data with a high level of representativeness. Some questions arise: whether the empirical evidence derived from the internal questionnaire can be applied to a broader range of other real estate construction enterprises? What is the stance of these enterprises regarding the adoption of robot construction, and what are the barriers that prevent them from embracing this technology? If they are inclined to implement robot construction, how much are they willing to invest in acquiring services, and what project costs do they expect to achieve? Within a predefined investment scenario, what is the collaboration model with Group B, and what are the rationales behind selecting this specific approach?

A thorough analysis of the above questions can shed light on the underlying reasons restricting the adoption of robot construction on the one hand. On the other hand, it can help tailor strategies for improving the promotion of current robot construction technology based on the expected needs of external enterprises. The aim is to provide clear policy insights for the transformation of intelligent construction in the real estate industry.

6.1 Questionnaire Design and Data Source

6.1.1 Questionnaire design

Questionnaire design is a critical component of the survey process, and its rationality and reliability will directly impact the survey data. Drawing on the questionnaire design process and principles outlined by Churchill (1979), this study determined the formal questionnaire items and conducted a formal questionnaire survey based on initial questionnaire items, expert input in interviews, and a small-scale pre-survey, to ensure the rationality of the questionnaire and the reliability of the results. The external questionnaire primarily targets external organizations' robot adoption to assess their willingness to adopt Group B’s robot construction technology. The specific questionnaire design process is similar to that of the internal questionnaire.

To begin, we conducted interviews with experts, scholars, and frontline staff such as managers, technical personnel, and business development professionals from some real estate project construction enterprises. We analyzed these interviews to extract insights into the general range of construction costs, prevalent construction modes, and factors influencing their readiness to embrace robot construction. Subsequently, we pinpointed the factors affecting the adoption of robot construction technology in construction enterprises, contrasting these findings with the influencing factors identified in our literature review to ensure they align with the industry’s real-world landscape, while guaranteeing that anticipated costs match the prevailing reality.

Secondly, well-established scales suitable for this study were identified by referencing existing relevant research. Using this foundation, the influencing factor scale and items for robot construction willingness were selected based on the research object and the characteristics of each influencing factor to be measured. Subsequently, the initial questionnaire items were finalized by assessing the clarity of articulation and the rationality of the elaborated content of each item and making necessary adjustments.

Third, we analyzed the small-scale pre-survey data to modify the initial questionnaire items. Based on this analysis and expert interviews, necessary corrections were made to finalize the formal version.

Following the research objectives, existing literature, above procedures, and pre-survey, we modified the initial external questionnaire to finalize the formal version. Appendix 3 details the formal external questionnaire. The external questionnaire consists of three parts. The first part is for providing basic information, including gender, age, education, enterprise location, nature, size, and project construction method. (2) Enterprises' willingness to adopt robot construction and their anticipated costs; (3) Respondents' evaluation of the prosperity and policy support for the adoption of robot construction. The external questionnaire contains 25 items and 65 sub-items.

6.1.2 Data source

As a regional manager of Group B, I have extensive industry experience Based on my human capital strength, the cooperative relations I have established in business interactions, and Group B's partnership, the questionnaire was sent to construction partners (mainly real estate project constructors). The external questionnaire aims to gauge external enterprises' willingness to adopt robot construction methods and their expectations regarding anticipated cost performance. The questionnaire primarily targets technical personnel and managers at different levels within construction enterprises involved in real estate projects, such as project managers and department heads. They possess a deep understanding of the adoption of robot construction technology within their enterprises, thus being able to differentiate between internal and external factors influencing the adoption of such technology. Moreover, they can better reflect their willingness to adopt robot construction technology and provide a more scientifically grounded estimate of the anticipated costs associated with its adoption. The empirical research focused on real estate projects, including construction projects from external enterprises that have implemented robot construction methods and those that have not. It also covered projects of various sizes—small, medium, and large—spanning different property ownership types (state-owned, private, etc.), diverse construction models (construction management, general contracting, etc.), and projects from different regions. By incorporating this diverse range of projects, the study aims to ensure a broad and representative sample for analysis.

The formal questionnaire survey was conducted from the end of November to the end of December 2023, utilizing both online and offline distribution and collection methods. Online distribution primarily involved the Wenjuanxing platform, and enterprise management personnel were invited through platforms such as WeChat, QQ, and email to complete the survey. Additionally, leaders, colleagues, and friends in real estate construction enterprises were invited to help forward and disseminate the questionnaire by sharing the survey link with relevant colleagues within the working group for participation in filling out the questionnaire. It is more convenient to fill in the questionnaire online.

Additionally, criteria were established to screen the collected questionnaires. For online questionnaire submissions, each IP address was restricted to one response, and responses completed in under 2 minutes were removed. To further assess the validity of the questionnaire, responses indicating repetitive or patterned answers were eliminated. The reliability of the questionnaire was determined by evaluating responses to the items on the current status of the robot construction adoption in real estate projects. Any surveys that feature unrealistic responses indicating a highly wide adoption of the technology were excluded. This approach resulted in the selection of a valid questionnaire.

6.2 External Questionnaire Pre-survey

6.2.1 Data collection of pre-survey questionnaire

By leveraging well-established scales and insights from interviews with experts, scholars, and professionals in the construction industry, this study has modified and enhanced the scales to develop the preliminary survey questionnaire on robot construction in real estate projects.

From May to June 2023, with the assistance of my personal and colleagues' networking resources, we carried out a pre-survey by distributing the initial questionnaire to relevant personnel at Zhejiang Weixing New Building Materials Co., Ltd., Zhongnan Group, Zhejiang Wanda Construction Co. Ltd., Zhejiang Neusoft Construction Co., Ltd., Kunmao Construction Group Co Ltd., and other similar enterprises. A total of 29 pre-survey questionnaires were distributed via traditional postal mail. Through postal mail, 29 pre-survey questionnaires were collected, all considered valid. This number met the minimum recommended quantity of 20 pre-survey questionnaires as suggested by previous studies.

The pre-survey was mainly based on an external questionnaire design to explore the willingness of external enterprises to adopt robot construction, the factors influencing this willingness, and their cost expectations associated with implementing robot construction methods. This approach aimed to ascertain the rationality, reliability, and validity of each item. The pre-survey was analyzed. This study focused on the statistical sample of the pre-survey, their cost expectations after robot construction adoption, and their grasp of the current robot construction trend, and refined the existing questionnaire based on the collected responses.

6.2.2 Descriptive statistics of pre-survey samples

Statistical analysis was performed on the 29 valid pre-survey samples collected, and the findings are presented in Table 6-1. The analysis reveals that males represent a significant majority in the pre-survey at 89.66%. Individuals with a bachelor’s degree or higher account for 93.11%, indicating a higher educational level. Those with 20 years or more of work experience make up 62.07%, while 86.21% have 5 years or more of experience in the construction industry. Project managers form the majority at 55.17%, senior management at 13.79%, and front-line managers or technical staff at 24.14%. This suggests that most respondents are business managers, with a diverse representation of management levels, showcasing a well-stratified sample. Most respondents work in enterprises with over 100 employees, comprising 72.41%, while those in enterprises with 30 to 100 employees account for 20.68%. This highlights the pronounced labor-intensive characteristic of construction enterprises. All surveyed companies are privately owned, with joint-equity enterprises representing 44.83%.

Table 6-1 Characteristic Analysis of Pre-survey Samples

Sample characteristics	Statistical criteria	Number of samples	Percentage
Gender	Male	26	89.66%
	Female	3	10.34%
Educational background	High school degree/technical secondary school degree and below	2	6.90%
	University degree/Junior college degree	25	86.21%
	Master’s degree or above	2	6.90%
Working years	20+ years	18	62.07%
	15–20 years	3	10.34%
	10–14 years	4	13.79%
	5–9 years	0	0.00%
	4 years and below	4	13.79%
Position	Front-line managers/technicians	7	24.14%
	Project general managers and deputy general managers	16	55.17%
	Managers and deputy managers of functional departments	2	6.90%
	Senior executives of the enterprises	4	13.79%
	Others	0	0.00%
Number of employees	Less than 10 employees	1	3.45%
	11–30 employees	1	3.45%
	31–50 employees	3	10.34%
	51–100 employees	3	10.34%
	Over 100 employees	21	72.41%
Enterprise nature	Private enterprise	16	55.17%
	Joint-equity enterprise	13	44.83%
	Hong Kong, Macao, and Taiwan-invested enterprise	0	0.00%
	State-owned and collective enterprise	0	0.00%

6.2.3 Analysis of willingness cost for real estate projects applying robot construction in the pre-survey

In a small-sample survey, the study delved into the willingness cost regarding robot construction adoption within these enterprises. According to the price sensitivity meter (PSM model) designed in the questionnaire, Figure 6-1 showcases the results of the PSM model for the willingness cost of robot construction per unit area of civil engineering projects. The findings indicate a cost range for robot construction of civil engineering projects per square meter between RMB 1,209 and RMB 1,283, with the lowest cost of around RMB 1,209, the highest at RMB 1,283, and an optimal cost point of approximately RMB 1,264, and a sub-optimal cost point of RMB 1,283.

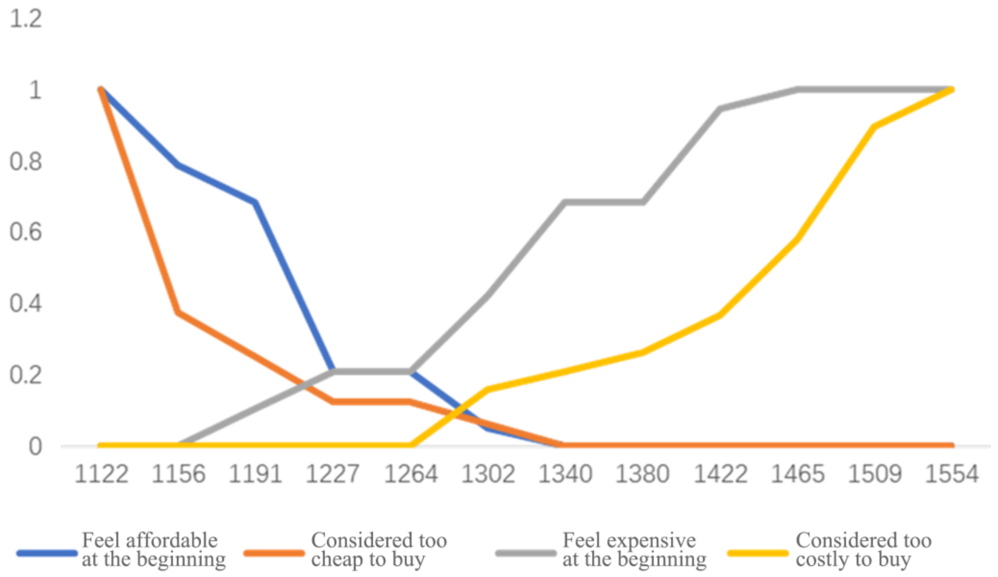

Figure 6-1 Willingness Cost for Robot Construction in Civil Engineering Projects

In Figure 6-2, the PSM model reflects the willingness cost of employing robot construction in interior decoration projects. The cost range for robot construction per square meter in interior decoration projects falls between RMB 424 and RMB 464, with the lowest cost of RMB 424, the highest cost point of approximately RMB 464, the optimal cost point of RMB 440, and the sub-optimal cost point of RMB 437.

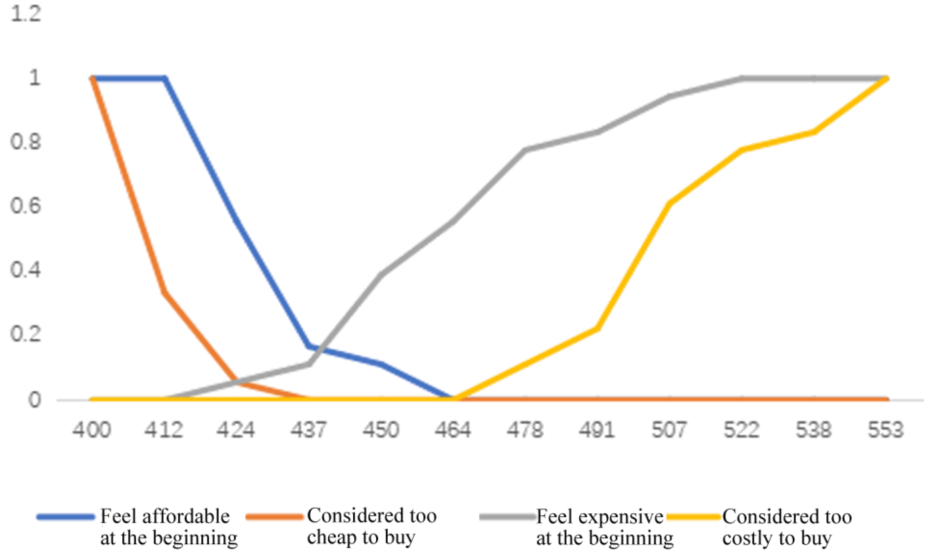

Figure 6-2 Willingness Cost for Robot Construction in Interior Decoration Projects

Figure 6-3 depicts the results of the PSM model regarding the willingness cost of management expenses for robot construction. The cost range for management expenses per square meter in robot construction is from RMB 50 to 59, with the lowest cost of around RMB 50, the highest cost of RMB 59, the optimal cost point of about RMB 55, and the sub-optimal cost point of RMB 57.

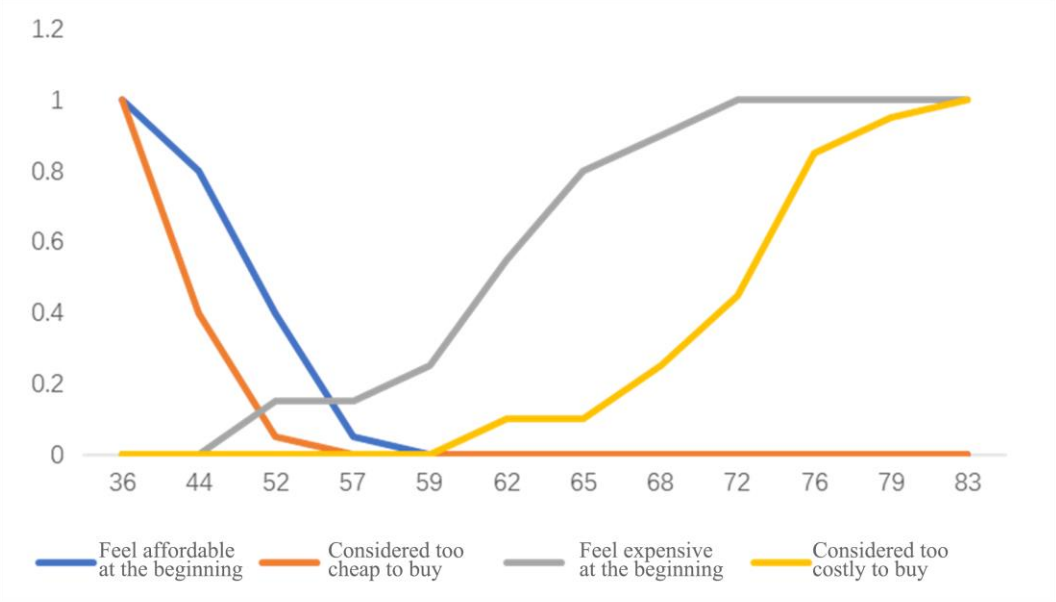

Figure 6-3 Willingness Cost of Project Management Expenses for Robot Construction

Based on the above PSM results, Table 6-2 summarizes the anticipated costs for robot construction of the above three projects. Based on the findings, external enterprises adopting robot construction methods are expected to fall within a cost range of RMB 1,683 to 1,806. The optimal cost is RMB 1,761, with the sub-optimal cost being RMB 1,775. It is crucial to note that in the accounting items for real estate project construction, another item is the interior installation project. Construction robots are currently unable to perform this task, and thus it can be controlled. Based on typical estimates, this cost is approximately RMB 216. Using this estimate, the total project's unit cost should range between RMB 1,899 and RMB 2,022, with an optimal cost of RMB 1,977 and a sub-optimal cost of RMB 1,991.

Table 6-2 Anticipated Cost of Real Estate Projects Adopting Robot Construction Technology Based on External Questionnaire Pre-survey

	Lowest cost	Sub-optimal cost	Optimal cost	Highest cost
Civil engineering projects	1,209	1,283	1,264	1,283
Interior decoration projects	424	437	440	464
Management expenses	50	55	57	59
Sub-total	1,683	1,775	1,761	1,806
Interior installation projects	216	216	216	216
Total	1,899	1,991	1,977	2,022

Based on this pre-survey data, the field survey of the MZQYB robot construction project (commenced in March 2021) was compared. This project is developed by Group B in the urban area of a third-tier city in Guangdong Province.

The unit total cost of the project is RMB 1,903.25. The pre-survey data closely matches the practical case data, suggesting that, to a certain extent, external enterprises anticipate higher costs for robot construction compared to the actual costs incurred by Group B. It is important to note that the pre-survey data has a limited sample size, which may affect the accuracy of the findings. This chapter delves deeper into analyzing the anticipated costs of real estate projects adopting robot construction by external enterprises.

In addition, the pre-survey questionnaire evaluates the collaboration intentions and models for robot construction projects between external enterprises and Group B across various price ranges. Considering the overall sample collection status, this study adjusted the external questionnaire accordingly. Combining structured interviews with expert input, the study also delved into the types of robotics technologies implemented by external enterprises, along with the factors influencing the adoption of construction robots, with the aim to examine the conditions under which robot construction methods can yield cost-effectiveness and enhanced efficiency.

6.3 Sample Analysis of Formal External Questionnaire

6.3.1 Distribution and collection of the formal questionnaire

Before conducting the formal questionnaire survey and data collection, the initial questionnaire items underwent modifications, additions, and deletions based on interviews and the pre-survey, to enhance the quality and validity of the questionnaire items. The external questionnaire targets real estate construction enterprises located in various regions, excluding Group B. The formal external questionnaire survey was conducted from November to the end of December 2023. Utilizing my human resource advantages, the questionnaire was distributed and collected “online,” mainly through the Wenjuanxing platform. Individuals such as real estate construction project leaders, managers, technical staff, and government personnel were invited to participate via enterprise workgroups, WeChat, QQ, email, and other channels. Colleagues, classmates, and friends in the real estate and construction industry were also invited to help circulate the questionnaire link to the workgroups for the relevant respondents to fill out. A total of 100 questionnaires were collected. The sample data mainly comprise 100 real estate projects from Qingdao Vanke, China Resources Center, Unicom, China Mobile, CCCG Real Estate Group, Huafa Group, AVIC Construction Holdings Group Co., Ltd., and Evergrande, among others. These enterprises are situated in over 20 cities including Guangzhou, Qingdao, Shenzhen, Shantou, Huizhou, Zhuhai, Changsha, Loudi, and Nanning. Additionally, some projects were sourced from overseas locations, including Delhi in India, Bangkok in Thailand, Phuket Island, and New York in the United States, constituting 16% of the sample.

6.4.2 Variable measures

(1) Scale for measuring factors influencing the willingness to adopt robot construction

To explore the willingness of external enterprises to embrace robot construction technology, this study drew upon research methodologies from scholars such as Y. Cai (2021) and Moore (1991). It assessed the factors influencing the application willingness of robot construction across seven dimensions: competitive pressures, government support, technological advantages, organizational consensus, resource readiness, perceived usefulness, and perceived ease of use. Table 6-3 summarizes the specific items for measuring these variables.

Table 6-3 Measure Items of Factors Influencing the Application Willingness of Robot Construction

Variable	Item No.	Item	Source
Competitive pressure	CP-1	Industry-leading enterprises have adopted robot construction technology.	Rogers (1983), Moore (1991), Kim et al.(2016), S. Liu (2018), Zhu et al. (2004), Chong & Ooi (2008), Premkumar & Roberts (1999), Jarvenpaa & Ives (1991), Lai (2018), Maduku et al. (2016), Davis (1989), Wu (2011), Davis (1989), Moore (1991)
	CP-2	The adoption of robotics technology can empower competitive advantages in the industry.	
Government support	PE-1	The government attaches importance to the adoption of robot construction technology in the construction sector.	
	PE-2	The government encourages enterprises to adopt robot construction technology through means such as tax incentives and rewards.	
Technological advantages	TA-1	Adopting robot construction can improve the production efficiency of construction enterprises.	
	TA-2	Utilizing robot construction technology can enhance the precision of construction.	
	TA-3	Applying robot construction technology can effectively achieve quality control in construction projects.	
	TA-4	Embracing robot construction technology can improve the safety of construction sites.	
Organizational consensus	MD-1	The enterprise promotes the adoption of new technologies.	
	MD-2	The enterprise's senior management views the adoption of robot construction technology as crucial for its digital and intelligent transformation and development.	
Resource readiness	RR-1	This enterprise possesses the requisite talent for implementing robot construction technology.	
	RR-2	The company has ample financial resources for applying robot construction technology.	
	RR-3	The enterprise has adequate funds to accommodate the process system changes brought about by adopting robot construction technology.	
Perceived usefulness	PU-1	Utilizing robot construction technology can help enterprises gain profits.	
	PU-2	The adoption of robot construction technology can enhance the efficiency and production modes of building products.	
	PU-3	Incorporating intelligent construction technology can enhance owner satisfaction.	
Perceived ease of use	PEU-1	It is easy to learn robot construction technology.	
	PEU-2	It is easy to carry out construction production and management through robot construction technology.	

(2) Selection of control variables

The selected control variables include management team size (MS), number of employees (WS), enterprise size (SIZE), enterprise nature (SOE), respondent’s years of industry experience (WT), gender (GEN), and education level (EDU). Regional (City) fixed effects were added to the model.

6.3.3 Characteristic analysis of sample demographic and project statistics

Table 6-4 reports the descriptive statistics of the formal questionnaire data.

Table 6-4 Characteristic Analysis of Formal Survey Samples

Sample characteristics	Statistical criteria	Number of samples	Percentage (%)
Gender	Male	66	66.00
	Female	34	34.00
Educational background	High school degree/technical secondary school degree and below	10	10.00
	University degree/Junior college degree	60	60.00
	Master's degree or above	30	30.00
Working years	20+ years	24	24.00
	15–20 years	24	24.00
	10–14 years	25	25.00
	5–9 years	20	20.00
	4 years and below	7	7.00
Position	Front-line managers/technicians	24	24.00
	Project general managers and deputy general managers	14	14.00
	Managers and deputy managers of functional departments	17	17.00
	Senior executives of the enterprises	27	27.00
	Staff of government departments	2	2.00
	Others	16	16.00
Number of employees	Less than 10 employees	4	4.00
	11–30 employees	6	6.00
	31–50 employees	12	12.00
	51–100 employees	12	12.00
	Over 100 employees	66	66.00
Enterprise size	Small enterprise (with total assets less than RMB 50 million)	6	6.00
	Medium enterprise (with total assets of RMB 50 million–800 million)	25	25.00
	Large enterprise (with total assets of more than RMB 800 million)	69	69.00
Enterprise nature	Private enterprise	61	61.00
	Joint-equity enterprise	26	26.00
	Hong Kong, Macao, and Taiwan-invested enterprise	0	0.00
	State-owned and collective enterprise	13	13.00

This study made some adjustments based on the aforementioned pre-survey. The primary adjustments included (1) increasing the scale investigation of project construction enterprises and enhancing the information in sample questionnaires; and (2) adjusting the respondents. Based on pre-survey findings and expert recommendations, the study broadened its scope to include government employees to gauge policy department perspectives on robot construction.

The sample data shows that males make up 66% of the respondents, reflecting the typical gender distribution in construction enterprises. The gender diversity among respondents has increased compared to the pre-survey samples. Moreover, 90% of respondents hold at least a junior college or bachelor’s degree, indicating a strong educational background and a good understanding of robot construction. Additionally, 93% of respondents have over 5 years of work experience, with 73% having 10 years or more. This suggests that most respondents possess extensive experience in real estate project construction, enhancing their ability to accurately evaluate robot construction adoption, willingness to adopt, cost experience in real estate projects, and other relevant factors. Of the respondents, 27% are senior executives, 17% are functional department managers, 14% are project leaders, and 24% hold front-line managerial positions. This distribution underscores their extensive project management experience and in-depth knowledge of robot construction adoption and factors influencing project costs. Moreover, 2% of respondents are government employees. Regarding the surveyed projects’ characteristics, 66% of enterprises employ over 100 individuals, while 24% have staff ranging from 30 to 100 members. The majority of surveyed enterprises are large-scale, with total assets exceeding RMB 800 million, comprising 69% of the sample. This aligns with the asset-heavy industry characteristics of the construction sector. Large enterprises tend to have a competitive edge in robot construction adoption. In terms of the nature of property rights, 87% of the surveyed enterprises are non-state-owned enterprises, while state-owned enterprises make up 13%. The sample now includes an expanded coverage compared to all non-state-owned enterprises surveyed in the pre-survey. Overall, the sample data are well-representative and can meet the needs of this study.

6.3.4 Descriptive statistics of items for measuring variables

A normal distribution test was conducted on the sample data, with the results presented in Table 6-5. The absolute value of skewness for each observed variable ranges from .044 to .699, while the absolute value of kurtosis ranges from .044 to .851. The results indicate that the data adheres to a normal distribution.

Table 6-5 Descriptive Statistics of Items for Measuring Variables

	Item	Sample size	Mean ± SD	25th percentile	Median	75th percentile	Kurtosis	Skewness
Competitive pressure	CP-1	100	4.100±1.251	3.000	4.000	5.000	-.180	-.350
	CP-2	100	4.200±1.231	4.000	4.000	5.000	-.146	-.391
Government support	PE-1	100	4.330±1.207	4.000	4.000	5.000	-.045	-.383
	PE-2	100	4.350±1.201	4.000	4.000	5.000	.044	-.388
Technological advantages	TA-1	100	4.430±1.183	4.000	4.000	5.000	.195	-.521
	TA-2	100	4.430±1.130	4.000	4.000	5.000	.649	-.615
	TA-3	100	4.410±1.138	4.000	4.000	5.000	.394	-.529
	TA-4	100	4.520±1.185	4.000	4.500	5.000	.502	-.699
Organizational consensus	MD-1	100	4.330±1.074	4.000	4.000	5.000	.815	-.546
	MD-2	100	4.280±1.164	4.000	4.000	5.000	.160	-.411
Resource readiness	RR-1	100	3.880±1.258	3.000	4.000	5.000	-.548	-.080
	RR-2	100	3.860±1.263	3.000	4.000	5.000	-.384	-.130
	RR-3	100	3.940±1.254	3.000	4.000	5.000	-.340	-.230
Perceived usefulness	PU-1	100	4.190±1.098	4.000	4.000	5.000	.613	-.340
	PU-2	100	4.270±1.145	4.000	4.000	5.000	.347	-.550
	PU-3	100	4.160±1.080	4.000	4.000	5.000	.547	-.473
Perceived ease of use	PEU-1	100	3.630±1.315	3.000	4.000	4.000	-.584	-.044
	PEU-2	100	3.790±1.266	3.000	4.000	5.000	-.521	-.204

6.4 Analysis of Current Adoption of Robot Construction and Adoption Willingness

6.4.1 Current adoption of robot construction

This section centers on how the surveyed enterprises utilize construction robots. Based on the survey results, 71% of external enterprises have not adopted robot construction technology, with only 29% indicating its implementation. Evidently, the current robot adoption rate still has room for improvement. (See Figure 6-4)

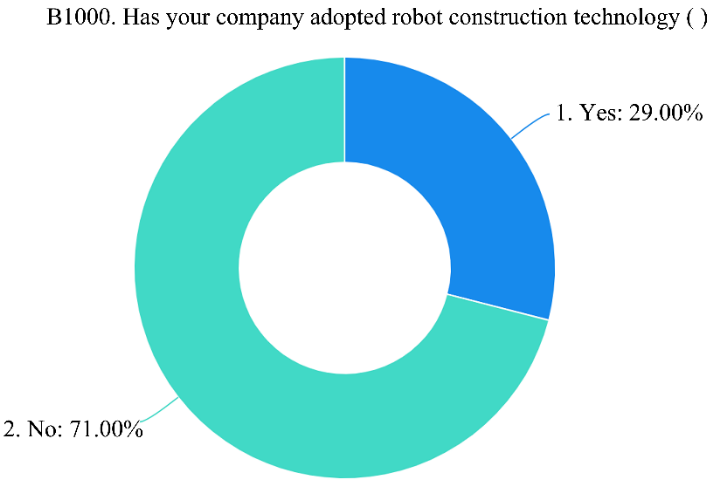

Figure 6-4 Adoption of Robotics Technology

6.4.2 Current adoption willingness

This section examines the current willingness of respondents to adopt robot construction technology. First, the overall attitude of the surveyed enterprises is depicted in Figure 6-5. It shows that 27% of the respondents exhibit a somewhat high willingness to adopt robotics technology, with only 7% and 6% showing a high and very high inclination respectively. In contrast, 10% of respondents have a very low willingness to adopt robotics technology, while 14% have a low willingness. The willingness of respondents to adopt robotics technology is notably low, with a considerable prevalence of non-acceptance attitudes. Overall, merely 40% exhibit a strong willingness to adopt robotics technology, with the remaining 60% displaying a less enthusiastic attitude.

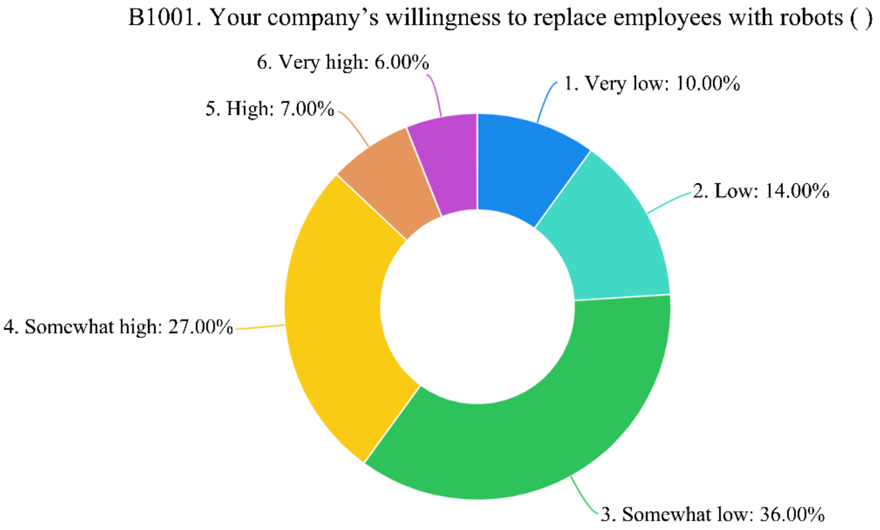

Figure 6-5 Respondents' Willingness to Apply Robots

The willingness to adopt robot construction technology mentioned earlier is just a general overview. It is important to refine the information further, compare it with the previous willingness results, and assess the consistency of the results. To facilitate the adoption of robot construction technology, it is essential to expand the scope of robotics technology. This study is also framed within the broader concept of robot construction. The scope should encompass information technology services with construction robots at the core. Therefore, in addition to core robotics technology, this study explores supporting the digitization of building construction, including software and hardware components like BIM, GIS, and IoT.

The willingness to adopt robot construction technology was analyzed based on the average value, with the results shown in Figure 6-6. It is evident that the average values for all technology applications fall below 5 points. This suggests that respondents' willingness to adopt robot construction technology is somewhat favorable but not particularly strong. Upon further comparison of the average values of each technology, the highest score is for AI technology at 4.46. This signifies that, in contrast to other technologies, current construction enterprises show the strongest willingness toward adopting AI technology, reflecting the ongoing rapid growth of AI. Moreover, BIM, UAV, and GIS score relatively high (4.41, 4.40, and 4.33 respectively). In comparison to other technologies, the current willingness of construction enterprises to embrace these three technologies is also promising. The scores for IoT, cloud computing, robotics technology, and augmented reality (AR) range between 4.20 and 4.30, positioning them at a moderate level. This suggests that construction enterprises are progressively embracing and experimenting with these technologies. The scores for big data, blockchain, virtual reality (VR), and 3D printing technologies are comparatively low. Notably, the score for blockchain is only 3.91, indicating that the adoption of blockchain by construction enterprises currently remains quite restricted, aligning closely with the actual scenario. This result is also in line with the previously mentioned low score for willingness to replace human workers with robots, indicating a lower willingness to apply robot construction. Against the backdrop of China’s strong promotion of intelligent construction within the real estate sector and its encouragement of innovative adoption of intelligent construction technology, construction enterprises will hasten the adoption and exploration of cutting-edge technologies, with robot construction technology at the forefront. This will lead to a gradual realization of broad technology deployment and application.

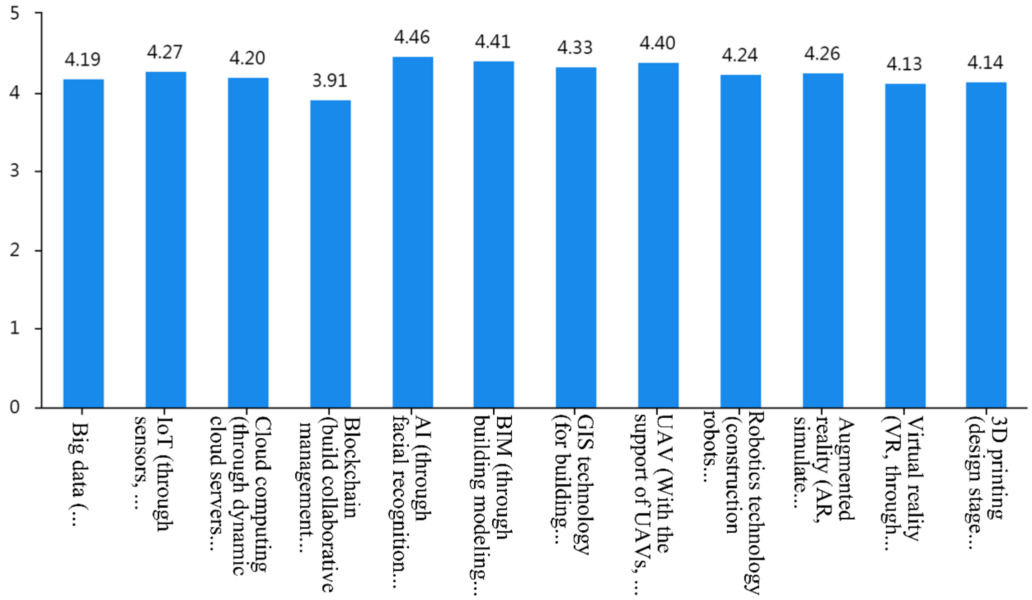

Figure 6-6 Adoption Willingness of Different Types of Robot Construction Technologies

6.5 Analysis of Factors Influencing Robot Construction Adoption

This section focuses on the empirical analysis of factors influencing the adoption of robot construction. The specific empirical model is as follows:

$$RobotA_i = \theta_0 + \theta_1 GP + \sum \theta_2 Controls + \sum \theta_3 City_i + \varepsilon_i$$

Equation 5-1

In this equation, RobotA represents the adoption willingness of robot construction, measured based on the scale regarding “the company’s willingness to replace employees with robots.” GP denotes the factors influencing adoption willingness, encompassing seven dimensions like competitive pressure as mentioned earlier, while Controls correspond to the group of control variables outlined above. Additionally, city fixed effects are incorporated into the model to control unobservable urban characteristics.

Table 6-6 reports the results. After integrating control variables and city fixed effects, it becomes evident that factors across seven dimensions, including competitive pressure, government support, technological advantages, organizational consensus, perceived usefulness, and perceived ease of use, substantially drive the adoption of robot construction. The empirical results show that real estate construction enterprises are willing to upgrade robot construction amidst competitive pressures and with government support. When there is an organizational consensus to upgrade the robot construction model and sufficient support resources are available, it enhances the adoption of robot construction technology. Moreover, the perceived usefulness and ease of use will support the promotion and application of robot construction technology when organization members perceive it as practical and user-friendly.

Table 6-6 Factors Influencing the Adoption of Robot Construction

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Willingness to adopt robot construction						
Competitive pressure	.376***						
	(4.23)						
Government support		.420***					
		(4.93)					
Technological advantages			.292***				
			(4.73)				
Organizational consensus				.511***			
				(6.31)			
Resource readiness					.320***		
					(4.41)		
Perceived usefulness						.385***	
						(5.70)	
Perceived ease of use							.300***
							(3.46)
Gender	-.421	-.299	-.334	-.212	-.400	-.415*	-.465*
	(-1.60)	(-1.16)	(-1.29)	(-.88)	(-1.53)	(-1.68)	(-1.72)
EDU	.217	.140	.102	.181	.272	.109	.344*
	(1.07)	(.70)	(.50)	(.98)	(1.36)	(.57)	(1.66)
WT	.193*	.161	.187*	.153	.143	.126	.198*
	(1.85)	(1.58)	(1.84)	(1.60)	(1.36)	(1.27)	(1.85)
Number of employees	-.051	-.175	-.117	-.145	-.123	-.113	-.113
	(-.36)	(-1.26)	(-.84)	(-1.11)	(-.87)	(-.85)	(-.77)
MS	.084	.147	.108	.105	.104	.100	.136
	(.68)	(1.23)	(.89)	(.93)	(.85)	(.86)	(1.07)
Enterprise nature	.106	.102	.064	.076	.036	.032	.152
	(.80)	(.79)	(.49)	(.63)	(.27)	(.26)	(1.12)
Enterprise size	.123	.168	.139	.138	.096	.170	.127
	(.60)	(.83)	(.68)	(.73)	(.47)	(.88)	(.60)
_cons	2.222**	2.490**	2.589***	2.459***	2.620***	2.830***	1.965*
	(2.27)	(2.60)	(2.67)	(2.75)	(2.66)	(3.04)	(1.96)
City	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
N	100	100	100	100	100	100	100
adj. R^2	.185	.231	.218	.322	.197	.282	.139

6.6 Analysis of Estimated Cost and Cooperation Mode of Real Estate Projects Willing to Adopt Robot Construction

6.6.1 Anticipated costs of projects applying robot construction

In the formal external questionnaire, the study delved into the willingness cost regarding robot construction adoption within these enterprises. According to the PSM model designed by the questionnaire, Figure 6-7 illustrates the results of the PSM model for the willingness cost of robot construction per unit area of civil engineering projects. The findings indicate an anticipated cost range for robot construction of civil engineering projects per square meter between RMB 1,237.86 and RMB 1,303.58, with the lowest cost of around RMB 1,237.86, the highest at RMB 1,303.58, and an optimal cost point of approximately RMB 1,270.5, and a sub-optimal cost (acceptable cost) point of RMB 1,266.75.

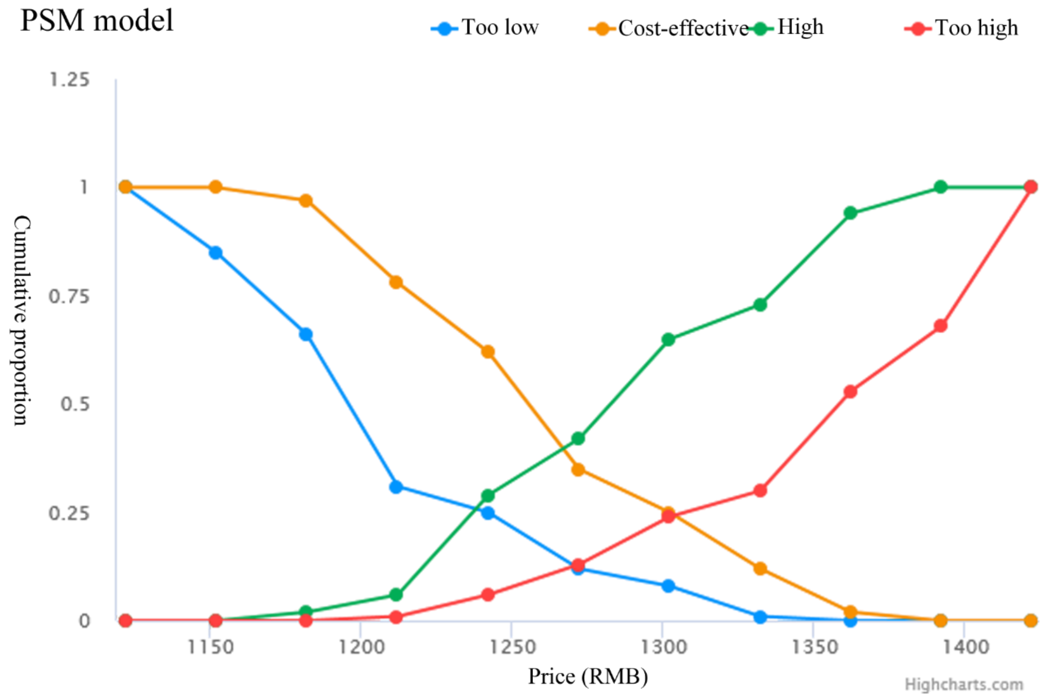

Figure 6-7 Willingness Cost of Civil Engineering Projects with Robot Construction

In Figure 6-8, the PSM model reflects the respondents' willingness cost of employing robot construction in interior decoration projects. The anticipated cost range for robot construction per square meter in interior decoration projects falls between RMB 461.88 and RMB 490.8, with the lowest cost of RMB 461.88, the highest cost point of approximately RMB 490.8, the optimal cost point of RMB 475, and the sub-optimal cost (acceptable cost) point of RMB 476.33.

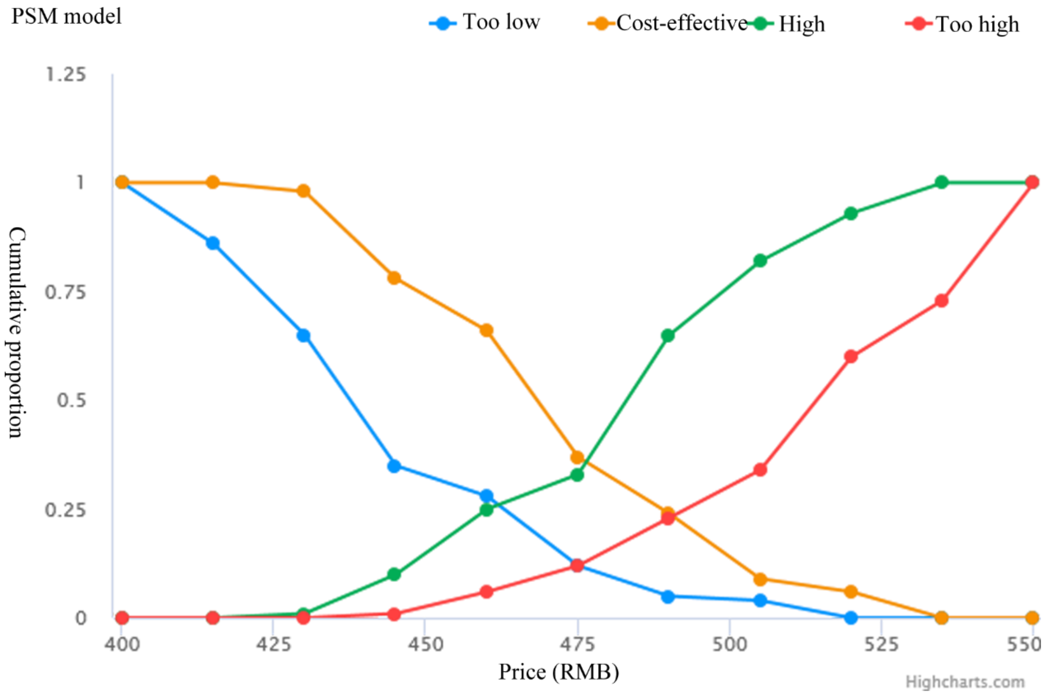

Figure 6-8 Willingness Cost for Robot Construction in Interior Decoration Projects

Figure 6-9 depicts the results of the PSM model regarding the respondents' willingness cost of the management expenses for robot construction. The anticipated cost range for management expenses per square meter in robot construction is from RMB 54.75 to 64.68, with the former being the lowest cost, the latter being the highest cost, the optimal cost point of about RMB 59.54, and the sub-optimal cost point of RMB 59.75.

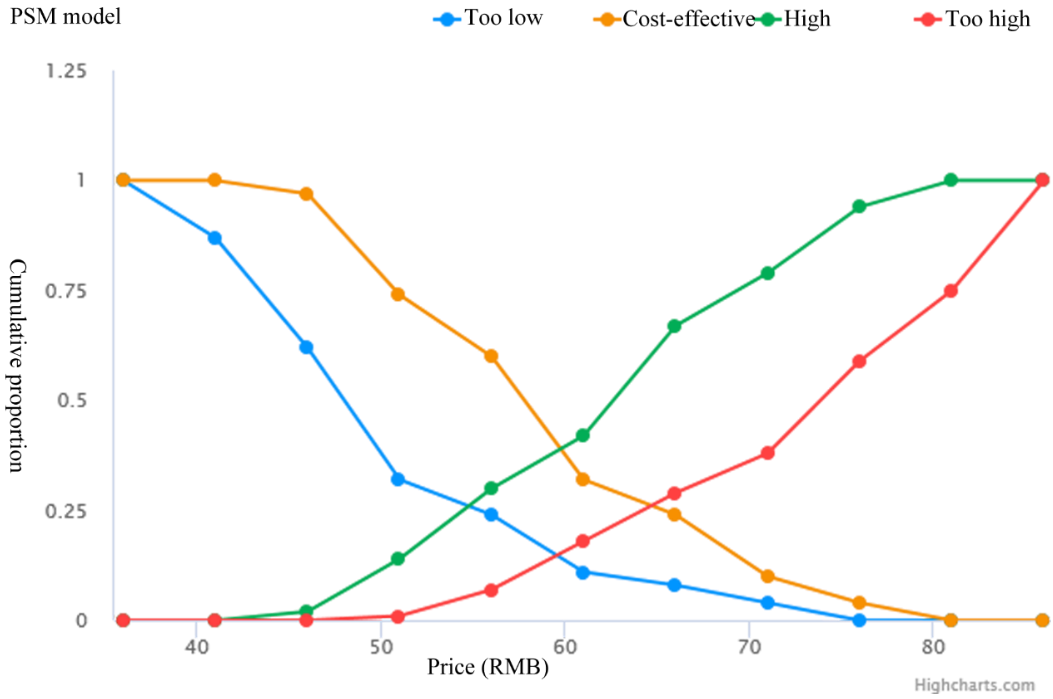

Figure 6-9 Willingness Cost of Project Management Expenses for Robot Construction

Based on the above PSM results, Table 6-7 summarizes the anticipated costs for robot construction of the above three projects. Based on the findings, external enterprises adopting robot construction methods are expected to fall within a cost range of RMB 1,754.49 to 1,858.84. The optimal cost is RMB 1,805.04, with the sub-optimal cost being RMB 1,802.83. It is crucial to note that in the accounting items for real estate project construction, another item is the interior installation project. Construction robots are currently unable to perform this task, and thus it can be controlled. Based on typical estimates, this cost is approximately RMB 216. Using this estimate, the total project's unit cost should range between RMB 1,970.49 and RMB 2,074.84, with an optimal cost of RMB 2,021.04 and a sub-optimal cost of RMB 2,018.83.

Table 6-7 Anticipated Cost of Real Estate Projects Adopting Robot Construction Technology Based on Formal External Questionnaire Survey

	Lowest cost	Sub-optimal cost	Optimal cost	Highest cost
Civil engineering projects	1,237.86	1,266.75	1,270.5	1,303.58
Interior decoration projects	461.88	476.33	475	490.58
Management expenses	54.75	59.75	59.54	64.68
Sub-total	1,754.49	1,802.83	1,805.04	1,858.84
Interior installation projects	216	216	216	216
Total	1,970.49	2,018.83	2,021.04	2,074.84

The willingness costs compared with those in the pre-survey are shown in Table 6-8. The cost data from the formal external questionnaire survey consistently exceeds that of the pre-survey. This indicates that as the sample size expands, the acceptable range of production costs also increases. The field survey of the MZQYB robot construction project (which commenced in March 2021) was compared. This project is developed by Group B in an urban area of a third-tier city in Guangdong Province. The unit total cost of the project is RMB 1,903.25. To a certain extent, external enterprises anticipate higher costs for robot construction compared to the actual costs incurred by Group B.

Table 6-8 Comparison of Anticipated Cost of Real Estate Projects Adopting Robot Construction Technology Based on Formal External Questionnaire Survey

	Lowest cost	Sub-optimal cost	Optimal cost	Highest cost
External questionnaire pre-survey	1,899	1,991	1,977	2,022
Formal external questionnaire survey	1,970.49	2,018.83	2,021.04	2,074.84

Figure 6-10 illustrates a further comparison of robot construction practices within the Group. The figure shows that the construction costs of real estate projects assessed by respondents exhibit notable discrepancies. Specifically, 21.54% of respondents consider the unit area cost to be around RMB 1,900, while 46.15% believe it to be about RMB 1,700, and 32.31% suggest it to be above RMB 2,100. Therefore, in terms of probability, the cost efficiency of the company's internal projects may either meet or fall below the expectations of external investors regarding project costs.

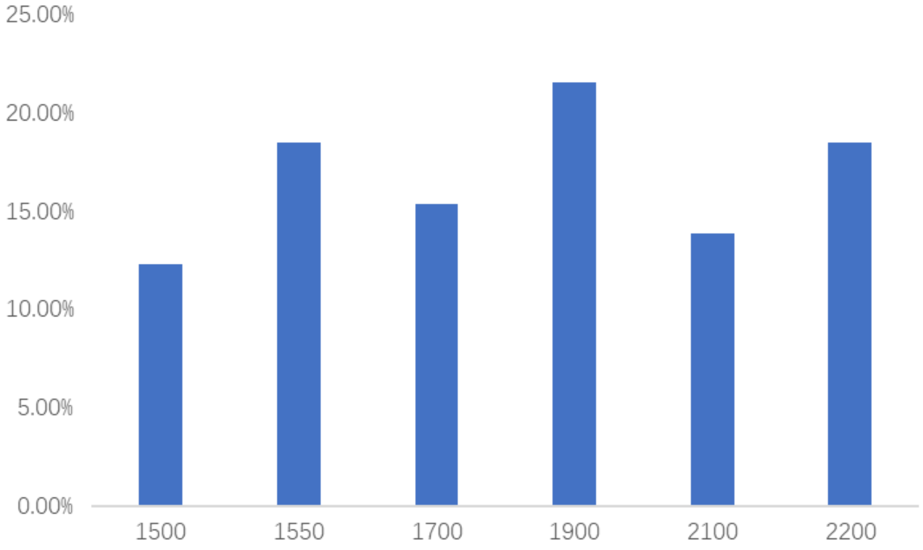

Figure 6-10 Cost of Real Estate Projects per Square Meter with Robot Construction in the Internal Questionnaire

In addition, the pre-survey questionnaire evaluates the collaboration intentions and models for robot construction projects between external enterprises and Group B across various price ranges.

6.6.2 Cooperation mode and cause analysis in the context of willingness cost

The current business models for robot construction in real estate projects primarily consist of four types: agent construction cooperation, EPC, fully entrusted property management, and agency services. Agent construction cooperation involves a partnership between land-owning clients and skilled agent construction parties possessing project development and construction expertise. In this mode, the client furnishes land resources, while the agent construction party leverages its brand, product, cost, financing, management, and team advantages to deliver comprehensive development and management services for the project. This ensures the seamless advancement of the project toward the ultimate profit objective. EPC stands for the general contracting of engineering design, procurement, construction, and other phases by the EPC contractor based on the agreement with the construction unit. The contractor assumes full responsibility for the project's quality, safety, construction timeline, and costs. Fully entrusted property management refers to the act of owners or the owners' assembly entrusting all responsibilities and authority of property management to a professional property management company, which is fully responsible for the property's daily operations, maintenance, and services. In this management model, the property management company assumes the rights and duties of property management on behalf of the owner as per the terms outlined in the entrusted contract. The primary goal is to deliver professional, standardized, and systematic property services to the owner. The agency service is a service model wherein a professional service provider manages and oversees an asset or service in lieu of the owner or asset proprietor. This service encompasses various aspects, including asset management, facility maintenance, and financial management. Its goal is to offer a comprehensive, one-stop management solution for the owner or asset owner to enhance asset utilization and value growth effectively. Under the aforementioned four modes, robot construction providers like Group B have application scenarios and the potential to modernize traditional business models.

Tables 6-9 through 6-11 show the cooperation modes based on varying willingness costs for civil engineering projects, interior decoration projects, and management expenses, respectively. It is evident that EPC is more prevalent, whereas the fully entrusted property management mode is less favored. Looking at the price trends, when the willingness cost is low, the proportion of agent construction cooperation is comparable to that of EPC. However, as costs increase, the benefits of EPC become more evident, particularly in interior decoration. As the anticipated cost rises, the proportion of non-cooperation also increases.

Table 6-9 Cooperation Mode by Willingness Cost of Civil Engineering Projects

Item\option	Agent construction cooperation	EPC	Fully entrusted property management	Agency service	Non-cooperation
1122	30(30%)	31(31%)	10(10%)	18(18%)	11(11%)
1156	26(26%)	32(32%)	13(13%)	19(19%)	10(10%)
1191	28(28%)	28(28%)	15(15%)	19(19%)	10(10%)
1227	23(23%)	31(31%)	15(15%)	22(22%)	9(9%)
1264	19(19%)	33(33%)	13(13%)	25(25%)	10(10%)
1302	16(16%)	35(35%)	16(16%)	23(23%)	10(10%)
1340	18(18%)	29(29%)	15(15%)	28(28%)	10(10%)
1380	18(18%)	30(30%)	14(14%)	26(26%)	12(12%)
1422	20(20%)	26(26%)	17(17%)	24(24%)	13(13%)
1465	20(20%)	24(24%)	14(14%)	27(27%)	15(15%)
1509	20(20%)	24(24%)	19(19%)	18(18%)	19(19%)
1554	19(19%)	23(23%)	17(17%)	20(20%)	21(21%)

Table 6-10 Cooperation Mode by Willingness Cost of Interior Decoration Projects

Item\option	Agent construction cooperation	EPC	Fully entrusted property management	Agency service	Non-cooperation
400	32(32%)	25(25%)	15(15%)	20(20%)	8(8%)
412	27(27%)	29(29%)	19(19%)	19(19%)	6(6%)
424	25(25%)	32(32%)	17(17%)	18(18%)	8(8%)
437	18(18%)	38(38%)	17(17%)	16(16%)	11(11%)
450	17(17%)	35(35%)	23(23%)	16(16%)	9(9%)
464	17(17%)	36(36%)	15(15%)	24(24%)	8(8%)
478	15(15%)	32(32%)	19(19%)	23(23%)	11(11%)
491	13(13%)	31(31%)	22(22%)	23(23%)	11(11%)
507	13(13%)	32(32%)	20(20%)	21(21%)	14(14%)
522	15(15%)	28(28%)	16(16%)	25(25%)	16(16%)
538	13(13%)	28(28%)	22(22%)	19(19%)	18(18%)
553	14(14%)	30(30%)	17(17%)	18(18%)	21(21%)

Table 6-11 Cooperation Mode by Willingness Cost of Management Expenses

Item\option	Agent construction cooperation	EPC	Fully entrusted property management	Agency service	Non-cooperation
36	27(27%)	30(30%)	13(13%)	19(19%)	11(11%)
44	27(27%)	27(27%)	14(14%)	21(21%)	11(11%)
52	24(24%)	31(31%)	14(14%)	20(20%)	11(11%)
57	19(19%)	35(35%)	14(14%)	22(22%)	10(10%)
59	13(13%)	39(39%)	18(18%)	18(18%)	12(12%)
62	13(13%)	34(34%)	21(21%)	20(20%)	12(12%)
65	13(13%)	31(31%)	24(24%)	21(21%)	11(11%)
68	12(12%)	24(24%)	26(26%)	23(23%)	15(15%)
72	13(13%)	22(22%)	23(23%)	24(24%)	18(18%)
76	13(13%)	22(22%)	21(21%)	25(25%)	19(19%)
79	13(13%)	19(19%)	13(13%)	33(33%)	22(22%)
83	14(14%)	20(20%)	17(17%)	23(23%)	26(26%)

In addition, this study delves into the factors influencing the choice of different contracting models, with the results outlined in Tables 6-12 to 6-14. The management mode is a crucial factor influencing the decision-making process in the collaboration between construction enterprises and robot construction providers. The minimal impact of the management approach is frequently the determining factor for their selection of EPC. As anticipated costs increase, the issue of diminishing resource efficiency due to over-investment emerges as a factor that deters them from opting for collaboration, leading them to lean toward agency services.

Table 6-12 Cooperation Mode by Willingness Cost of Civil Engineering Projects				
Item\option	Small investment	Small impact of management mode	Excessive investment	Great impact of management mode
1122	32(32%)	26(26%)	26(26%)	16(16%)
1156	30(30%)	32(32%)	24(24%)	14(14%)
1191	28(28%)	29(29%)	31(31%)	12(12%)
1227	20(20%)	36(36%)	29(29%)	15(15%)
1264	16(16%)	37(37%)	32(32%)	15(15%)
1302	15(15%)	39(39%)	28(28%)	18(18%)
1340	14(14%)	27(27%)	41(41%)	18(18%)
1380	13(13%)	28(28%)	42(42%)	17(17%)
1422	14(14%)	22(22%)	44(44%)	20(20%)
1465	12(12%)	27(27%)	39(39%)	22(22%)
1509	12(12%)	29(29%)	34(34%)	25(25%)
1554	10(10%)	24(24%)	37(37%)	29(29%)

Table 6-13 Cooperation Mode by Willingness Cost of Civil Engineering Projects				
Item\option	Small investment	Small impact of management mode	Excessive investment	Great impact of management mode
400	33(33%)	29(29%)	24(24%)	14(14%)
412	29(29%)	31(31%)	28(28%)	12(12%)
424	28(28%)	28(28%)	30(30%)	14(14%)
437	19(19%)	35(35%)	31(31%)	15(15%)
450	18(18%)	36(36%)	33(33%)	13(13%)
464	14(14%)	38(38%)	36(36%)	12(12%)
478	13(13%)	30(30%)	45(45%)	12(12%)
491	13(13%)	35(35%)	40(40%)	12(12%)
507	15(15%)	27(27%)	40(40%)	18(18%)
522	17(17%)	30(30%)	32(32%)	21(21%)
538	14(14%)	25(25%)	37(37%)	24(24%)
553	13(13%)	25(25%)	39(39%)	23(23%)

Table 6-14 Cooperation Mode by Willingness Cost of Civil Engineering Projects

Item\option	Small investment	Small impact of management mode	Excessive investment	Great impact of management mode
36	32(32%)	31(31%)	23(23%)	14(14%)
44	29(29%)	28(28%)	30(30%)	13(13%)
52	28(28%)	29(29%)	31(31%)	12(12%)
57	17(17%)	36(36%)	33(33%)	14(14%)
59	16(16%)	39(39%)	33(33%)	12(12%)
62	13(13%)	37(37%)	35(35%)	15(15%)
65	14(14%)	27(27%)	45(45%)	14(14%)
68	12(12%)	27(27%)	43(43%)	18(18%)
72	9(9%)	28(28%)	43(43%)	20(20%)
76	9(9%)	32(32%)	36(36%)	23(23%)
79	7(7%)	30(30%)	37(37%)	26(26%)
83	10(10%)	29(29%)	32(32%)	29(29%)

Chapter VII Research Conclusions and Contributions

7.1 Main Conclusions

Leveraging the human capital advantage within B Group, I conducted research and analyzed the cost effect of applying construction robots for the first time through the lens of internal enterprise management. Based on field surveys, interviews, and pertinent preliminary studies, an internal questionnaire for Group B and an external questionnaire for non-Group B enterprises were developed. Through the Wenjuanxing platform and other channels, 162 internal and 100 external survey samples were obtained respectively.

In the internal questionnaire analysis, the statistical findings indicate that robot construction can lower production costs by approximately 5%, labor expenses by around 10%, and management expenses by about 10%. Notably, in terms of labor replacement, this can lead to a reduction in construction personnel by roughly 30% while necessitating a 5% increase in management staff. It is crucial to emphasize that the benefits of robot construction in cutting material and measurement expenses are not remarkable. This discrepancy may arise from the fact that, when contrasted with traditional production methods, construction robots are more suitable for typical and straightforward scenarios. However, their processing efficiency in complex environments is not as precise as that of human labor, making it challenging for these two cost control aspects to exhibit advantages. Moreover, commencing from the outcome variables of average costs and redundancy costs within the project, the cost effect stemming from the degree of robot construction utilization within the project was empirically explored. The study found that the adoption of robot construction significantly suppresses average costs and redundancy costs. The mechanism path analysis reveals that robot construction highlights several technological advantages, such as reducing production cycles, enhancing production quality, ensuring production safety, and improving the production environment. Additionally, it demonstrates exceptional adaptability, like budget cost control and flexible resource allocation. The technological advantages and adaptability can effectively reduce the average costs and redundancy costs of real estate projects. Based on the mediating effect model, it was identified that technological advantages and adaptability mediate the relationship between robot construction and the costs of real estate projects. Through heterogeneity analysis, it was discovered that the cost effect of robot construction on real estate projects presents notable non-structural features. With an increase in labor wages at project locations, the cost-reduction effect of robot construction tends to diminish. In the context of large-size project construction teams and project management teams, robot construction has a more prominent impact on reducing both the average costs and redundancy costs of real estate projects. The moderating effect analysis reveals that the key mechanism by which robot construction reduces the costs of real estate projects encompasses three dimensions of management change: organizational consensus, organizational learning, and human-robot collaboration. Within an environment of organizational consensus cohesion, knowledge dissemination and absorption through organizational learning, and effective human-robot collaborative operations, the expected effect of robot construction in lowering both the average costs and redundancy costs of real estate projects can be fully realized and even strengthened. Finally, the extended research found that robot construction can significantly improve organizational performance while reducing costs.

In terms of external questionnaire analysis, it has been discovered that competitive pressure, government support, organizational consensus, technological advantages, resource readiness, perceived usefulness, and perceived ease of use all play significant roles in enhancing enterprises' willingness to adopt robot construction models. Based on the PSM survey assessing respondents' WTP, it was observed that the willingness cost for real estate projects constructed with robots varies from RMB 1,970.49 to 2,074.84, surpassing Group B's cost of robot construction projects. Considering this, the cost of Group B's robot construction projects can effectively align with anticipated market costs, signifying the potential for advancing the adoption of robot construction methods. In contrast with the current sluggish progress of intelligent construction within the industry, there is an urgent need to vigorously advocate for increased application in the future.

The study's policy implications encompass:

First, it is crucial for the construction sector to change in intelligent construction, with a particular emphasis on the real estate industry. The scale and coverage of construction robots substantially trail behind that of the manufacturing industry. Empirical evidence indicates that the implementation of robot construction can markedly decrease enterprises' costs. Many construction enterprises should actively pursue the advancement of intelligent construction. This move not only positions them strategically in a fiercely competitive market but also stands as an essential decision to navigate cyclical industry downturns. The cost-cutting and efficiency-enhancing impact of robot construction methods can serve as a valuable reserve to leverage during economic downturns.

Second, the promotion and application of intelligent construction should follow a differentiated strategy. For non-scale projects, robot construction does not consistently reduce costs; it is more fitting for large-scale projects. Additionally, it is essential to take into account market variations. In scenarios characterized by insufficient labor supply and high labor costs, the effect of promoting robot construction will be more pronounced. Therefore, it is crucial for pioneering enterprises to spearhead the research and development as well as the implementation of construction robots. Should these innovations filter down to small and medium-sized enterprises, they must employ tailored strategies. These leading entities should thoroughly assess market traits and deliver specialized services that align with market characteristics and demands. The government should introduce targeted support policies, creating a comprehensive support framework that includes tax incentives and talent provision for regions with high economic development and leading enterprises. Moreover, there should be initiatives to facilitate the expansion of construction robot enterprises from more developed regions to lesser developed areas and smaller businesses.

Third, within the realm of intelligent construction upgrades in the construction industry, particularly within the real estate sector, while the utilization of construction robots is paramount, there is a greater necessity for restructuring management practices. This kind of restructuring entails, from a senior leadership standpoint, the consistent acknowledgment of the future of intelligent construction. It requires taking the lead in advancement and mitigating conflicts between intelligent construction and the company's existing management team. Moreover, there is a need to bolster organizational learning, encompassing not only the adoption of new technologies but also the introduction and establishment of a proficient and technologically adept talent framework. This fosters robust knowledge sharing and dissemination within the organization. At the same time, enhancing human-robot collaboration is vital. As construction robots supplant manual labor, they introduce new responsibilities for workers, necessitating a deeper partnership between humans and machines. Construction robots will only see extensive adoption when organizations perceive them to be operationally feasible, valuable, and easy to learn.

7.2 Research Innovations

Compared with existing studies, this study makes innovations in three aspects:

First, it enriches the literature system of factors influencing enterprise costs. The existing literature on cost influencing factors has predominantly focused on macroeconomics (Anderson et al., 2003; Banker et al., 2010a), system design

(Q. Cheng & Xiong, 2016; Hu Jun et al., 2020; Chen, 2021), board governance (Liang, 2016), management traits (Chung et al., 2019; Y. Geng & Y. Ma, 2020; Yang et al., 2020), enterprise features (Banker & Chen, 2006a; Balakrishnan & Gruca, 2008; L. Zhou et al., 2019), and stakeholders (Jiang et al., 2017; Huang Lei, 2019). In recent years, a shift has been observed toward examining the impact of digital production modes like intelligent manufacturing on corporate cost stickiness (Quan & C. Li, 2020; Y. Yue & Gu, 2021). Nevertheless, constrained by the availability of data concerning robots and cost management, the conclusions drawn have been somewhat generalized, lacking in-depth research into the structural effects of costs. By leveraging questionnaire data, this study delves into the differentiation strategy and implementation pathway of enterprise cost management through the lens of the innovative production mode of robot construction in real estate projects. This endeavor aims to enhance analytical precision while broadening the research ambit within cost and management accounting.

Second, it broadens the research scope of robot adoption. Existing research on the economic management effects of robot adoption primarily concentrates on areas such as economic growth (Acemoglu & Restrepo, 2018a), production efficiency (Acemoglu & Restrepo, 2018c; Graetz & Michaels, 2018), technological innovation (Deng Yue & Jiang Wanyi, 2022; L. Feng et al., 2023), value chain enhancement (Huang Liangxiong et al., 2023), employment (Autor & Salomons, 2018; Kong et al., 2020; Li Lei et al., 2021), low carbon (Huang et al., 2022; X. Pan et al., 2017), and business model innovation (Chen Jian & Y. Liu, 2021; G. Han & Li Wenrui, 2021; Li Honglei & Huang Sujian, 2017). However, research is scarce on the implications of robot adoption on enterprise cost management. The few available studies predominantly rely on norm-based research paradigms and illustrative analyses (G. Han & Li Wenrui, 2021), lacking empirical deductions concerning real-world effects. This study utilizes questionnaire data on construction robots to scrutinize the cost of real estate projects. It delves deeply into the intrinsic cost management within specific organizational structures, and establishes the underlying logic between construction robot production modes and corporate cost management, thereby expanding the research landscape on the operational and managerial impacts of robots.

Third, this study integrates the aspect of management change into the evaluation of the cost management impact of robotics implementation on the internal operations of micro-enterprises. It aims to pinpoint the essential mechanism through which robot adoption facilitates enterprises in their transformation and upgrading processes. The previous literature predominantly expounds on the trajectory and structure of management change crucial for the transformative growth of enterprises amidst the rise of robots, often employing normative frameworks and demonstrative analyses (Goles et al., 2019; Xiao Jinghua, 2020; P. Xu & X. Xu, 2020; Y. Qi & X. Xiao, 2020). However, there is a limited amount of research focused on the role of management change factors in driving the cost management effects of robot adoption through empirical deductions. In this study, the analytical framework for “robot construction-real estate project costs” incorporates the management change factor, unveiling the key mechanism through which robot construction influences real estate project cost management. The research conclusion offers substantial theoretical and practical insights that can serve as a guide for promoting the adoption of robot construction, devising adaptive management change strategies within enterprises, and formulating transformational upgrading strategies.

7.3 Research Limitations and Prospects

At present, few studies focus on empirically deducing the impact of robot construction, especially that on construction costs. One of the challenges is the difficulty in obtaining finely detailed data. Leveraging human capital, I conducted internal and external questionnaire surveys on robot construction. By focusing on real estate projects as research objects, I collected questionnaire samples with detailed information. This breakthrough addresses the sample data issue that current research aims to overcome but has not yet resolved. By utilizing exceptional experimental samples, this study aims to address questions regarding the cost effect of real estate projects adopting robot construction, the influence mechanism path, optimization strategies, and more. It seeks to identify the circumstances that are conducive to harnessing the cost reduction and efficiency enhancement effects of robot construction. Moreover, with the assistance of the external questionnaire, this study seeks to determine the expected value of cost reduction through robot construction for real estate construction enterprises at present. The response to the aforementioned question entails two key aspects. On the one hand, it provides a consistent evaluation tool for the real estate construction industry to bridge the intelligence gap between industries and offers clear policy implications on intelligent construction upgrades in construction enterprises. On the other hand, it offers promotion strategies for companies that specialize in comprehensive solutions for construction robots. This includes enhancing ease of use in product design, extending ample technical support to partners, and accurately forecasting the cost expectations of potential customers for product pricing. Therefore, this study holds a significant breakthrough value. However, there are still some limitations and opportunities for further improvement.

First, the questionnaire was developed and refined by drawing upon existing research and expert opinions. However, due to constraints in my abilities and time limitations, there is potential for enhancing its scientific validity and the depth of its items. In the future, by establishing a more scientific framework, the investigation of costs associated with traditional construction can be expanded to facilitate a more robust comparative analysis. Furthermore, the respondents for the questionnaire will be broadened to not only assess the current usage of robot construction within the Group but also to extend the distribution of questionnaires across the robot construction industry as a whole.

Second, this study demonstrates the cost variations of real estate construction enterprises during the implementation of robot construction through empirical deductions and explores the impact of management changes. It can be argued that this holds distinct practical significance. This analysis highlights the crucial aspects of the evolution of robot construction within the future construction industry. Moving forward, it remains essential to delve into specific cases to elucidate and refine the management change measures that ought to be implemented. These matters warrant further exploration and discussion.

Third, the current promotion of robot construction is not yet widespread, and its application proves to be more effective in the realm of real estate construction. It is essential to further elucidate the existing obstacles in practice. This study conducts a preliminary analysis of the cost effect of robot construction in diverse market settings. To better understand the varying outcomes in different market environments, a larger sample size is required for a comprehensive discussion. This step may aid in analyzing the underlying reasons for the limited promotion observed in reality.

References

Acemoglu, D., Lelarge, C. and Restrepo, P., 2020, “Competing with Robots：Firm-Level Evidence from France”, *AEA Papers and Proceedings*, Vol.110，pp.383~388.

Acemoglu, D. and Restrepo, P., 2020, “Robots and Jobs: Evidence from US Labor Markets”, *Journal of Political Economy*, Vol.128(6), pp.2188~2244.

Acemoglu, D. and Restrepo, P., 2019, “Automation and New Tasks: How Technology Displaces and Reinstates Labor”, *Journal of Economic Perspectives*, Vol.33(2), pp.3~30.

Acemoglu, D. and Restrepo, P., 2018a, “The Race between Man and Machine: Implications of Technology for Growth, Factor Shares, and Employment”, *American Economic Review*, Vol.108(6), pp.1488~1542.

Acemoglu, D. and Restrepo, P., 2018b, “Modeling Automation”, *AEA Papers and Proceedings*, Vol.108, pp.48~53.

Acemoglu, D. and Restrepo, P., 2018c, “Artificial Intelligence, Automation and Work”, NBER Working Paper, No.24196.

Acemoglu, D. and Restrepo, P., 2018d, “Demographics and Automation”, NBER Working Paper，No.24421.

Acemoglu, D., 2012, “Introduction to Economic Growth”, *Journal of Economic Theory*, Vol.147(2), pp.545~550.

Acemoglu, D. and Autor, D., 2011, “Skills, Tasks and Technologies: Implications for Employment and Earnings”, *Handbook of Labor Economics*: *Elsevier*, Vol.4, pp.1043~1171.

Acemoglu, D., 2002, “Directed Technical Change”, *Review of Economic Studies*, Vol.69, pp.781~810.

Bruce Kogut, Udo Zander. Knowledge of the Firm, Combinative Capabilities, and the Replication of Technology[J]. Organization Science, 1992, 3(3): 383-397.

Chen, C., Li, X. [Xing], & Qiu, Z. (2022). Research progress of construction robots. *Journal of Architecture and Civil Engineering*, *39*(04), 58-70.

Chen, C., Li, X. [Xing], Qiu, Z., Yao., W., & Zhu, H. (2022). Research progress of construction robots. *Journal of Architecture and Civil Engineering*, (4), 58-70.

Chen, D., Wang, L., & Chen, A. (2020). Digitalization and strategic management theory: Review, challenges and prospects. *Management World*, *36*(05), 220-236+20.

Chen, G. [Guoquan], Wang, J., & Lin Y. (2021). A study on the process model of organizational digital transformation and corporate case analysis. *Management Review*, (11), 28-42.

Chen, H., Wang, W. [Wenhua], & Liu, L. (2023). Research on the impact of artificial intelligence on cost stickiness of enterprises. *Science Research Management*, *44*(1), 16-25.

Chen, J. [Jiaying], Zhao, P., & Zhao, Y. [Yong]. (2022). Robots and informal employment. *Economic Perspectives*, (12), 67-83.

Chen, J. [Jing], Zeng, D., & Ouyang, X. (2021). Knowledge recombination capability and high-tech firm performance: The contingent role of slack resources and innovation openness. *Journal of Industrial Engineering and Engineering Management*, *35*(03), 23-33.

Chen, L. [Liangyuan], Zhang, Y., Lin, J., & Li, L.[Lanyu]. (2023). Industrial robot application and employment: Evidence from enterprise survey. *Statistical Research*, (7), 85-97.

Chen, Y. [Yuanyuan], Zhang, J., & Zhou, Y. (2022). Industrial robots and spatial allocation of labor. *Economic Research Journal*, (1), 172-188.

Cheng, H., Wang, Z. [Zeyu], & Chen, J. [Jia]. (2020). Robots and wages: the mediating effects of labor quality——Based on the China Enterprise General Survey (CEGS). *Journal of Macro-quality Research*, *8*(03), 1-13.

Cheng, H., & Yuan, L. (2020). Robotics, process innovation and quality improvement: Findings based on China Enterprise General Survey. *South China Journal of Economics*, (01), 46-59.

Deng, Y. [Yue], & Jiang, W. [Wanyi]. (2022). Industrial robot, management ability and enterprise technological innovation. *China Soft Science*, (11), 129-141.

Dong, X., Pan, D., & Chi, R. (2022). How have industrial robots reshaped China's employment structure? *Economic Perspectives*, (12), 51-61.

Duan, H., Zhang, F., Chen, G. [Gaohong], Chen, L. [Linxin], & Luo, Q. (2022). The practice and development of intelligent construction driven by construction robots. *Construction Economics*, (11), 5-12.

Duan, H., Zhang, F., Chen, G. [Gaohong], Luo, Q., & Wu, L. (2022). Lean construction and management practice based on construction robot—Take the refined decoration of Guangzhou ST project as an example. *Guangdong Architecture Civil Engineering*, (12), 10-26.

Fan, Q., Lu, Y., Li, G. et al. (2021). Innovation and practice of intelligent construction management for large-scale hydropower projects in the lower reaches of the Jinsha River. *Management World*, *37*(11), 206-226+13.

Fan, C., & Deng, Y. [Yunxue]. (2022). Workers' fear of unemployment under the background of "machines replacing humans": Evidence from matched "employer-employee" survey data for Guangdong's manufacturing industry. *Sociological Review of China*, (2), 67-87.

Feng, L., Yuan, F., & Liu, X. [Xiaoyi]. (2023). Industrial robots and enterprise innovation—Evidence from manufacturing enterprises in China. *China Economic Quarterly*, (4), 1264-1282.

Geng, B. (2018). Research on influencing factors of BIM technology adoption in construction enterprises. Chongqing: Chongqing University.

He, B., Zhao, N., He, Q. [Qinqing], & Hu, W. (2022). Adaptive change of digital management from the perspective of management model transformation: A case study of ByteDance company. *Journal of Beijing Jiaotong University (Social Sciences Edition)*, (4), 29-36.

He, J., & Yan, S. (2024, April 7). Human-machine division of labor: Generation logic, mode type and action mechanism. *Nankai Business Review*, 1-20.

He, J., & Yan, S. (2023). Human-machine division of labor: Generation logic, mode type and action mechanism. *Nankai Business Review*.

He, X., & Liu, K. (2023). Robots, job tasks and employment polarization effect: Evidence from China's industrial enterprises. *The Journal of Quantitative & Technical Economics*, (4), 52-71.

He, X., Zhu, G., & Feng, D. (2023). Industrial robot and labor income share—Evidence from China's industrial enterprises. *China Industrial Economics*, (4), 98-116.

Huang, G., Guo, Y., & Lu, Q. (2022). Research on the development mode of building industrialization based on intelligent construction. *Construction Economics*, *43*(03), 28-34.

Huang, M., & Li, L. [Lin]. (2020). Research on project management theory and model under the background of big data. *Journal of Xiangtan University (Philosophy and Social Sciences)*, *44*(03), 25-30.

Ji, L., Deng, B., & Mao, H. (2014). Budget constraint, government intervention, and project cost: Empirical evidence from China’s state-owned large construction enterprises. *Nankai Business Review*, *17*(03), 94-102.

Jiang, W. [Wei], Gong, S., & Li, X. [Xitao]. (2022). Robot shock, capital-embodied technological progress and carbon reduction of manufacturing sector theoretical analysis and empirical evidence from China. *China Industrial Economics*, (10), 24-42.

Jiang, Y., Li, Q., Liu, H., Guo, Q., & Miao, M. (2023). The impact of consumer forgiveness towards the apologizer after AI robot service failure. *Nankai Business Review*.

Kim S., Park C. H., Chin S. Assessment of BIM acceptance degree of Korean AEC participants[J]. KSCE Journal of civil engineering, 2016, 20(4): 1163-1177.

Lai Y., Sun H., Ren J. Understanding the determinants of big data analytics (BDA) adoption in logistics and supply chain management[J]. The International Journal of Logistics Management, 2018, 29(2): 676-703.

Lee, G., Lee, W. J. Psychological Reactance to Online Recom1mendation Services. Information and Management, 2009, 46(8): 448-452.

Li, H. (2022). Cost risk management of construction enterprises. *Journal of Shanxi University of Finance and Economics*, (S1), 33-34.

Li, L. [Lei], & Ma, H. (2023). “Reshoring” and the stability of foreign investment: An analysis based on the adoption of robot in developed countries. *Management World*, *39*(10), 41-59.

Li, L. [Lei], Wang, X. [Xiaoxia], & Bao, Q. (2021). Employment Effects of robots: Mechanism and China’s experience. *Management World*, (9), 104-119.

Li, Y., Chen, Y. [Yuan], & Yu, H. (2024, April 7). A New Way to alleviate the bullwhip effect: Intelligent decision-making robot with human-computer collaboration. *Chinese Journal of Management Science*, 1-12.

Li, Y. [Yong], Chen, Y. [Yuan], & Yu, H. (2022). A New Way to alleviate the bullwhip effect: Intelligent decision-making robot with human-computer collaboration. *Chinese Journal of Management Science*.

Lin, L., & Lyu, W. (2019). The impact of digital transformation on management reform of manufacturing enterprises: A case study based on Kutesmart and Haier. *Scientific Decision Making*, (1), 85-98.

Liu, J. [Jin], & Wan, Z. (2023). Intelligent transformation and labor cost viscosity: Empirical evidence from listed manufacturing companies. *Journal of Anhui University (Philosophy and Social Sciences Edition)*, *47*(03), 133-144.

Liu, J. [Junyong], An, N., Duan, W. et al. (2022). Cost management reform from the perspective of structural theory: Empirical findings of a public hospital. *Journal of Central University of Finance & Economics*. (03), 59-68.

Liu, S. [Shuang]. (2018). Research on influencing factors of BIM technology adoption in construction enterprises. Shenzhen: Shenzhen University.

Liu, Y., Dong, J., & Wei, J. (2020). Digital innovation management: Theoretical framework and future research. *Management World*, (7), 198-217.

Liu, Z., Liu, S. [Shinan], Zhao, Y. [Yuhong] et al. (2019). Development status and future trends of intelligent construction technology. *Architecture Technology, 50*(07), 772-779.

Lyu, M., & Xu, J. [Jialin] (2012). On the internal control expert system——A case of GLNT's purchasing cost control. *Accounting Research*, (12), 61-67.

Mao, C., & Peng, Y. (2020). The theoretical framework and core logic of intelligent construction. *Journal of Engineering Management*, *34*(05), 1-6.

Mao, H., Zhu, B., & Wang, T. (2012). The effect of organizational environment on engineering project cost management: A case study on China Railway Erju Co.Ltd. *Nankai Business Review*, *15*(01), 102-112.

Moore G. C., Benbasat I. Development of an instrument to measure the perceptions of adopting an information technology innovation[J]. Information systems research, 1991, 2(3): 192-222.

Qi, Y., & Xiao, X. (2020). Enterprise management change in the era of digital economy. *Management World*, (6), 135-152.

Qi, J., & Fu, J. (2022). Where do the low-skilled laborers go in the era of “machine substitution”? —A study based on China labor-force dynamic survey data. *Population Research*, (4), 114-128.

Qi, J., & Zhang, Z. (2022). Robotic applications and export product scope adjustments: Can efficiency and quality be achieved simultaneously? *The Journal of World Economy*, (9), 3-31.

Quan, X., & Li, C. (2022). Cost stickiness mitigation effect of intelligent manufacturing: On a quasi-natural experiment of Chinese intelligent manufacturing demonstration project. *Economic Research Journal*, (4), 68-84.

Rogers E. M. The Diffusion of Innovations (3rd) [M]. New York: The Free Press, 1983.

Shen, P., Wan, D., & Xu, J. [Jinan] (2021). How does human-computer interaction perception affect consumer well-being in the online retail context—From the perspective of autonomy. *Nankai Business Review*, *24*(06), 26-40.

Sheng, D., & Bu, W. (2022). The usage of robots and enterprises’ pollution emissions in China. *The Journal of Quantitative & Technical Economics*, (9), 157-176.

Sohn, D. Anatomy of Interaction Experience: Distinguishing Sensory, Semantic, and Behavioral Dimensions of Interactivity. New Media & Society, 2011, 13(8): 1320-1335.

Song, X., & Zuo, M. (2022). How do industrial robots affect employment in the manufacturing industry?—An analysis on listed manufacturing companies, *Economic Perspectives*, (7), 70-89.

Su, S., Lei, J., Ma, S. et al. (2019). Research and application on technology of intelligent building robot. *Construction Technology*, *48*(22), 16-18+25.

Su, Z., Wei, J., & Hu, G. (2023). Research on co-evolution mechanism of enterprise strategic renewal and organizational structure reform. *Nankai Business Review*, *26*(02), 61-72.

Venkatesh V., Davis F. D. A theoretical extension of the technology acceptance model: Four longitudinal field studies[J]. Management science, 2000, 46(2): 186-204.

Wang, H. [Hongwei], Zhong, B., Li, Y. [Yongkui] et al. (2022). Management theory and method of intelligent construction, operation and maintenance for large-scale complex projects. *Journal of Management Science*, *35*(01), 55-59.

Wang, H. [Hui], & Chang, Y. (2017). The influence of organizational creative climate and work motivation on employee's creative behavior. *Journal of Management Science*, *30*(03), 51-62.

Wang L. J., Huang X., Zheng R. Y. The Application of BIM in Intelligent Construction[J]. Applied Mechanics Materials, 2012, 188.

Wang, W. [Wen]. (2020). Does Industrial intelligence promote high-quality employment in the digital economy era. *Economist*, (04), 89-98. DOI:10.16158/j.cnki.51-1312/f.2020.04.010.

Wang, X. [Xiaojuan], Zhu, X. [Xi'an], & Wang, Y. (2022). The Impact of robot application on manufacturing employment. *The Journal of Quantitative & Technical Economics*, (4), 88-106.

Wang, Z. [Zhenyuan], & Yao, M. (2022). The impact of human-robot collaboration on employees in the workplace. *Foreign Economics & Managemen*t, *44*(9), 86-102.

Wei, J., Liu, J. [Jialing], & Liu, Y. (2021). New trends and problems of innovation strategy theory in the context of new organization. *Management World*, *37*(07), 182-197+13.

Wu, X., Xiao, J., & Wu, J. (2022). New organizational learning for human-AI collaboration: A multi-case study from a scenario perspective. *China Industrial Economics*, (02), 175-192.

Xiao, J., & Li, W. (2020). The impact of intelligent manufacturing on enterprise strategic change and innovation: Analysis on the perspective of resource base reform. *Research on Financial and Economic Issues*, (02), 38-46.

Xu, P., & Xu, X. (2020). Change logic and analysis framework of enterprise management in the era of artificial intelligence. *Management World*, (1), 122-129.

Xu, J. [Jian], Ji, K., Liu, X. [Xiaoting], & Xia, Y. (2022). Robotics application, gender wage gap, and common prosperity. *The Journal of Quantitative & Technical Economics*, (9), 134-156.

Ye, Y., Li, X. [Xin], & Liu, G. (2022). Digital transformation and corporate human capital upgrade. *Journal of Financial Research*, (12), 74-92.

Yoo, W. S., Lee, Y., Park, J. The Role of Interactivity in E-tailing: Creating Value and Increasing Satisfaction. Journal of Retailing and Consumer Services, 2010, 17(2): 89-96.

Yu, X., & Zhou, Q. (2018). Impact of external search tactics and knowledge absorptive capacity on technology innovation performance. *Science Research Management*, *39*(8), 11-18.

Yue, Y., & Gu, M. (2021). The Impact of intelligentization on cost stickiness among manufacturing companies. *Financial Economics Research*, *36*(03), 91-106.

Yue, Y., & Gu, M. (2021). The Impact of intelligentization on cost stickiness among manufacturing companies. *Financial Economics Research*, *36*(03), 91-106.

Zhan, D., Zheng, Z., Shi, Y., & Cao, X. (2022). An overview of application and development of construction robots technology. *Building Construction*, (10), 2474-2477.

Zhao, B., & Xie, Y. (2016). Study on the factors of BIM technology adoption in real estate enterprises. *Journal of Engineering Management*, *30*(02), 142-146.

Zhi, X., Yang, Z., Wang, C. et al. (2022). Business model transformation, organizational structure innovation and enterprise cost management—Case study based on Haier chain group organization. *China Soft Science*, (08), 92-102.

Zhi, X., Yang, Z., Wang, C., & Huang, R. (2022). Business model transformation, organizational structure innovation and enterprise cost management—Case study based on Haier chain group organization. *China Soft Science*, (8), 92-102.

Zhong, Y. (2023). Research on the influence mechanism of intelligent construction technology on dual innovation of employees in construction enterprises. Xi’an University of Architecture and Technology.

Zhu, X. [Xiaomei], Wang, S., & He, Q. [Qin] (2021). Impact of skill requirements on employees’ thriving at work: From the perspective of artificial intelligence embedding. *Foreign Economics & Management*, *43*(11), 15-25.

Appendix

Appendix 1: Reliability Test

SPSS 26.0 was utilized for conducting a reliability test, and the outcomes of the robot construction adoption scale can be observed in Table 1. The standardized Cronbach's α value is .936, surpassing .7. Furthermore, all items demonstrate CITC values above .5. Further analysis revealed that Cronbach's α for each variable as a whole surpassed the values when scale items were deleted, demonstrating that the formal survey data exhibited high internal consistency and successfully passed the reliability test.

Table 1 Reliability Analysis Results of Robot Construction Adoption Scale

Dimension	Item	CITC	Cronbach's α if item deleted	Cronbach α based on standardized terms
Robot construction	R-1	.807	.924	.936
	R-2	.789	.926	
	R-3	.769	.929	
	R-4	.857	.918	

The production efficiency scale results are shown in Table 2. The standardized Cronbach's α values for the adaptability scale and technological advantage scale are .910 and .909, respectively, exceeding .7. Furthermore, all items' CITC values are above .5. Further analysis revealed that Cronbach's α for each variable as a whole surpassed the values when scale items were deleted, demonstrating that the formal survey data exhibited high internal consistency and successfully passed the reliability test. To sum up, the data are highly reliable and suitable for further analysis.

Table 2 Reliability Analysis Results of Robot Construction Production Efficiency

Dimension	Item	CITC	Cronbach's α if item deleted	Cronbach α based on standardized terms
Adaptability	AB-1	.840	.853	.910
	AB-2	.823	.867	
	AB-3	.795	.890	
Technological advantages	TA-1	.825	.864	.909
	TA-2	.829	.861	
	TA-3	.801	.883	
	TA-4	.775	.789	

The management change scale results are shown in Table 3. The standardized Cronbach's α values for the organizational consensus scale, organizational learning scale, and human-robot collaboration scale are .944, .920, and .954, respectively, all surpassing .7. Moreover, all items exhibit CITC values exceeding .5. Further analysis revealed that Cronbach's α for each variable as a whole surpassed the values when scale items were deleted, demonstrating that the formal survey data exhibited high internal consistency and successfully passed the reliability test. To sum up, the data are highly reliable and suitable for further analysis.

Table 3 Reliability Analysis Results of Management Change

Dimension	Item	CITC	Cronbach’s α if item deleted	Cronbach α based on standardized terms
Organizational consensus	MD-1	.883	.926	.944
	MD-2	.793	.936	
	MD-3	.822	.933	
Organizational learning	OL-1	.813	.897	.920
	OL-2	.890	.871	
	OL-3	.831	.891	
Human-robot collaboration	LR-1	.748	.954	.954
	LR-2	.825	.946	
	LR-3	.831	.946	
	LR-4	.881	.942	

The project cost scale results are shown in Table 4. The standardized Cronbach’s α values for the average cost scale and redundancy cost scale are .905 and .899, respectively, both exceeding .7. Additionally, the CITC value for all items is above .5. Further analysis revealed that Cronbach’s α for each variable as a whole surpassed the values when scale items were deleted, demonstrating that the formal survey data exhibited high internal consistency and successfully passed the reliability test. To sum up, the data are highly reliable and suitable for further analysis.

Table 4 Reliability Analysis Results of Project Cost and Structural Cost

Dimension	Item	CITC	Cronbach's α if item deleted	Cronbach α based on standardized terms
Average cost	MC-1	.825	.851	.905
	MC-2	.842	.839	
	MC-3	.767	.901	
	MC-2	.820	.864	
Redundancy cost	RC-1	.802	.855	.899
	RC-2	.791	.864	
	RC-3	.809	.849	

The project performance scale results are shown in Table 5. The standardized Cronbach's α value is .922, surpassing .7. Furthermore, all items demonstrate CITC values above .5. Further analysis revealed that Cronbach's α for each variable as a whole surpassed the values when scale items were deleted, demonstrating that the formal survey data exhibited high internal consistency and successfully passed the reliability test. To sum up, the data are highly reliable and suitable for further analysis.

Table 5 Reliability Analysis Results of Project Performance

Dimension	Item	CITC	Cronbach's α if item deleted	Cronbach α based on standardized terms
Project performance	I-1	.803	.905	.922
	I-2	.881	.878	
	I-3	.819	.899	

Appendix 2: Validity Test

The scale used in this study was developed by referencing existing literature and interviewing experts and experienced practitioners in the construction industry, ensuring robust content validity. Prior to conducting the validity analysis, the KMO measure and Bartlett's Test of Sphericity were performed. As shown in Table 6, whether tested individually or collectively, the KMO values for the robot construction adoption scale, project cost scale, production efficiency scale (adaptability and technological advantage scales), management change scale, and project performance scale were all greater than .7. Additionally, the Bartlett's Test of Sphericity was significant ($P < .001$).

Table 6 Results of the KMO Test and Bartlett's Test of Sphericity

	KMO	df	Approximate Chi-square of Bartlett's Test of Sphericity	Sig.
Robot construction adoption scale	.851	6	437.516	0
Adaptability scale	.747	3	311.484	0
Technological advantage scale	.835	6	452.831	0
Project cost scale	.919	21	978.327	0
Management change scale	.939	45	1595.039	0
Project performance scale	.743	3	314.113	0
All variable scales	.956	465	5820.366	0

(1) Convergent validity

This study includes 31 significant variables and 162 collected questionnaires, meeting the requirement that the sample size be more than five times the number of variables, thus allowing for confirmatory validity tests. The convergent validity test was conducted using Amos 23.0, with the results shown in Table 7. The Average Variance Extracted (AVE) values for the 9 latent variables were .725, .759, .728, .705, .696, .759, .699, .741, and .758, respectively, all exceeding .50. The composite reliability (CR) values were .913, .904, .914, .905, .873, .904, .874, .919, and .904, respectively, all surpassing .70. Additionally, the standardized factor loadings of items were greater than .50, indicating that the good convergent validity of variable measure scale in this study.

In this study, Amos 23.0 was utilized to conduct confirmatory factor analysis (CFA), evaluating the validity of each factor (see Figure 1).

Table 7 Convergent Validity Test Results

Latent variables	Measure item (manifest variable)	Standardized loading coefficient	CR	AVE
Robot construction	R-1	.877	.913	.725
	R-2	.861		
	R-3	.865		
	R-4	.800		
Adaptability	AB-1	.863	.904	.759
	AB-2	.876		
	AB-3	.874		
Technological advantages	TA-1	.891	.914	.728
	TA-2	.880		
	TA-3	.840		
	TA-4	.798		
Average cost	MC-1	.866	.905	.705
	MC-2	.820		
	MC-3	.825		
	MC-4	.846		
Redundancy cost	RC-1	.854	.873	.696
	RC-2	.847		
	RC-3	.801		
Organizational consensus	MD-1	.876	.904	.759
	MD-2	.848		
	MD-3	.890		
Organizational learning	OL-1	.850	.874	.699
	OL-2	.888		
	OL-3	.766		
Human-robot collaboration	LR-1	.860	.919	.741
	LR-2	.884		
	LR-3	.762		
	LR-4	.929		
Project performance	I-1	.878	.904	.758
	I-2	.906		

Table 7 Convergent Validity Test Results

Latent variables	Measure item (manifest variable)	Standardized loading coefficient	CR	AVE
	I-3	.826		

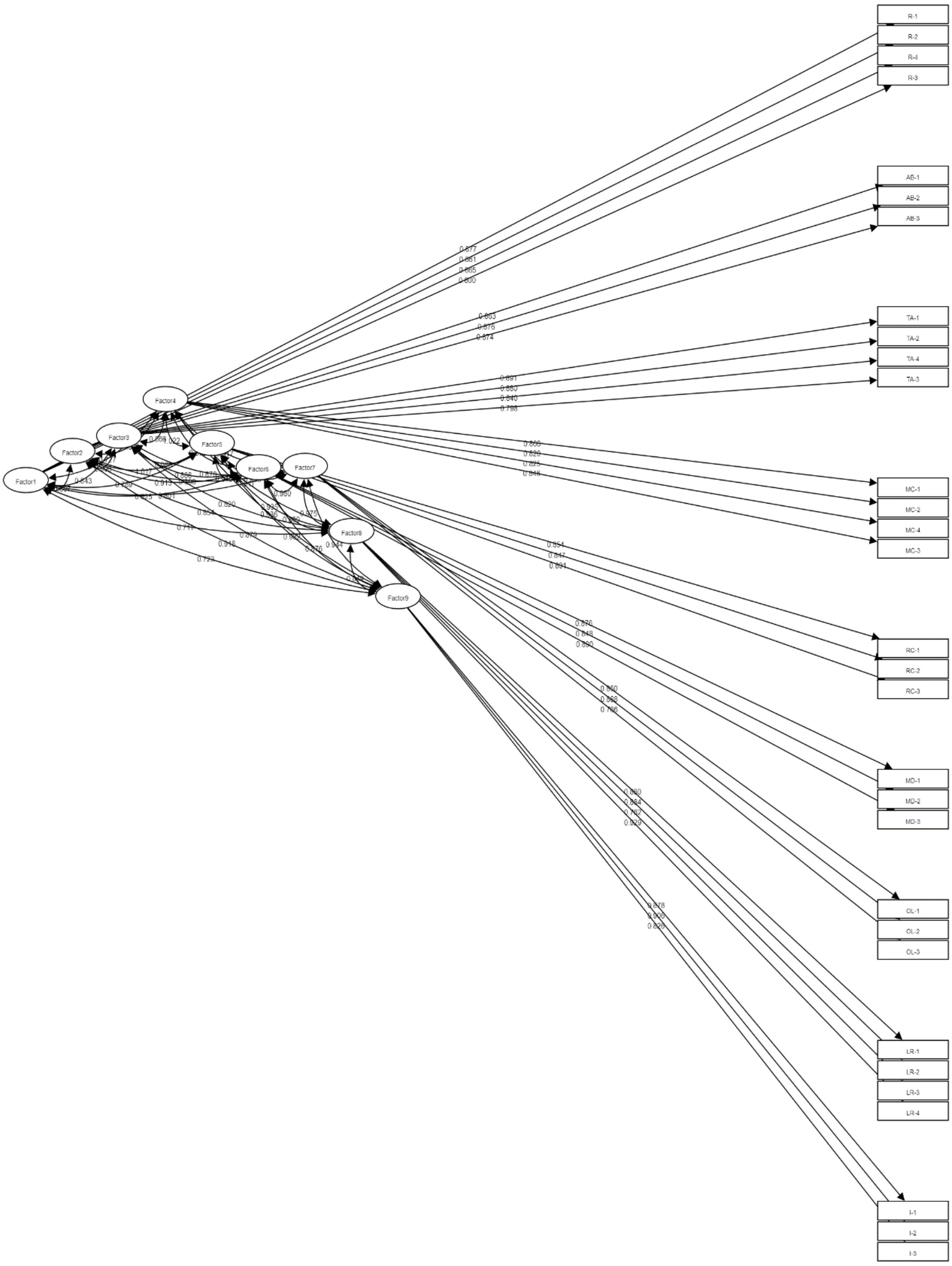

Figure 1 Multi-factor Confirmatory Analysis

(2) Discriminant validity

Further discriminant validity tests were conducted, with results shown in Table 8. The absolute values of the correlation coefficients (values below the diagonal) between each variable and other variables were less than .85, and all were lower than the square root values of the AVE for the variables (values on the diagonal in bold), indicating the measure scale's good discriminant validity.

Table 8 Discriminant Validity: Pearson Correlation Coefficient and Square Root of AVE

Latent variables	Robot construction	Adaptability	Technological advantages	Average cost	Redundancy cost	Organizational consensus	Organizational learning	Human-robot collaboration	Project performance
Robot construction	.851								
Adaptability	.726	.871							
Technological advantages	.756	.704	.853						
Average cost	.651	.737	.770	.840					
Redundancy cost	.701	.804	.766	.798	.835				
Organizational consensus	.752	.825	.810	.787	.846	.871			
Organizational learning	.713	.797	.788	.821	.736	.770	.836		
Human-robot collaboration	.638	.782	.739	.802	.749	.794	.772	.861	
Project performance	.670	.725	.808	.737	.761	.791	.738	.774	.871

Note: The blue numbers on the diagonal represent the square root of AVE.

Appendix 3: Test of Common Method Bias

Common method biases, which are errors caused by factors such as the environment, measure tools, and characteristics of measure items, were controlled in this study through methods such as anonymous surveys, the use of multiple items to measure the same variable, and the collection of questionnaires both online and offline during the questionnaire design and actual survey process. Additionally, SPSS 26.0 was employed to test common method bias using Harman's single-factor test, with results shown in Table 9. Nine factors with eigenvalues greater than 1 were extracted without rotation, and the first factor's variance explained was less than the critical criterion of 40%, indicating no significant common method bias.

Table 9 Test Results of Common Method Bias

S/N	Extract square sum load		
	Total	Variance explained ratio (%)	Cumulative (%)
1	6.059	19.545	19.545
2	5.727	18.475	38.020
3	4.464	14.399	52.420
4	3.035	9.790	62.210
5	2.838	9.155	71.364
6	1.604	5.175	76.539
7	1.254	4.046	80.585
8	1.242	4.006	84.592
9	.469	1.514	86.106