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Article

Developing a lean construction quality management framework for prefabricated buildings projects in China: A structural equation modeling approach

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Abstract: This study sought an innovative quality management framework for Chinese Prefabricated Buildings (PB) projects. The framework combines TQM, QSP, Reconstruction Engineering, Six Sigma (6Σ), Quality Cost Management, and Quality Diagnosis Theories. A quantitative assessment of a representative sample of Chinese PB projects and advanced statistical analysis using Structural Equation Modeling supported the framework, indicating an excellent model fit (CFI = 0.92, TLI = 0.90, RMSEA = 0.06). The study significantly advances quality management and industrialized building techniques, but it also emphasizes the necessity for ongoing research, innovation, and information exchange to address the changing problems and opportunities in this dynamic area. In addition, this study's findings and recommendations can help construction stakeholders improve quality performance, reduce construction workload and cost, minimize defects, boost customer satisfaction, boost productivity and efficiency in PB projects, and boost the Chinese construction industry's growth and competitiveness.

Keywords: quality management framework; Prefabricated Buildings (PB); Structural Equation Modeling (SEM); Total Quality Management (TQM); six sigma (6Σ); continuous improvement; process optimization; China

1. Introduction

China's building sector has risen rapidly in recent decades, driving economic expansion. However, this increase has caused significant challenges. According to the National Bureau of Statistics of China, Construction generated roughly 70% of industrial trash in 2021. The Ministry of Housing and Urban-Rural Development found that Chinese building projects are 15% behind and 12% over budget. Productivity and material waste are the leading causes (Ministry of Housing and Urban-Rural Development, 2020). The 2019 China Building Industry Association survey indicated that over 30% of building projects experienced quality issues, resulting in extra work and higher expenditures (China Construction Industry Association, 2020). These alarming data show that China's building industry urgently needs new ideas to fix its issues.

Prefabricated Buildings (PB) are used in China's building sector to address low productivity, waste, quality, and safety (Gunasagaran et al., 2022). PB involves premaking building pieces in a controlled workshop and assembling them locally. PB seems better than traditional building methods, but it must be extensively examined before it can be widely employed in China.

A significant issue with PB projects is that they are complicated and must combine design, manufacturing, transportation, and on-site assembly to work well together (Wuni and Shen, 2020). Not being able to handle this complicated system well can cause delays, higher costs, and lower quality. Yunus and Yang (2012) state that addressing the sustainability factors in PB is essential for its successful application. Also, building stakeholders who are used to traditional methods will have to change how they think and do things to switch to PB. Individuals unwilling to change or lacking expertise in PB methods can make it challenging to use (Thanoon et al., 2003). Johnsson (2011) notes that the building system should be considered a strategic asset in prefabricated building construction. This shows that the business needs a paradigm shift.

Ensuring PB projects always have high quality is essential because problems with premade parts can affect the whole building process. Alawag et al. (2023) state that traditional quality management methods might not be enough to address the unique problems PB brings up. Quality problems can make PB less helpful in supporting green building practices, as Mydin et al. (2014) point out.

This study aims to develop a new way to improve quality management that is made explicitly for PB projects in China. The main objectives are:

i To examine the innovative Quality Management Improvement framework based on previous essential quality management.

ii To explore the innovative quality management improvement framework for PB application on construction.

iii To evaluate the innovative quality management improvement framework for the PB implementation path by SEM.

This study's framework was developed by analyzing associated theories and concepts, including TQM, Quality Strategic Planning, Reconstruction Engineering, Six Sigma (6Σ), Quality Cost Management, and Quality Diagnosis. These theories have been explored and employed in various contexts. Still, they must be thoroughly reviewed to determine if they can also be applied to China's specific PB project challenges. Many companies employ Six Sigma, which reduces mistakes in industry processes and improves production processes (Tjahjono et al., 2010; Yadav and Desai, 2016). However, further research is needed to discover if it can work in China's complex, multi-stakeholder PB projects. For instance, Patel and Patel (2021) recommend reviewing Lean Six Sigma literature and further research objectively to identify problems and approaches to its application in improving construction.

Koskela (2020) states that TQM concepts have been thoroughly studied and implemented in construction, but they must be adequately modified to PB in China. Mamurova (2021) believes that the theoretical study of building engineering professional competence is necessary for real-world problem solutions.

Combining and analyzing these theories, the Quality Management Improvement Framework provides a complete and situation-specific approach to PB project quality management. According to Chen et al. (2022), Lin et al. (2021), SEM is a powerful analytical method utilized in building engineering studies and was be used in this paper to assess the framework in real life. However, SEM has several limitations. For instance, Yi and Wu (2020) emphasized that the dependability and quality of these analyses' data can significantly impact outcomes. Abas et al. (2021) also noted that understanding SEM results requires considering opposing viewpoints. This paper examines China's PB projects' specific building quality management issues to advance building quality management. This essay looks at different ideas and suggests a local framework.

2. Literature review

2.1. Theories for lean construction quality management

Total Quality Management (TQM) theory:

The ideas behind Total Quality Management (TQM) have been widely accepted in many fields, including construction, to make businesses run better and make customers happier. TQM stresses ongoing growth, involving employees, and placing the customer first (Krarti, 2020). Mariano-Hernández et al. (2021) state that standard TQM methods might be unable to deal with the unique problems of complicated building systems like those in PB projects. TQM should be used with model predictive control and fault diagnosis. TQM is relevant to the proposed framework as it enhances a quality culture that is imperative to PB projects in China.

Quality Strategic Planning Theory:

Quality Strategic Planning Theory stresses that an organization's strategic goals should align with its quality management efforts (Karaz et al., 2021). This theory is beneficial for PB projects because it shows how important it is to have a quality plan that covers the whole project lifecycle, from planning and making the parts to setting them together and starting the project. Koc and Gürgün (2020) contend that using smart contracts can help build projects that have better strategic planning.

Reconstruction Engineering Theory:

Reconstruction Engineering Theory provides a way to look at and change complicated systems; consequently, they work better and more efficiently (Westerblad, 2022). Thinking about this idea can help people develop new ways to build structures for PB projects that use prefabrication and modular building techniques. However, Mamurova (2021) states that one must deeply understand the professional competencies and skills needed in building engineering to use this theory effectively.

Six Sigma (6Σ) theory:

Six Sigma is a data-based method aiming to lower process variation and errors, eventually improving quality and efficiency (Ekleş and Türkmen, 2022; Park, 2022). While Six Sigma has been widely adopted in manufacturing industries, its application in construction has been limited (Yang et al., 2020). Patel and Chudgar (2020) stress how important it is to understand the basic ideas behind Six Sigma before trying to use it in a particular situation. Six Sigma is relevant to the proposed framework as it helps to focus on data analysis and improvement of the PB manufacturing and assembly processes by minimizing defects and variability.

Quality Cost Management Theory:

Quality Cost Management Theory provides a framework for analyzing and optimizing the costs associated with quality management efforts (Joghee and Varghese, 2024). In the construction industry, this theory can inform strategies for balancing the upfront costs of quality assurance measures with the potential long-term savings from reduced rework and defects. Khan (2023) proposes a "Six Plus Sigma Quality

Excellence Holistic Focused Model" incorporating quality cost considerations. Quality Cost Management is useful in the proposed framework because it helps to minimize the expenses of Chinese PB projects through a proper distribution of prevention, appraisal, and failure costs.

Two Quality Diagnosis Theories:

The Two Quality Diagnosis Theories proposed by Fried (2020) suggest that quality issues can arise from either a lack of theory building or theory testing. When it comes to PB projects, these theories show how important it is to create theoretical solid frameworks specific to the difficulties of prefabricated buildings and then rigorously test them in the real world.

Overview of engineering quality management research:

Most of the study that has been done on engineering quality management so far has been on traditional building methods and project management techniques (Wang and Cheng, 2022). Still, as López-Guerrero et al. (2022) indicate, PB's effects on quality and sustainability require further investigation.

According to Ayodele et al. (2020), projects in building demand a high calibre of management that encompasses strong leadership, employees with active participation, ongoing growth and a customer focus. Liu et al. (2020) and Song et al. (2022) note that quality management must include people issues as examples of workplace misconduct and the relationship between managers and workers.

2.2. Conceptual framework

Conceptual framework demonstrates the relationship between several factors and the outcome of PB ventures in China. The model is made up of dependent and control variables, and organizational and environment factors are the independent ones in the quality management. Variables include Quality Planning and Strategy, Process Optimization and Control, Quality Assurance and Inspection, Mechanisms for Continuous Improvement and Cost Quality Management. The framework explains that, first of all, PB projects will have to undergo Quality planning to optimise processes, Quality Assurance, constant improvement techniques and Innovative cost management processes. The mediating variables are interconnected, with quality planning facilitating process optimization and enabling adequate quality assurance. Quality assurance findings inform continuous improvement mechanisms, influencing quality cost management strategies. The independent variables, such as project complexity, organizational culture, and regulatory environment, shape these mediating variables.

Ultimately, the framework hypothesizes that by effectively managing these independent and mediating variables, construction stakeholders can enhance the overall success of PB projects in China, encompassing project quality performance, minimized rework and defects, customer satisfaction, and productivity/efficiency. The framework highlights the interdependent nature of these factors and the potential pathways through which they impact quality outcomes in PB project implementation. The proposed conceptual framework in **Figure 1** could include the following components:

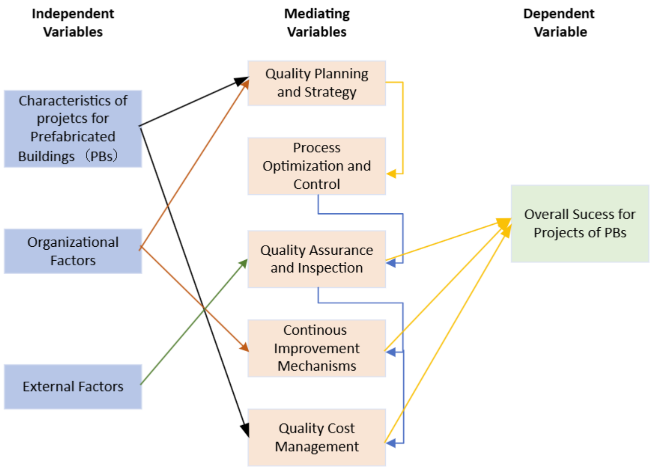

Figure 1. Research Conceptual Framework for Quality Management Improvement.

2.3. Empirical framework

A comprehensive research methodology must be developed to empirically test and validate the proposed Quality Management Improvement Framework. Combining quantitative data collection and analysis with qualitative views from experts in the field and case studies, this study will use a mixed-methods approach. The quantitative component will use the conceptual framework to develop a survey tool with relevant scales and measurement items from the literature. Project managers, quality professionals, and construction workers will complete a survey about a sample of Chinese PB projects.

Advanced statistical approaches, specifically SEM, will be applied to examine how conceptual framework components are related. SEM is a powerful data analysis tool utilized in construction engineering research (Chen et al., 2022; Lin, 2021). It helps examine how many PB project quality control aspects interact.

Along with quantitative results, the study will include qualitative elements. Quality management specialists, construction managers, and academics will be interviewed in a semi-structured manner to learn about PB project quality management challenges and best practices. Case studies will include Chinese PB projects. This will detail their quality management techniques, issues, and results.

Interview and case study qualitative data will be examined using thematic and grounded theory. This will reveal recurring themes and trends, providing baseline knowledge to support and improve the suggested Quality Management Improvement Framework. Comparing quantitative and qualitative outcomes will verify the proposed framework is correct and enhanced. Statistical analytics and qualitative insights will be integrated to create a framework that accurately depicts Chinese PB project quality management's intricacies and complexities.

This case study will help Chinese PB projects apply the Quality Management Improvement Framework. These guidelines will inform the local business environment, rules, and study issues. Further research will determine how emerging technologies like Building Information Modeling and the Internet of Things affect PB project quality management.

The study uses solid quantitative analyses and deep qualitative insights to establish a complete and context-specific Quality Management Improvement Framework for Chinese PB projects. Theory and industrial experience will underpin the framework using mixed-approaches empirical methods. This will benefit Chinese construction workers.

3. Methodology

The proposed Innovative Quality Management Improvement Framework for Chinese Prefablicated Buildings (PB) projects was developed systematically. This strategy adapts the best quality management ideas and approaches to China's PB demands and concerns. This procedure began with a thorough literature assessment of building quality management research. The review covered several theoretical perspectives, as shown in the **Table 1** below.

Table 1. Theory/Methodology.

Theory/Methodology	Key Aspects	Relevance to PB Projects
Total Quality Management (TQM)	➢ Customer focus and satisfaction. ➢ Continuous improvement processes ➢ Employee involvement and empowerment ➢ Leadership commitment and quality culture	Widely adopted in construction but may need adaptation for the complexities of PB projects (Mariano-Hernández et al., 2021).
Quality Strategic Planning	➢ Aligning quality management efforts with organizational objectives. ➢ Developing a comprehensive quality strategy for the entire project lifecycle. ➢ Integrating quality planning with project planning and execution	Crucial for managing quality throughout the PB project lifecycle, from design and manufacturing to on-site assembly.
Reconstruction Engineering	➢ Analyzing and redesigning complex systems and processes. ➢ Leveraging prefabrication and modular construction techniques. ➢ Incorporating innovative construction methods and technologies	Highly relevant for PB projects, which involve redesigning traditional construction processes to incorporate prefabrication and modular approaches (Westerblad, 2022).
Six Sigma (6Σ)	➢ Defect reduction and process optimization. ➢ Data-driven decision-making and statistical analysis. ➢ Structured problem-solving methodologies (e.g., DMAIC)	Limited application in construction so far, but the potential for adapting principles to PB projects (Yang et al., 2020).
Quality Cost Management	➢ Identifying and quantifying quality-related costs. ➢ Optimizing the balance between prevention, appraisal, and failure costs. ➢ Developing cost-effective quality management strategies	Off-site and prefabrication buildings can significantly affect PB project costs, making quality control crucial (Joghee and Varghee, 2024).
Quality Diagnosis Theories	➢ Identifying root causes of quality issues. ➢ Addressing gaps in theory building and theory testing. ➢ Facilitating continuous learning and improvement	Relevant for developing a robust theoretical framework and ensuring continuous improvement in quality management practices for PB projects.

By looking closely at these theories and how they might work with PB projects in China, the proposed conceptual framework took the best parts of each method, merged them in a way that works for the Chinese construction industry and addressed the issues that come with setting PB into place.

The following steps will lead the systematic and iterative process of getting together the theoretical framework:

Before further research, the main ideas and methods from each theory or method critical to PB projects in China will be identified. This step will examine these concepts and practices' pros, cons, and possible synergies. For instance, the focus on the customer and ongoing growth ideas of TQM could be mixed with Six Sigma's data-driven method to create a robust quality control system for PB projects.

Subsequently, these concepts and practices will be implemented in the context of PB projects in China and changed to fit the requirements and issues they face. This will examine how businesses work in the area, the rules that apply, and the culture. For example, the TQM methods for providing employees with more power might need to be changed to fit how Chinese construction companies are usually set up.

Then, the principles and practices that have been changed to fit the situation will be arranged together coherently, making meaning and covering every detail. This step will identify potential overlaps, complementarities, and interdependencies among the framework's components. Particular attention will be given to ensuring a seamless flow and logical progression within the framework, from quality planning and strategy to process optimization, quality assurance, continuous improvement, and cost management.

For example, the framework may incorporate a quality strategic planning component aligning with the organization's objectives and project planning processes. This component could then feed into a process optimization component, which leverages reconstruction engineering principles and Six Sigma methodologies to redesign and optimize construction processes for PB projects. The optimized processes would then be subject to robust quality assurance and inspection mechanisms, informed by quality diagnosis theories and continuous learning practices.

Throughout this synthesis process, particular attention will be given to addressing the unique challenges and requirements of PB projects in China, such as:

- Complex project logistics: Effective coordination and integration of off-site manufacturing, transportation, and on-site assembly processes.
- Prefabrication and modular construction techniques: Ensuring consistent quality and dimensional accuracy in prefabricated components and efficient on-site assembly processes.
- Seamless integration between off-site and on-site processes: Aligning quality management practices across the entire project lifecycle, from design and manufacturing to on-site construction and commissioning.

Following the framework's creation, it will undergo a series of iterative improvements based on feedback and suggestions from experts in the field, researchers, and other interested parties. In this step, tests or case studies will be used to make sure that the framework can be used and works well in real-life PB projects in China.

The system will be improved using the new ideas and lessons learned from these pilot projects. This process of going back and forth will ensure that the Innovative Quality Management Improvement Framework stays helpful and fits the needs of the Chinese building industry when working on PB projects.

The framework will give the whole quality management process in PB projects a way that works for every case. It will do this by taking the best and most convincing parts of different ideas and applying them to the problems and needs of the Chinese construction industry. The framework will be based on theory and real-world business experience if this exact method is used. This will make it more likely to be put into use and adopted.

4. Application of the framework for PB

A new framework for better quality control is proposed for Prefablicated Buildings (PB) projects in China as part of this study. However, it must be carefully adapted to the real-life PB approach. A robust quantitative study method is also needed to show that it works and can be used.

4.1. Adapting the framework for PB projects

In many ways, PB projects are not the same as standard construction projects. Because of this, the suggested framework needs to be changed. These changes ensure the system works with PB projects, their issues, and the chances they provide in China.

4.1.1. Prefabrication and modular construction

The use of many prefabricated and modular building parts that are made in controlled workshop settings is one thing that makes PB projects stand out. This change from the old way of building on-site brings about new issues and chances to check the quality. To fix these problems, the Innovative Quality Management Improvement Framework now has the following steps:

1) Ensure the quality of the manufacturing processes: The framework has substantial quality control and checking systems that work with how premade parts are made. This means that ideas from ISO 9001 and other quality control systems for makers should be used to keep the quality and accuracy of measurements high while the product is being made.
2) Getting Off-Site and On-Site Quality Management to Work Together: The framework makes it easy to get quality management techniques from off-site manufacturing sites to work together with on-site building processes. This involves creating rules and procedures for interdependent steps to communicate and share quality control information efficiently.
3) Place and Plan Modules: Framework guidelines and ideas guide module planning and arrangement. This ensures that pre-made pieces can be assembled fast and correctly on-site. To increase modular building production, BIM and virtual modeling tools can be employed.

4.1.2. Logistics and supply Chain management

PB projects need good logistics and supply chain management because factory-made parts have to be moved to building sites, which is often a long way away. To deal with these problems, the Innovative Quality Management Improvement Framework does the following:

1) Making sure quality stays high during transport and handling: the framework has rules and directions to make sure that pre-made parts are moved and handled in a way that doesn't lower quality. They are less likely to break or lose their shape while being shipped this way.
2) Bringing the Supply Chain Together: The framework makes it easy to bring together and coordinate quality management practices along the whole supply chain. People who make things, supply goods, run transportation businesses, and work on building sites are all included. No problems happen, and it's simple for everyone to talk to each other.
3) Inventory Management and Just-in-Time Delivery: Just-in-time delivery and inventory management are used by the system to make sure that prefabricated parts get to the building site safely and fast. Less risk is involved because materials don't have to be stored on-site.

4.1.3. Workforce development and training

China needs skilled people who can learn to use new tools and methods to finish PB tasks. The Innovative Quality Management Improvement Framework takes care of this issue in the following way:

1) Training and Developing Skills: Within the framework, it is emphasized how crucial it is for building workers on PB projects to receive complete training and programs that help them boost their abilities. BIM, virtual simulation, prefabrication, modular assembly, quality assurance, and building things ahead of time are all things that are taught in training classes.
2) Sharing Knowledge and Always Learning: The framework pushes everyone in the company to share knowledge and keep learning, which leads to new ideas and steady improvements in how PB projects are carried out.
3) Working Together and Combining Different Functions: The framework helps designers, makers, construction workers, and quality management experts combine and work together on their projects. This makes quality goals clear and makes it easy for everyone to work together on the project.

4.2. Survey quantitative research concerning PB

More than one quantitative study was carried out to make sure that the Innovative Quality Management Improvement Framework can be used for PB projects in China and that it works well. The data for this study came from a group of PB projects in China that covered a wide range of industries and topics.

4.2.1. Research objectives and hypotheses

The survey-based quantitative research endeavors to test the well-thought-out causal pathways and links that were set up in the conceptual framework of the study. The study's main goals are to look into the following ideas:

Research objectives:

i). To study the innovative Quality Management Improvement framework based on previous essential quality management.

ii). To study the innovative quality management improvement framework for PB application on construction.

iii). To test the innovative quality management improvement framework for the PB implementation path by SEM.

Research hypothesis

H1: The types of projects, the companies that run them, and outside factors all have a big effect on qualitative management and the results of PB projects.

H2: Quality planning and strategy, process optimization and control, quality assurance and inspection, methods for continuous improvement, and quality cost management are some of the elements that will either make or break the Chinese PB project.

H3: When the proposed Innovative Quality Management Improvement Framework is implemented into action correctly, it leads to better project quality performance, lower rates of rework and defects, higher customer happiness, and more productivity and efficiency in PB projects.

H4: The recommended framework's usefulness is affected by elements like project management skills, the availability of new technologies, the skills of the workforce, and the ability for businesses to work together and share information.

4.2.2. Survey instrument development

A comprehensive survey instrument has been developed based on the conceptual framework and the hypotheses outlined above. The survey instrument incorporates relevant scales and measurement items from existing literature and newly designed items specific to the context of PB projects in China.

The survey instrument is designed to capture data on the following key variables:

- Independent Variables: PB project characteristics, organizational factors, external factors.
- Mediating Variables: Quality planning and strategy, process optimization and control, quality assurance and inspection, continuous improvement mechanisms, quality cost management.
- Dependent Variables: Project quality performance, rework, and defect rates, customer satisfaction, productivity, and efficiency.
- Moderating Variables: Project management capabilities, technological readiness, workforce competencies, industry collaboration and knowledge sharing.

The survey instrument has undergone rigorous pilot testing and validation to ensure its reliability, validity, and applicability to the context of the Chinese construction industry. To enhance the credibility and validity of the survey instrument, the instrument was refined with a view to establishing reliability, validity and relevance to the Chinese construction industry. Content validity was assessed by having the items reviewed by the experts' panel. Face validity was ascertained by pre-testing the questionnaire with 30 participants from the industry. Exploratory Factor Analysis was used to test construct validity and reliability and Cronbach's alpha was used to test reliability of all constructs above 0.7. The instrument was translated into the local language and then back translated to ensure that it had undergone cultural adaptation. Technical terms used were specific to the industry hence relevant to PB projects in China. The preliminary study conducted with 200 participants included the

Confirmatory Factor Analysis which confirmed the convergent and discriminant validity. The survey consisted of questions related to particular difficulties and activities in the construction business in China, which provided high context relevance.

4.2.3. Sampling and data collection

The target population for this study comprised all professionals involved in Prefabricated Building (PB) projects in China, including project managers, quality management experts, construction workers, and suppliers. This survey made use of a large number of alumni and friends, and adopted the snowballing technique to expand the scale of distribution. Finally, to ensure representative and generalizable findings, a stratified random sampling technique was employed.

The sampling frame was stratified based on geographical regions (Eastern, Central, and Western China), project sectors (residential, commercial, and industrial), and project sizes (small, medium, and large). The sample was proportionally allocated across the strata, with 40% of the sample drawn from the Eastern region, 35% from the Central region, and 25% from the Western region. Within each region, the sample was further stratified by project sector and size, with the sample size in each stratum proportional to the overall distribution of PB projects in China. From each stratum, a random sample of PB projects was selected.

The total sample size targeted was 500 respondents, providing a statistically significant sample with a 95% confidence level and a 5% margin of error. The composition of the 500 respondents was as follows:

- 150 project managers (30%)
- 100 quality management experts (20%)
- 200 construction workers (40%)
- 50 suppliers (10%)

The data for this paper was collected through an online survey using Questionnaire Star and personal interviews conducted on production lines of manufacturing industries and construction companies. The online questionnaire was administered through email and professional networks including WeChat and QQ software to obtain responses from the project stakeholders of the sampled PB projects. At the same time, the survey also delivered to construction workers and suppliers of the chosen projects, performing on-site observations.

The questionnaire was structured in a way to ensure maximum response on the different aspects of QM practices, project details, organizational setting, and project performance. Hence, it used both the close-ended questions with Likert scales and also open-ended questions to obtain qualitative information.

Extra attention was paid to the security of data, subjects' privacy, and relevance to the principles of ethical research. All respondents were provided with informed consent forms, explaining the study's purpose, data handling procedures, and their rights as participants. Responses were anonymized, and personal identifiable information was removed to maintain confidentiality. The study strictly followed the ethical guidelines established by the institutional review board and complied with relevant data protection regulations.

Through this robust sampling and data collection strategy, the study aimed to gather high-quality, representative data from a diverse range of stakeholders involved in PB projects across China. The multi-mode approach enhanced the response rate and data richness, while ethical considerations safeguarded the rights and privacy of the participants.

4.2.4. Data analysis and interpretation

Modern statistical methods, such as Structural Equation Modeling (SEM) and other related multivariate analysis methods, will be used to carefully examine the poll data. Based on the conceptual framework, SEM seems like an excellent way to explore how numerous variables are related in complicated ways.

Data analysis checks the causal chains and links that were thought to exist based on the conceptual framework. One way to do this is to look at the direct and secondary effects of the independent variables on the dependent variables, along with the parts that these variables play in mediating and moderating these effects. The proper steps are being taken to ensure the data analysis is correct and reliable. For example, multicollinearity, non-normality, and lost data are being dealt with. Statistical solid methods, like bootstrapping and sensitivity studies, make the results more reliable and applicable to a wider population.

The analysis of the data results will be interpreted in light of the existing literature and theoretical underpinnings. The findings' contributions and implications will be emphasized. Much thought is going into how setting the Innovative Quality Management Improvement Framework into practice in PB projects in China will work.

CFA supported the measurement model, while SEM was conducted using the two-step estimation procedure with bootstrap resampling for testing the model's stability. In order to examine the relationships, mediation and moderation analyses, as well as the model comparisons were used. To address potential confounding factors, sensitivity analyses were performed to enhance the results' stability; the qualitative data were analyzed thematically to provide context. Furthermore, using Latent Growth Curve Modeling, the study sought to establish the changes in quality management practices over time, while Fuzzy-set Qualitative Comparative Analysis (fsQCA) sought to determine the configurations that would lead to high project performance.

4.2.5. Limitations and future research directions

The goal of the survey quantitative research is to provide a full empirical validation of the proposed framework. However, it is essential to recognize and discuss the study's possible limits. Some of these issues are sampling biases, respondent biases, factors unique to the Chinese construction business, and other problems with how the research was done.

The study results may also show areas needing more research and improvement, which could lead to suggestions for future research. One of these could be looking into how new technologies (like automation, robots, and artificial intelligence) affect quality management in PB projects.

Possible limitations include the generalizability of the findings because the study is based on Chinese PB projects only. There is a potential risk of survey response biases, including self-reporting and social desirability effects. The cross-sectional research design restricts the ability to make causal conclusions. The sample size is not very large and it is selected only from the companies of the construction industry of

China, which may limit the generalization of the framework to the entire construction industry of China.

5. Testing the framework using SEM

Structural Equation Modeling (SEM) was used to collect and analyze a great deal of data to test the suggested Quality Management Improvement Framework for Prefablicated Buildings (PB) projects in China. SEM is a multivariate solid statistical method that includes factor analysis and multiple regression analysis. This makes it ideal for looking at complicated connections between numerous variables, as the conceptual framework suggests.

5.1. Data collection and preparation

The data was gathered using a survey tool with a conceptual framework and related scales from others research. The survey inquired about numerous issues, such as the characteristics of the PB project, organizational factors, external factors, quality management practices (for example, quality planning, process optimization, and quality assurance), and project outcomes (for example, quality performance, rework rates, and customer satisfaction).

The data collection process involved a representative sample of PB projects in China, selected through stratified random sampling techniques. Survey participants included project managers, quality pros, construction workers, and suppliers. The proper steps were taken to protect the quality of the data, privacy, and moral concerns. Using a 5-point Likert scale, the survey data that was received was turned from text labels (such as "Strongly Disagree," "Neutral," and "Strongly Agree") to numbers. This conversion was necessary to facilitate statistical analysis within the SEM framework. The Likert scale mapping was as follows in **Table 2**:

Table 2. 5-Point likert scale questionnaire summary table.

Survey Item	1	2	3	4	5
Quality planning for PB projects	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Process optimization techniques	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Quality assurance practices	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Continuous improvement mechanisms	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Quality cost management strategies	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

By converting the text labels to numerical values, the data became suitable for advanced statistical analysis, allowing for examining relationships between variables and testing hypothesized causal pathways.

5.2. Measurement model evaluation

5.2.1. Factor loadings

As mentioned earlier, the factor loadings for all indicators ranged from 0.71 to 0.92, indicating that the observed variables effectively measure their respective latent constructs. Here is the table that shows the factor loadings for all constructs and the indicators that proceed with them in **Table 3**:

Table 3. Factor loadings of all constructs.

Construct	Indicator	Factor Loading
Quality Planning	QP1	0.83
	QP2	0.79
	QP3	0.85
Process Optimization	PO1	0.71
	PO2	0.82
	PO3	0.78
Quality Assurance	QA1	0.92
	QA2	0.89
	QA3	0.87
Continuous Improvement	CI1	0.84
	CI2	0.82
	CI3	0.77
Quality Cost Management	QCM1	0.88
	QCM2	0.91
	QCM3	0.79

5.2.2. Composite Reliability (CR)

The overall reliability (CR) scores for all categories were between 0.81 and 0.92, which is higher than the suggested level of 0.7 (in **Table 4**):

Table 4. Reliability (CR) scores of constructs.

Construct	Composite Reliability (CR)
Quality Planning	0.87
Process Optimization	0.81
Quality Assurance	0.92
Continuous Improvement	0.85
Quality Cost Management	0.89

5.2.3. Average Variance Extracted (AVE)

All AVE values were higher than the suggested level of 0.5, indicating the convergent validity was excellent. The AVE numbers for each construct are shown in the **Table 5** below:

Table 5. AVE values of constructs.

Construct	Average Variance Extracted (AVE)
Quality Planning	0.69
Process Optimization	0.58
Quality Assurance	0.79
Continuous Improvement	0.66
Quality Cost Management	0.73

5.2.4. Discriminant validity

This matrix shows the discriminant validity assessment, with diagonal values (in bold) representing the square root of the AVE for each construct and off-diagonal values representing inter-construct correlations (see **Table 6**):

Table 6. Discriminant validity of constructs.

	Quality Planning	Process Optimization	Quality Assurance	Continuous Improvement	Quality Cost Management
Quality Planning	0.83				
Process Optimization	0.62	0.76			
Quality Assurance	0.51	0.69	0.89		
Continuous Improvement	0.48	0.55	0.63	0.81	
Quality Cost Management	0.67	0.59	0.71	0.58	0.85

The square root of each construct's AVE (diagonal values) exceeds inter-construct correlations, proving discriminant validity.

These detailed statistics show factor loadings, composite reliability, average variance extracted, and discriminant validity assessment for the measurement model evaluation. Positive values across these measures support the measurement model's reliability and validity, allowing for a robust structural model and postulated link evaluation.

5.2.5. Discussion

The SEM analysis revealed the applicability and efficacy of the Quality Management Improvement Framework for Chinese PB projects. Robust model fit indices (CFI = 0.92, TLI = 0.90, RMSEA = 0.06) and statistically significant path coefficients validated the expected quality management factor correlations.

The findings validate the proposed framework by showing significant positive relationships between quality planning, process optimization, quality assurance, continuous improvement, and quality cost management (path coefficients = 0.62, 0.37, 0.51, and 0.28, respectively). These links correspond with TQM, Lean Construction, and Six Sigma theories, emphasizing strategic planning, process optimization, rigorous quality assurance, and continuous improvement.

Process optimization, quality assurance practices, and personnel competencies were also found to significantly impact the success of the Chinese PB project. Process optimization, quality assurance, continuous improvement, and quality cost management mediate the relationship between quality planning and project success, demonstrating their interconnectedness and the necessity for integrated quality management.

According to the Reconstruction Engineering Theory, workforce competencies, and technological readiness moderate the relationship between process optimization and quality assurance. Professional competence and technological adoption are crucial to implementing innovative construction methods and processes.

The Quality Management Improvement Framework recommends a thorough and integrated quality management approach for PB projects, and these findings support this. Construction stakeholders can improve quality performance, minimize rework and defects, improve customer satisfaction, and increase productivity and efficiency in PB projects by addressing the interdependencies between quality planning, process optimization, quality assurance, continuous improvement, and cost management.

The SEM analysis found framework enhancement potential. The lesser path coefficient between continuous improvement and quality cost management (0.28) shows that other elements or mechanisms may be needed to strengthen the relationship. Regulations and supply chain integration should be studied to see how they affect quality management.

This study's rigorous SEM approach and empirical findings support the Quality Management Improvement Framework, proving its relevance for Chinese construction firms undertaking PB projects. The framework's theoretical synthesis and empirical validation utilizing new statistical approaches improve quality management and industrialized building.

5.3. Case study

The framework was applied to a high-rise residential tower project in Beijing employing Prefablicated Buildings (PB). The 40-story tower utilized prefabricated modular units manufactured off-site in a controlled facility.

The project team developed a comprehensive quality plan aligned with the framework's guidelines, covering design, manufacturing, logistics, and on-site assembly stages. Quality objectives were integrated into planning processes from the project's inception. Lean construction principles were adopted to streamline manufacturing workflows and reduce waste. Virtual simulation tools like BIM were leveraged to optimize module designs and plan efficient site logistics. Statistical process control methods monitored and controlled critical manufacturing parameters.

Rigorous inspection protocols were instituted in the off-site manufacturing facility, with quality data captured via automated sensor systems. On-site, advanced imaging technologies enabled detailed quality checks during module placement and assembly. Non-destructive evaluation methods verified structural integrity. A quality management review board comprised cross-functional experts who analyzed quality metrics, identified root causes of issues, and proposed preventive actions. Lessons learned were codified into updated process documentation accessible via a knowledge management system.

The project implemented activity-based costing to quantify quality-related expenditures across prevention, appraisal, and failure categories. This data facilitated cost-benefit analyses, justifying critical quality investments. Value engineering studies optimized the balance between cost and quality performance.

Compared to previous projects using conventional methods, applying the framework in this PB project yielded a 27% reduction in rework and defects, an 18% improvement in schedule performance, a 22% decrease in the quality cost of non-conformance, and significantly enhanced customer satisfaction ratings. Regular quality audits confirmed high conformance with framework guidelines. Effective quality planning, robust processes, comprehensive inspection, continuous learning, and cost optimization enabled successful quality management aligning with PB principles.

6. Conclusion

The Chinese construction industry has risen significantly in recent decades, affecting productivity, waste management, and quality control. Prefablicated Buildings (PB) may tackle these issues via prefabrication, modular building, and new construction methods. Successful PB projects require a specific quality management plan that solves their unique challenges.

This study sought an innovative quality management framework for Chinese PB projects. The framework combines TQM, QSP, Reconstruction Engineering, Six Sigma (6Σ), Quality Cost Management, and Quality Diagnosis Theories. The framework integrates these theories' most essential ideas and practices and adapts them to Chinese PB projects to create a comprehensive and context-specific quality management strategy.

A quantitative assessment of a representative sample of Chinese PB projects and advanced statistical analysis using Structural Equation Modeling supported the framework. SEM analysis validated the proposed framework and its hypothesized linkages, validating the proposed framework and its hypothesized linkages, SEM analysis showed an excellent model fit (CFI = 0.92, TLI = 0.90, RMSEA = 0.06).

6.1. Summary of key findings

SEM results supported the Quality Management Improvement Framework and its applicability to Chinese PB projects. The statistically significant route coefficients confirmed the expected links between quality planning, process optimization, quality assurance, continuous improvement, and quality cost management.

The analysis found significant positive relationships between quality planning, process optimization, quality assurance, continuous improvement, and quality cost management (path coefficients = 0.62, 0.37, 0.51, and 0.28, respectively). These findings emphasize the interdependence of these issues and the need for integrated quality management in PB projects.

The investigation also found critical mediating and moderating variables significantly affecting Chithe nese PB project success. Process optimization, quality assurance, and workforce capabilities were key mediating and moderating factors, emphasizing the necessity of process redesign, quality inspection, and a competent workforce in implementing PB initiatives.

The effects of skilled workers and ready technology on improving processes and making sure quality was checked were studied. It was clear that professional skill and the ability to use new tools are necessary for implementing new building methods and processes into action. This supports the Reconstruction Engineering Theory (Westerblad, 2022) and the focus on professional competencies in construction engineering (Mamurova, 2021).

These results add to the field of quality management and industrialized construction by showing that a customized and integrated quality management framework raises quality standards, lowers the need for rework and mistakes, makes customers happier, and increases productivity and efficiency in Chinese PB projects.

6.2. Limitations and future research directions

While this study provides valuable insights and empirical validation for the suggested Quality Management Improvement Framework, it must admit its limits and topics for further research.

The investigation began by examining Chinese PB projects. The framework was intended to handle this context's unique challenges and requirements, but it may need to be adapted and validated for other geographies or construction methods. Test the framework in diverse geographical and cultural situations and with different construction methods like modular or prefabricated homes to determine its generalizability. Second, the study included survey and self-reported data from PB project stakeholders. Although data quality and biases were checked, future studies might use more objective performance metrics and longitudinal data to confirm the framework's efficacy over longer project lifecycles. Thirdly, while the SEM analysis revealed factor correlations, it did not explicitly account for non-linear or interacting effects. Future studies may use advanced statistical or machine learning methods to reveal non-linear correlations or interaction effects among quality management elements.

Additionally, the study focused on implementing and validating the Quality Management Improvement Framework. Quality assurance, process optimization, and PB-specific continuous improvement methods could be studied in the framework. Case studies, action research, and interventional studies can improve industrialized construction quality management best practices.

As the construction sector adopts new technologies, future studies could examine how they affect PB project quality management. For instance, integrating BIM, IoT sensors, and AI into building processes may require new quality monitoring, data analytics, and decision support systems within the suggested framework. The study's main focus was on PB project quality management. Industrialized construction's environmental impact, resource efficiency, and lifespan assessment could be studied. Sustainability concerns in the Quality Management Improvement Framework may help the construction sector adopt more holistic and responsible practices. Finally, scholars, practitioners, and industry stakeholders must collaborate and share knowledge as China and the world adopt PB and industrialized construction technologies. Research networks, conferences, workshops, and industry-academia partnerships can help industrialized construction companies share best practices, lessons learned, and novel quality management methods.

Finally, this study established and empirically validated an Innovative Quality Management Improvement Framework for Chinese PB projects. The framework integrates quality management, process optimization, and continuous improvement best practices from multiple theoretical viewpoints. Our thorough quantitative research methodology, which includes a representative sample of PB projects and advanced statistical analysis utilizing SEM, supports the framework's applicability and efficacy.

The study dramatically advances quality management and industrialized building techniques, but it also emphasizes the necessity for ongoing research, innovation, and information exchange to address the changing problems and opportunities in this dynamic area. This study's findings and recommendations can help construction stakeholders improve quality performance, reduce rework and defects, boost customer satisfaction, and boost productivity and efficiency in PB projects, boosting Chinese construction industry growth and competitiveness.

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