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How Do Developers Influence the Transaction Costs of China's Prefabricated Housing Development Process? An Investigation through the Bayesian Belief Network Approach

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Abstract: The implementation of prefabricated housing (PH) has become prevalent in China recently due to its advantages in enhancing production and energy-saving efficiency within the construction system. However, stakeholders may not always fully realize the benefits of adopting PH due to the emergence of transaction costs (TCs) in the development process of such projects. This study investigated the strategies for developers to make rational choices for minimizing the TCs of the PH project considering their own attributes and external constraints. A Bayesian Belief Network model was applied as the analytical method, based on surveys conducted in China. A single sensitivity analysis indicated that developers influence the TCs of PH through the following three most impactful factors: prefabrication rate, PH experience, and contract payment method. Integrated strategies are recommended for developers in various situations based on a multiple sensitivity analysis. Developers facing challenges due to high prefabrication rates are advised to reduce the risks by procuring highly qualified general contractors and adopting unit-price contracts. For developers with limited PH experience, adopting the Engineering–Procurement–Construction procurement method is the most efficient way to reduce their TCs in the context of China's PH market. This study contributes to the current body of knowledge concerning the effect of traders' attributes and choices on TCs, expanding the application of TC theory and fulfilling the study on the determinants of TCs in construction management.

Keywords: prefabricated housing; transaction costs; production efficiency; Bayesian Belief Network

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1. Introduction

Nowadays, sustainable development has become a promising direction for global construction practitioners. China has made significant efforts to incorporate sustainability into its enormous construction business. Adopting prefabrication in the housing sector is one of the major practices to achieve sustainability in the construction system while ensuring higher quality, innovative products, and established management processes [1]. Typically, prefabricated buildings are developed by adopting modular and lean precast components, evolving the traditional construction mode from the cast-in-place method to on-site assembly [2]. The Chinese authority has put much effort into advocating for PH since 2016, when it announced the aim that at least 30% of new construction should be prefabricated by 2026 [3]. Recently, the significance of prefabricated housing has again been underlined for the high-quality development of China's construction industry in the "fourteenth-five-year plan" [4]. However, the Chinese construction industry's transformation from conventional production to prefabrication is facing significant challenges. The new approach risks a mismatch between the traditional management practices and the newly established prefabrication production process, thus causing considerable transaction costs (TCs) in the forms of additional capital, time, and labor [1,5].

TCs in PH are defined as costs beyond traditional production expenses, encompassing activities such as information searching, negotiation, contracting, monitoring, and enforcement, which manifest as risks, time, labor efforts, and more [6]. These TCs can result in disputes, delays, and limited production efficiency, imposing burdens on stakeholders and hindering their enthusiasm [7]. TCs are commonly recognized in the traditional construction industry and are even more significant in innovative sectors due to their higher proportion of total costs [5]. However, there is currently a lack of understanding and investigation of TCs in the field of PH, while the invisibility of these TCs has made them vital obstacles for PH. In the context of China's PH, stakeholders bear significant TCs in addressing the frictions that arise during the development of PH projects [6]. Therefore, understanding and minimizing TCs in PH necessitate a focus on the perspective of developers, which holds high practical value and importance.

Developers, acting as the primary clients in most private PH projects in China, play a crucial role in defining project characteristics and assembling the project team [8]. Many TCs in the project development process are directly linked to developers' attributes and choices. Of particular significance, the procurement methods chosen by developers determine specific transaction procedures, ultimately impacting the TCs in the projects [9]. Developers' choices regarding payment methods shape contractual relationships in PH project development, leading to varying TCs related to communication and coordination. Furthermore, the selection of capable partners and contractors by developers influences effective communication, mutual trust, and sound relationships throughout the PH project's development [10]. However, developers in China's PH industry face significant challenges when making rational choices to avoid unexpected TCs, given their limited knowledge of TCs and the presence of internal and external constraints within the complex transaction environment. These constraints can stem from policies such as the mandatory requirement in Shanghai that new single PH buildings must have a prefabrication rate of no less than 60% [11]. A developer's experience in PH is typically fixed and is considered a given condition that can be improved over the long term but is unlikely to change significantly within a single project's development process. This lack of knowledge and experience presents challenges for developers in controlling TCs in PH projects. As Winch [12] argues, TCs tend to be higher in situations where the ability to make rational decisions is limited. However, limited research exists on understanding how developers' attributes and choices influence TCs in PH projects, let alone providing rational strategies for minimizing these TCs.

In light of the challenges faced in practice and the existing research gap, this study aims to examine how developers' attributes and choices influence TCs and to offer dynamic strategies for TC reduction in improving the process efficiency of PH project development. To achieve this goal, the following sub-objectives are outlined:

(1) Elucidating the mechanism through which developers influence process efficiency in PH project development from the perspective of TCs.
(2) Identifying the critical attributes and decision-making points of developers that significantly influence their TCs during PH project development.
(3) Exploring optimal strategic combinations of developers' attributes and decisions to minimize TCs across the diverse and challenging scenarios encountered during PH project execution.

The expected findings and insights gleaned from this study on the influence of developers on TCs in Chinese PH projects hold significant relevance and applicability in an international context. First, stakeholders involved in PH projects globally, particularly developers, stand to benefit from the strategies and recommendations outlined herein. By uncovering the intricate relationships between developers' choices and TCs, this study equips developers with practical tools and strategies to analyze, predict, and mitigate TCs in their projects. These insights are pivotal for informed decision-making, maximizing economic efficiency, and ensuring successful PH project outcomes. Second, policymakers seeking to foster a conducive institutional environment for PH development can leverage these findings to inform regulatory frameworks and industry policies. While this study is anchored in the Chinese context, its methodological approach and strategic recommendations are transferable and adaptable to other countries and regions with burgeoning PH industries. As the global construction sector increasingly embraces prefabrication techniques, the lessons learned and strategies proposed in this study have broader implications for optimizing PH project efficiency and promoting sustainable construction practices worldwide.

2. Developers' Transaction Costs in the Prefabricated Housing Development Process

2.1. Role of Developers in Prefabricated Housing

Prefabricated housing (PH) construction has gained significant attention in the global construction industry due to its transformative potential and inherent advantages. The PH development process involves the manufacturing of building components off-site, which are then transported and assembled on-site [13]. This streamlined process offers several merits, such as reduced construction time, enhanced quality control, minimized material waste, and improved sustainability through efficient resource utilization [14]. These advantages align with global initiatives for sustainable development and green building practices, making PH a crucial component of future construction endeavors worldwide. However, despite its promise, challenges persist in achieving optimal process efficiency in PH projects. Issues such as coordination complexities [10], logistical hurdles, regulatory constraints [5], and supply chain disruptions [13] can hinder the process efficiency of PH.

Developers play a pivotal role in the implementation and advancement of PH, often assuming dual roles as sponsors and clients in the Chinese context. At the project level, developers are central to project initiation, execution, and outcomes, encompassing key decisions and stakeholder engagements. While developers indeed play a vital role, it is crucial to note that PH projects have unique characteristics that shape developers' roles differently compared to traditional construction projects. The PH development process comprises stages such as conception, design, manufacturing, construction, and maintenance (Figure 1), each overseen by developers who influence project characteristics such as the scale, location, ownership type, and stakeholder engagement [6,15]. Throughout this entire process, the developers also function as orchestrators of a complex network of stakeholders including designers, contractors, regulatory bodies, and the public [16]. Unlike traditional projects, PH projects require intricate coordination among stakeholders due to the off-site fabrication and on-site assembly nature of prefabricated components [5].

On an industry-wide scale, developers not only shape project characteristics but also drive innovation, sustainability, and efficiency in the PH sector. As pioneers of PH practices in China, developers navigate an evolving landscape marked by technological advancements, regulatory shifts, and dynamic market conditions [17]. These elements significantly influence the subsidy policies, pricing of prefabricated components and units, generalization of manufacturing and assembly techniques, and education of professionals, highlighting developers' critical role in steering the sector's trajectory.

Despite their pivotal role, developers encounter considerable challenges in ensuring efficient PH project execution, bearing a high volume of TCs throughout the PH development process. Their decision-making power and organizational attributes significantly impact subsequent project stages. Challenges such as selecting prefabrication technologies, optimizing supply chains, and ensuring project scalability underscore the need to comprehend developers' influence on TCs. However, in practice, developers of PH projects may not always be able to make rational choices in the complex and competitive market environment [10]. Bounded rationality acknowledges that the decisions of rational people are bounded by the information available, the time, their cognition, and their ability to foresee all contingencies [18]. Constrained by their internal or external environment, the irrational decisions of developers, in many cases, result in higher TCs, and thus poor production efficiency in PH projects.

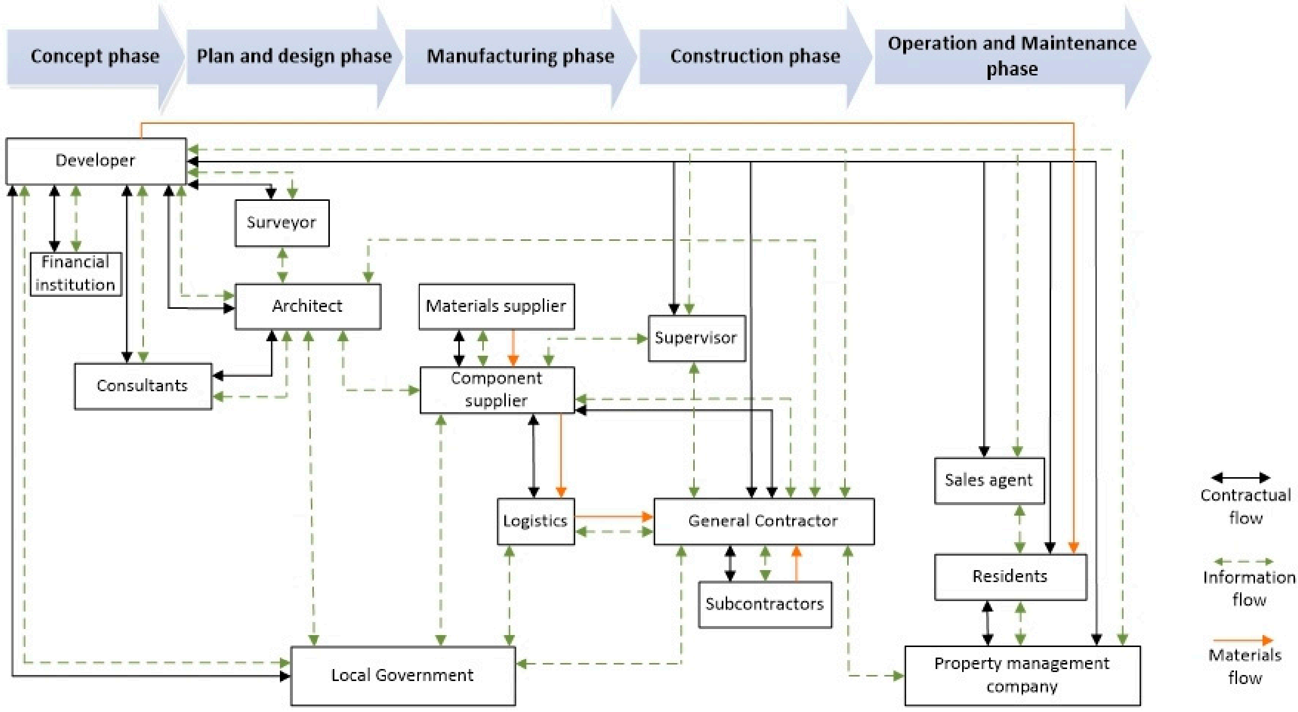

Figure 1. The development process of a typical PH project in China [6].

2.2. Transaction Costs in PH from the Developers' Perspective

Transactional cost theory, introduced by Coase in 1937, has transcended industries and geographical boundaries, finding application in various sectors worldwide, including construction. It has proven instrumental in addressing efficiency challenges not only in project management but also in institutional governance on a global scale. TCs, defined as the costs associated with the exchange of goods or services, are pervasive across economic organizations globally [19]. These costs are intricately tied to the bounded rationality of individuals and the uncertainties inherent in transactional activities, elements that hold true regardless of the region or industry. TCs in the construction field are generally understood as all expenditures excluding production costs, which are expenses incurred for project management and control [20]. The adverse effects of TCs extend beyond individual construction projects, significantly hindering the overall growth of the building market economy on a global level [5]. Therefore, prioritizing efforts to identify and mitigate redundant TCs becomes imperative not just for specific projects but also for enhancing the operational efficiency of the entire building development process worldwide.

PH has introduced a new transaction mode in China's construction market, which poses significant challenges for developers and exposes them to a wider array and higher volume of TCs. TCs in construction projects encompass various costs associated with risks, time delays, information searching, negotiation, contracting, organizational set-up, monitoring, enforcement, and more [6]. To specifically examine the TCs faced by developers in the PH development process, this study adopts a transaction cost economics framework, aiming to understand the nature of TCs based on their categorization. Previous studies, such as those by Mundaca T, Mansoz [21], and Kiss [22], have categorized TCs in energy efficiency projects and passive house renovations, respectively. Building upon a comprehensive literature review regarding normal TCs in construction and friction in the PH process, this study defines the TCs in PH projects into three distinct categories: due diligence, negotiation, and monitoring and enforcement, as outlined in Table 1.

Table 1. Sources of TCs in PH projects from the perspective of developers.

TC Category	Code	Sources of TCs	Reference
Costs of Due Diligence	CDD_1	Preparation of a project brief.	[21]
	CDD_2	Evaluating the project's feasibility.	[22]
	CDD_3	Identifying experienced PH partners.	[23]
	CDD_4	Consulting agencies about prefabrication in the conceptual and design phase.	[18]
	CDD_5	Learning new technologies and digesting fresh information.	[6]
	CDD_6	Making decisions regarding prefabrication technologies, the prefabrication rate, etc.	[17]
	CDD_7	Preparing and participating in the land bidding.	[24]
	CDD_8	Surveying the land.	[24]
	CDD_9	Procuring the general contractor.	[6]
	CDD_{10}	Drafting, negotiating, and signing the sale contracts.	
Costs of Negotiation	CN_1	Obtaining approvals and permits.	[25]
	CN_2	Preparing and negotiating for the financing.	[22]
	CN_3	Searching for, digesting, and communicating information regarding the architectural design.	[23]
	CN_4	Collecting information, communicating, and coordinating to complete the detailed design for PH.	[26]
	CN_5	Setting up the project organization.	[27]
	CN_6	Communicating, negotiating, managing time delays, and reworking from the design changes.	[28]
	CN_7	Taxation paid by the developer.	[10]
Costs of Monitoring and Enforcement	CME_1	Disputing costs.	[29]
	CME_2	Communicating, monitoring, and performing quality inspections for the assembly.	[6]
	CME_3	Advertising, popularizing, and promoting the PH projects.	[6]

Costs of Due Diligence: These include investments in information investigation, including the costs of collecting and assessing the information, throughout the whole process of PH projects. TCs can arise from various procurement activities, such as conducting preliminary design work, translating the client's needs, providing training, and conducting site visits [30]. Significant sources of due diligence TCs include efforts related to project brief development, feasibility studies, and partner search activities [23]. Additionally, TCs associated with information analysis and exchange during the contract signing process may be significantly higher due to the application of new technologies. For developers in the prefabricated housing sector, the additional work of searching for and analyzing information is also recognized as a burden in the decision-making process [17].

Costs of Negotiation: These include the efforts of obtaining permits, negotiating the design planning, and arranging finances. The architectural design of PH projects requires more effort to search for, learn, and communicate information compared with its conventional counterpart [23]. Notably, a detailed design in a PH project would typically consume the extra efforts of professionals due to the added work of the assembly [26]. Moreover, the design change is among the most severe hindrances in PH projects [28], generating additional communication, negotiation, time delays, and reworking.

Costs of Monitoring and Enforcement: These include costs for making the monitoring plan, continually supervising the production performance, and enforcing the required contracts. To ensure the quality of unfamiliar assembly works, developers usually expend extra costs for quality inspection and construction supervision. Additional time and costs can arise from formulating solutions for disputes [27]. Additionally, as the initial owners of most private PH projects in China, developers also bear TCs related to advertising and selling the PH products [6].

2.3. Developers' Impacts on Shaping the TCs of PH

Stakeholders are vital in shaping the TCs according to Williamson [31], while developers of PH projects are cognized as the core stakeholders that influence the transaction efficiency through their unique attributes and influential choices. In revealing the causes of TCs, new industrial economists believe that TCs are generally determined by the asset specificity, uncertainty, and frequency of the transaction process [32]. Therefore, for understanding the determinants of TCs in the development process of PH projects, developers' attributes and choices on the project level were identified from the existing literature based on three categories: asset specificity, uncertainty, and frequency.

1. Asset specificity

The decisions made by developers regarding the prefabrication rate have a direct impact on the technical complexity of the design and assembly process, thereby influencing the asset specificity of PH projects. In line with TC theory, asset specificity is a fundamental determinant of TCs, and the prefabrication rate serves as an indicator of asset specificity, being closely linked to TCs in PH projects [29]. In the context of China, the prefabrication rate is measured according to the ratio of the prefabricated volume to the total volume of the materials for a building [33]. It is currently the most effective variable to evaluate the prefabrication degree of a PH project in China [34]. This study categorizes the prefabrication rate of PH projects in China into three levels: low (<60%), medium (60–75%), and high (>75%), based on the Chinese Standard for Assessment of Prefabricated Building since 2017. Developers' decisions on prefabrication rates determine the technical complexity of assembly, thus influencing the costs for subsequent activities, such as identifying experienced partners and consulting with agencies; learning techniques; and procuring general contractors [17]. Different prefabrication rate levels can also impact negotiation costs, architectural design costs, detailed design costs, and the rate of design changes [35]. In the evolving Chinese PH market, the target prefabrication rate of a project must initially comply with the requirements of local authorities, which subsequently influences developers' choices regarding the qualifications of general contractors. However, it is important to note that most Chinese contractors lack experience in PH, particularly for projects with high prefabrication rates, resulting in increased production uncertainties and higher TCs. Therefore, from the developers' perspective, when a high prefabrication rate is mandated, engaging a highly qualified general contractor presents a lower risk due to their strong background and capability in procuring resources to address potential technical challenges [36].

Collaboration experience with the same partner is a critical factor influencing TCs as it leverages the partner's knowledge specificity [37]. The skills, knowledge, and experience possessed by specific staff members are transaction-specific 38]. When developers have established a relationship with a group of familiar collaborators, their due diligence costs for identifying partners and procuring contractors can be significantly reduced [17]. Moreover, challenges related to communication, negotiation, and coordination during the detailed design and design changes can be better managed when stakeholders have previous collaborative experience [9].

Developers' specific experience plays a crucial role in reducing TCs, particularly when the knowledge gained from past experience is applied to future projects. Developers' experience from previous PH projects contributes to cost savings in due diligence activities such as project briefing, feasibility studies, decision making, and learning [38]. This experience also facilitates smoother communication and negotiation processes, particularly in securing financing [39]. Additionally, during the design phase, developers with experience in PH projects tend to have a lighter workload in architectural designs and detailed designs compared to those without such experience [40].

2. Uncertainty

The competitiveness of developers plays a significant role in governing the transaction process and influencing TCs, as suggested by TC theory [31]. In China's housing development market, the annually released list of the Top 100 Real Estate Enterprises indicates a firm's competitiveness according to 52 business indices, including profitability, solvency, operation, risk resistance, and sustainable development capacity. The developers' ranking indicates their different resources to guarantee production. Developers ranked in the top positions, such as the top 10 enterprises with revenues exceeding CYN 85 billion (2019), possess greater resources for ensuring production, including accessing new information, procuring partners, and securing financing [41]. Also, their solid capabilities and reputable status enable them to reduce procurement costs by gaining trust when seeking collaborators [17]. Furthermore, the professional background of competitive developers facilitates smoother negotiations with local authorities and financial institutions [42]. Moreover, the existing literature indicates that larger developers put more effort into promoting and advocating for prefabrication, contributing to the overall promotion of the PH industry [43].

The qualification level of the contractor procured by a developer play a crucial role in minimizing and managing uncertainties during the project development process. Considering the trend that the EPC mode is increasingly being advocated as the dominant procurement method for PH projects in China [44], general contractors have become the key stakeholders with whom developers have intensive interactions and transactions. In this context, the qualifications of the general contractors have a significant impact on production efficiency and directly influence TCs in the project development process. Residential contractors in China are classified into four levels (special grade, first grade, second grade, and third grade) based on their assets, key personnel, completed project performance, and technical equipment [45]. Contractors with high qualifications usually present an excellent background for building trust and confidence in cooperation with developers, resulting in different negotiation capabilities. A highly qualified contractor would improve the quality and efficiency of a detailed design because PH requires contractors' opinions to ensure the feasibility of the detailed design [40]. Furthermore, the qualifications of the general contractors directly affect the developers' costs for monitoring and enforcement. Contractors with good contract management practices can reduce monitoring costs and minimize disputes during construction [27].

3. Frequency

The developer's choice of the project procurement method defines the particular procedure of transactions in a construction project, which sets off a chain reaction in the subsequent activities; therefore, it is of vital importance for determining the TCs [9]. The commonly adopted contract procurement methods for PH projects include the traditional Design–Bid–Build (DBB) and Design–Build (DB) methods, and the recently promoted Engineering–Procurement–Construction (EPC) method [6]. Compared with the traditional DBB mode in that the design, manufacturing, and construction are achieved through separate contracts, the increasingly implemented EPC mode represents the developers' decision to choose turnkey contracts that place all design-related, precast component supply, and assembly responsibilities on one general contractor. The TCs of negotiations vary greatly based on the amount of information needing to be processed and codified in different procurement situations [46]. In the DBB procurement method, the detailed design is usually completed before construction because the stages of design and construction are separated. Thus, intensive negotiation and coordination between the architect, component supplier, and contractors are needed during the design phase to ensure technology consistency for a successful assembly. Comparatively, in the integrated delivery modes, such as DB, there are lower TCs for the detailed design but higher TCs for negotiation during construction [47]. Furthermore, for procuring the general contractor, the costs of due diligence depend on the procurement method. Costs for searching and evaluating the candidate contractors are different for DB and DBB projects, depending on whether the supplier of the prefabricated components is integrated into the developers' business model. Furthermore, the payment method often highly corresponds with the project procurement method adopted. Lump-sum and cost-plus-fee payment methods are the dominant contract payment methods, particularly for DB projects [48]. The procurement method determines the purchasing process undertaken to gain the product. The appropriate payment method is the strategy of paying for the product. Naturally, a rational and reasonable match between the project procurement system and the contract payment method is expected to maximize the project's performance in the implementation stage [47].

The contract payment method of PH projects is usually agreed upon between the developer and the general contractor, which defines the transaction frequency and methods in the development process. The commonly adopted contracts in Chinese PH projects fall into four types based on the payment methods, including lump-sum, unit-price, cost-plus-fee, and guaranteed maximum price methods. The varied contract payment methods can lead to the diversity of TCs in a construction project [49]. Compared with a cost-plus-fee contract, a lump-sum contract allocates more uncertainties to the general contractor, thus is more likely to bring about additional costs from contractual disputes. In addition, the payment method determines the developers' costs for monitoring and enforcing the contract. For example, the unit-price arrangement necessitates more monitoring from the developers, and is mainly applied in projects where the volume of work is still an assumption [47]. In addition, when adopting different contracts and considering the different requirements for the contractors, the costs that the developer pays to search for, assess, and procure the general contractor are different.

To summarize the statements above, Table 2 describes developers' attributes and choices that could influence TCs and presents the hypothesized relationships between these developer-related factors and the TCs of PH projects.

Table 2. Hypothesized relationships between developer-related factors and TCs.

Influencing Factor	Related Category of TCs	Related Sources of TCs
Prefabrication Rate	Costs of Due Diligence	CDD_3 CDD_4 CDD_5 CDD_9
	Costs of Negotiation	CN_3 CN_4 CN_6
	Costs of Monitoring and Enforcement	CME_2
Project Procurement Method	Costs of Negotiation	CN_4
	Costs of Due Diligence	CDD_9
Contract Payment Method	Costs of Due Diligence	CDD_9
	Costs of Monitoring and Enforcement	CME_1 CME_2
Collaboration Experience	Costs of Due Diligence	CDD_3 CDD_9
	Costs of Negotiation	CN_4 CN_6
	Costs of Monitoring and Enforcement	CME_1

Table 2. *Cont.*

Influencing Factor	Related Category of TCs	Related Sources of TCs
PH Experience	Costs of Due Diligence	CDD_1 CDD_2 CDD_3 CDD_4 CDD_5 CDD_6 CDD_9
	Costs of Negotiation	CN_2 CN_3 CN_4
Competitiveness of the Developer	Costs of Due Diligence	CDD_3 CDD_5 CDD_9
	Costs of Negotiation	CN_1 CN_2
	Costs of Monitoring and Enforcement	CME_3
Qualification of the General Contractor	Costs of Due Diligence	CDD_9
	Costs of Negotiation	CN_4 CN_6
	Costs of Monitoring and Enforcement	CME_1 CME′

3. Methodology

To explore strategies for the developers to reduce TCs in PH, the approach of the Bayesian Belief Network (BBN) is adopted as the primary analysis approach in this study. For developing a TC-predicting BBN model, a perception-based survey was conducted based on a comprehensive literature study for developing a theoretical framework of TCs, developers' attributes and choices, and the relationships between these two sources of variables. This survey aimed to gather information on developers' attributes and choices, as well as collect data on the perceived scale of the TCs. The BBN model was then developed based on structured relationships between the developer-related factors and the TCs, then trained using the data gathered from the questionnaire survey. A single-contributor sensitivity analysis and a multiple sensitivity analysis were conducted to predict the impact of developer-related factors on TCs and provide strategies for minimizing them. Figure 2 provides an overview of the research design, including the literature study, questionnaire survey, development of the BBN model, and data analysis.

3.1. Questionnaire Survey

In the pursuit of comprehensively gathering data on the magnitude of TCs throughout the PB supply chain and the prevailing state of developers' attributes and choices, a meticulously designed questionnaire was fashioned based on the theoretical framework derived from the literature study. The main purpose of the questionnaire design considered three aspects. The first section focused on the developers' attributes and choices in their most recent participation in a PH project, while it was ensured that the personal and project information of the respondents was kept anonymous. Descriptive statistics for these factors are presented in Table 3. The second section aimed to assess the extent of twenty TCs using a five-point Likert-type scale, ranging from "1" (very low) to "5" (very high). The third section requested participants to rate the strength of the influence between developers' choices and TCs on a scale from "1" (no influence) to "5" (significant influence).

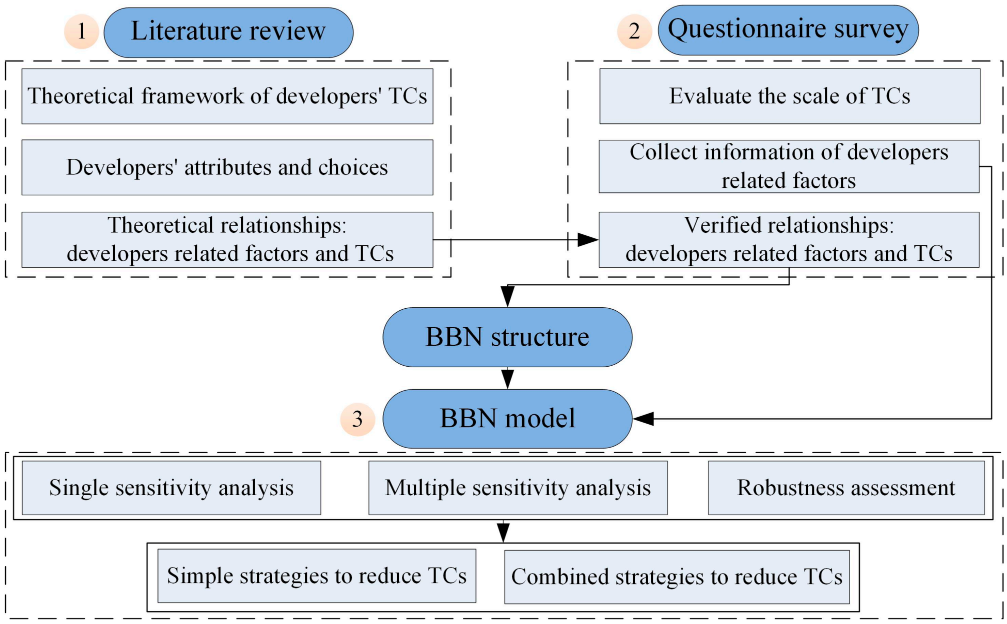

Figure 2. Overview of the research design.

Table 3. Descriptive statistics of the developer-related factors that influence TCs.

	Developers' Attributes and Choices	**States of the Factors**	**Percent %**
F1	Prefabrication Rate	Low Medium High	44.13 44.94 10.93
F2	Project Procurement Method	DBB DB EPC Others	35.63 27.94 17.81 18.62
F3	Contract Payment Method	Lump-sum Unit-price Cost-plus-fee Others	48.99 23.48 17.41 10.12
F4	Collaboration Experience	Yes No	72.90 27.10
F5	PH Experience	Low: <3 Y Medium: 3–10 Y High: >10 Y	43.32 40.89 15.79
F6	Competitiveness of Developer	TOP 10 10–50 50–100 Lower than 100	19.43 20.65 18.62 41.30
F7	Qualification of the General Contractor	Special grade First grade Second grade Third grade	29.96 40.08 17.81 12.15

The data collection process involved administering an online questionnaire survey to gather insights from professionals within the Chinese construction industry. Specifically targeting experts affiliated with the Chinese prefabricated building platform (http://www.precast.com.cn/ (accessed on 17 April 2024)), which operates under the purview of multiple

Chinese Building Industrialization Associations, the survey was designed to tap into the knowledge and experiences of individuals deeply involved in the Chinese PH sector. This platform, with a history spanning over a decade, provides a robust and dependable avenue for engaging with industry professionals. To maintain the integrity and validity of the collected responses, the survey was exclusively directed at individuals currently employed by PH developers. The survey instrument was disseminated via a dedicated professional link (https://www.wjx.cn/ (accessed on 17 April 2024)), resulting in over 1500 visits. Rigorous data cleaning procedures were then employed to meticulously screen for extreme and missing values, culminating in the retention of 589 valid questionnaires. This stringent process was crucial in upholding the quality of the survey data and ensuring the accuracy of the subsequent analyses and findings.

3.2. Bayesian Belief Network Model

Based on the data collected from the questionnaire survey, a BBN model was built to illustrate the relationships among the attributes, decisions, and TCs through probability calculations, in order to further recognize the influential determinants for exploring strategies to reduce the developers' TCs in PH projects. The adoption of the BBN in this study is justified for several compelling reasons. Firstly, the BBN serves as a directed graphical model, offering a flexible framework for capturing and modeling the causal interrelationships among variables. This capability enables the explicit representation of causal links between determinants and outcomes, providing invaluable theoretical insights and quantitative guidance for modeling developer-related factors and TCs. Secondly, the BBN is adept at handling uncertainty and updating predictions based on new information, thereby enhancing management practices, particularly in the context of long-term construction processes [50]. Its successful application in analyzing safe work behaviors and their contributing factors has already demonstrated significant efficiency gains in safety management within construction projects [51]. The BBN not only identifies critical attributes and decisions but also reveals optimal pathways for improving outcomes through probabilistic analyses. This facilitates a comprehensive exploration of strategies to reduce TCs across various scenarios of PH implementation. In essence, the BBN's capacity to elucidate complex causal relationships, conduct probabilistic analyses, and navigate intricate inferences [52] underscores its superiority for complex network analyses and dynamic inference tasks compared to traditional linear analysis methods such as correlation analysis, logit regression analysis, and structural equation modeling.

A standard BBN model consists of two critical parts—qualitative and quantitative [53]. The qualitative part is used to form the relationships among the variables, which can be represented by directed acyclic graphs (DAGs). These graphs construct complex causal relationships, consisting of nodes representing discrete or continuous variables, and link causal relationships between the nodes. The nodes that are designated as the starting ones (and so do not have an inward arrow) are called the parent nodes. The other nodes, which have inward arrows connected to them, are the child nodes. In this study, all of the nodes are represented by discrete variables. The quantitative part of the BBN is the parameter-learning part. The joint conditional probability distributions model the dependence relations among the variables. The complexity of the model increases with the number of variables and their states. There is a conditional probability table (CPT) for each variable, which presents the probabilities of the variable according to the various states of its parent nodes. One of the most significant advantages of using Bayesian Networks is to facilitate flexible inference with partial information. Figure 3 gives an example of a BBN. When the information of other variables $(\cup = \{X_1, X_2, X_3, X_4, X_6\})$ is available, the probability of the variable X_5 can be calculated as follows:

$$\begin{aligned} P(X_5|U) &= \frac{P(X_1)P(X_2)P(X_3)P(X_4|X_1,X_2)P(X_5|X_2,X_3)P(X_6|X_4,X_5)}{\sum_{X_5} P(X_1)P(X_2)P(X_3)P(X_4|X_1,X_2)P(X_5|X_2,X_3)P(X_6|X_4,X_5)} \\ &= \frac{P(X_5|X_2,X_3)P(X_6|X_4,X_5)}{\sum_{X_5} P(X_5|X_2,X_3)P(X_6|X_4,X_5)} \end{aligned} \quad (1)$$

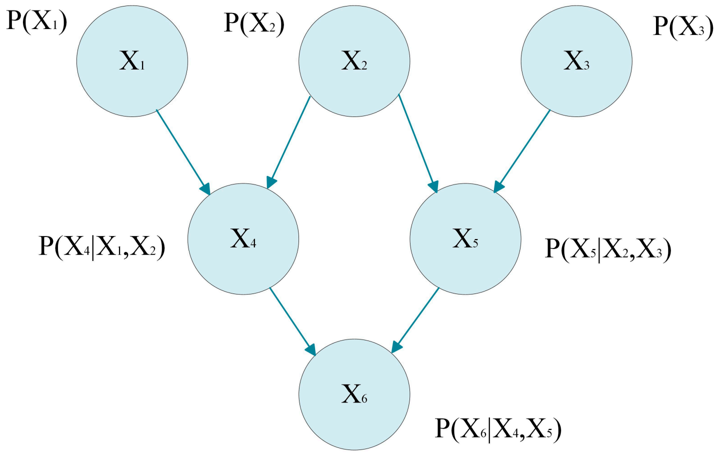

Figure 3. An example of a simple Bayesian Belief Network.

4. Developing the Bayesian Belief Network

The BBN model for TCs requires three main elements: (1) a validated structure that describes the relationships between the nodes (including the relationships between the factors, and the relationships between the factors and the TCs); (2) the states of the factors; and (3) the values of the TCs.

4.1. Structure of the BBN Model

The first step before BBN calculation is to formulate the structure of the causal network. The Bayesian Network for controlling TCs is structured through extensive literature studies and a questionnaire survey. The relationships between developer-related factors have been clarified through the literature study, which were further validated using data collected in the third section of the questionnaire. Precisely, we calculated the influence of each factor (attributes and choices) on the different types of TCs by averaging the TC items within each category. Relationships were considered effective if their influence surpassed a threshold of 3.3, as indicated in Table 4.

Table 4. The validated relationships between the developer-related factors and TCs.

Attributes and Choices	Type of TCs	Codes of TCs	Mean of the Influence on TC Items	Mean of the Influence on the Type of TCs
Prefabrication Rate	Costs of due diligence	CDD_3 CDD_4 CDD_5 CDD_9	3.22 3.30 3.32 3.21	3.26
	Costs of negotiation	CN_3 CN_4 CN_6	3.32 3.11 3.41	3.28
		CME_2	3.38	3.38 *
Project Procurement Method	Costs of due diligence	CDD_9	3.25	3.25
	Costs of negotiation	CN_4	3.33	3.33 *
Contract Payment Method	Costs of due diligence	CDD_9	3.16	3.16
	Costs of monitoring and enforcement	CME_1 CME_2	3.43 3.38	3.40 *
Collaboration Experience	Costs of due diligence	CDD_3 CDD_9	3.42 3.32	3.07
	Costs of negotiation	CN_4 CN_6	3.43 3.51	3.47 *
	Costs of monitoring and enforcement	CME_1	3.53	3.53 *

Table 4. *Cont.*

Attributes and Choices	Type of TCs	Codes of TCs	Mean of the Influence on TC Items	Mean of the Influence on the Type of TCs
PH Experience	Costs of due diligence	CDD_1 CDD_2 CDD_3 CDD_4 CDD_5 CDD_6 CDD_9	3.26 3.28 3.33 3.36 3.42 3.37 3.26	3.33 *
	Costs of negotiation	CN_2 CN_3 CN_4	3.44 3.32 3.56	3.44 *
Competitiveness of the Developer	Costs of due diligence	CDD_3 CDD_5 CDD_9	3.46 3.36 3.31	3.38 *
	Costs of negotiation	CN_1 CN_2	3.35 3.45	3.40 *
	Costs of monitoring and enforcement	CME_3	3.27	3.27
Qualification of the General Contractor	Costs of due diligence	CDD_9	3.24	3.24
	Costs of negotiation	CN_4 CN_6	3.40 3.40	3.40 *
	Costs of monitoring and enforcement	CME_1 CME_2	3.39 3.35	3.37 *

Note: * indicates that the mean influence of that particular developer-related factor is higher than the threshold (3.3).

Table 5 summarizes the relationships for structuring the BBN model. The structure illustrates the relationships between developer-related factors and three categories of TCs on the first level. The due diligence costs are influenced by developers' PH experience and competitiveness. The negotiation costs are determined by the project procurement method, developers' collaboration experience, competitiveness, and PH experience. The costs of monitoring and enforcement are primarily influenced by developers' choices regarding the prefabrication rate, contract payment method, and general contractor qualification. On the second level, the structure highlights the impact of the project procurement method on the choice of payment method. Additionally, the qualification of the general contractor is influenced by the prefabrication rate and project procurement method.

Table 5. Description of the relationships for structuring the Bayesian Belief Network.

Code	Node Description	Preceding Node(s)	Following Node(s)
F1	Prefabrication rate	--	F7, CME
F2	Project procurement method	--	F3, F7, CN
F3	Contract payment method	F2	CME
F4	Collaboration experience	--	CN, CME
F5	Experience in prefabrication	--	CDD, CN
F6	Competitiveness of the developer	--	CDD, CN
F7	Qualification of the contractor	F1, F2	CME
CDD	Costs of due diligence	F5, F6	TCs
CN	Costs of negotiation	F2, F4, F5, F6	TCs
CME	Costs of monitoring and enforcement	F1, F3, F4, F7	TCs
TCs	Transaction costs	CDD, CN, CME	

4.2. Conditional Probability Distributions of the Bayesian Belief Network Model

Based on the validated relationships among the developer-related factors and the TCs, the processed data were imported into Netica 23.0 for analysis. The case-learning method was adopted in this study for the input data in Netica. The setting of expectation-maximization (EM) learning was used because there were minimal missing values in the raw data from the questionnaires [54]. Figure 4 shows the final developed BBN model for the TCs of China's PH projects.

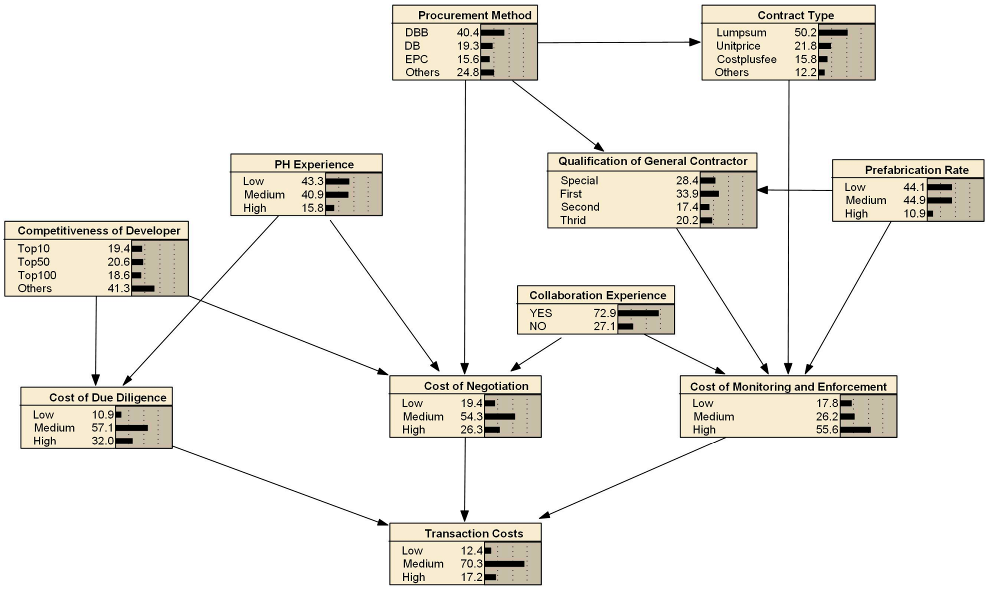

Figure 4. Bayesian Belief Network model of TCs in Chinese PH projects.

The original contribution from the use of the BBN model arises from its handling of uncertainties, while the uncertainties under different situations can be measured by using a conditional probability table (CPT). The CPT shows the probability (in terms of percentage) of the factor that was determined by the survey data in this study. For example, the conditional probability of node (F7) relies on its parent nodes—prefabrication rate (F1) and procurement method (F2), conventionally written as P(P(F7 | F1), F2). In this case, there are twelve possible conditional probability states, which are assigned based on knowledge of the parent node, such as (F1 = low, F2 = DBB), (F1 = low, F2 = DB), and (F1 = low, F2 = EPC). The total of the probabilities of the perceived behavioral control node in each role should be equal to one, which is illustrated in Table 6. Accordingly, the elements for the CPT of F7 would be $4 \times 3 \times 4 \times 2 \times 3 = 288$. The sample size of this research is decided by the largest elements in the conditional probability table among all of the nodes. As a consequence, at least 288 samples should be input to ensure that adequate data can be supplied to make the conditional probability table, a condition that is met in this study.

Table 6. Conditional probability table for the qualification of the general contractor—P (F7 | F1, F2).

Condition		F7 Qualification of the General Contractor			
F1 Prefabrication Rate	**F2 Procurement Method**	**Special Grade**	**First Level**	**Second Level**	**Third Level**
Low	DBB	0.341	0.295	0.182	0.182
Low	DB	0.190	0.477	0.286	0.048
Low	EPC	0.353	0.471	0.118	0.058
Low	Others	0.222	0.222	0.111	0.444
Medium	DBB	0.436	0.385	0.154	0.026
Medium	DB	0.190	0.514	0.216	0.081

Table 6. *Cont.*

Condition		F7 Qualification of the General Contractor			
F1 Prefabrication Rate	F2 Procurement Method	Special Grade	First Level	Second Level	Third Level
Medium	EPC	0.250	0.400	0.250	0.100
Medium	Others	0.467	0.267	0.133	0.133
High	DBB	0.600	0.398	0.001	0.001
High	DB	0.091	0.634	0.273	0.091
High	EPC	0.285	0.571	0.143	0.001
High	Others	0.250	0.740	0.001	0.001

5. Bayesian Belief Network Analysis Results

To examine the effects of developer-related factors on TCs, sensitivity analyses using the BBN were conducted. The single sensitivity analysis aimed to identify simple strategies that would lead to the most significant improvements in TCs. By analyzing the individual impacts of the developer-related factors, specific areas for improvement could be identified. The multiple sensitivity analysis, on the other hand, focused on identifying effective combined strategies for PH developers to minimize TCs when facing diverse challenges.

5.1. Single Sensitivity Analysis

For assessing the sensitivity of each factor to the final TCs, the Sensitivity to Finding method was adopted. The sensitivity of a variable to a finding can be measured using the index of mutual information (MI). MI reflects the level of predictability of one parameter when information on another parameter is available [55]. As shown in Table 7, the MI results between the developer-related factors and the TCs indicate the importance of each factor.

Table 7. Sensitivity analysis results of the node "TCs" in the BBN model.

Node	Node Description	MI	Percent
TCs	Transaction costs	1.16813	100
CN	Costs of negotiation	0.34292	29.40
CDD	Costs of due diligence	0.18339	15.70
CME	Costs of monitoring and enforcement	0.08189	7.02
F1	Prefabrication rate	0.02393	2.05
F5	PH experience	0.01373	1.18
F3	Contract payment method	0.01342	1.15
F2	Procurement method	0.00733	0.63
F6	Competitiveness of the developer	0.00201	0.17
F7	Qualification of the general contractor	0.00084	0.07
F4	Collaboration experience	0.00057	0.02

Table 7 shows that the MI value for "costs of negotiation" is the largest, which means that it is the most critical contributor to the final TCs. Additionally, according to the simple sensitivity analysis, it can be inferred that the factors having the most considerable effects on the TCs are the prefabrication rate (F1), PH experience (F5), and contract payment method (F3).

To further investigate the specific impact of these dominant choices, the proportions of TCs at different levels were calculated considering various states of the attributes and choices (as shown in Table 8). The BBN analysis indicated that the "low-level" prefabrication rate resulted in the lowest possibility (15.2%) of high TCs. This possibility increased to 32.8% when a high prefabrication rate was set, indicating a strong increasing effect of the prefabrication rate (F1) on the TCs. Moreover, it is not surprising that the higher the developers' experience (F5), the lower the TCs. The possibility of high TCs was only 8.6%

when the experience was at a high level. As for the influence of the contract payment method (F3) on the TCs, adopting lump-sum contracts was found to result in the lowest possibility of "high" TCs, with a possibility of 15.2% (see Table 8).

Table 8. The achievable proportion of TCs by changing the most influential factors.

	Influential Choices	TCs			
		States	**Low**	**Medium**	**High**
F1	Prefabrication Rate	Low	11.7	73.1	**15.2**
		Medium	13.5	71.1	15.5
		High	10.1	57.1	32.8
F5	PH Experience	Low	12.6	64.7	22.6
		Medium	14.9	70.3	14.9
		High	5.48	85.9	**8.6**
F3	Contract Payment Method	Lump-sum	11.3	73.5	**15.2**
		Unit-price	14.4	68.8	16.8
		Cost-plus-fee	14.0	68.7	17.3
		Others	11.5	62.0	26.5

5.2. Multiple Sensitivity Analysis

In addition to the simple strategies regarding individual factors, developers can further reduce their TCs by considering more than one action. Multiple sensitivity is one of the main advantages of the BBN model, wherein the posterior probability of a variable can be determined by integrating two or more hypotheses. The automatic inference function of the BBN model investigates the most beneficial combinations of the factors in different situations. Backward reasoning was applied in this study to explore the most positive combinations of strategies for developers to minimize TCs (see Table 9).

Table 9. Combined strategies for minimizing the TCs when developers face different challenges.

Scenarios		**Combined Choices**	**TCs (%)**		
			Low	**Medium**	**High**
No constraints		F1 = Low F5 = High F3 = Lump-sum	3.2	94.2	2.6
Prefabrication rate	Medium	F3 = Unit-price F7 = Special grade	11.3	68.6	20.1
	High	F3 = Unit-price F7 = Special grade	16.3	73.5	11.2
Experience in PH	Low	F2 = EPC	20.1	59.4	20.5
	Medium	F2 = EPC	1.8	92.7	5.5

Scenario 1: High Prefabrication Rate Challenge

For certain types of projects, the prefabrication rates are decided by the local authority or decided by the decision-makers of the real estate companies. In those cases, high TCs will occur at a 32.8% level of possibility. Investigations were carried out to explore the combined strategies. Notably, with high prefabrication rates, the possibility of high TCs can be reduced dramatically from 32.8% to 11.2% when procuring special-grade general contractors and adopting unit-price contracts. This strategy also fits the situation when a medium level of prefabrication rate is required.

Scenario 2: Limited Experience in PH

Currently, there are still limited numbers of experienced developers for PH projects in China. As analyzed, limited experience raises the chance of high TCs from due diligence and negotiation. Investigations were carried out to adjust other factors that impact the costs of due diligence and negotiation. The BBN model indicated that the possibility of incurring "high" TCs is 22.6% and 14.9% when the developers have low-level and medium-level experience in PH, respectively. This possibility can be reduced when the EPC procurement method is adopted (as shown in Table 9). Especially for the developers with a medium level of experience, the choice of using the EPC contract showed an extremely low possibility (5.5%) of redundant TCs.

Scenario 3: Ideal Situation for Developers

An ideal situation to minimize TCs involves allocating the influential choices to their most favorable states without constraints. For the developers who have an absolute right to make such choices, investigations with the BBN model were carried out to identify the most efficient strategy for minimizing the TCs. As illustrated in Table 9, the lowest possibility (2.6%) of "high" TCs was achieved when the most influential factors were ordered at certain states (F1 = low; F5 = high; F3 = lump-sum).

5.3. Robustness Assessment of the BBN Model

To enable the further applicable adoption of this BBN model in the PH industry, its accuracy and robustness are required to be at acceptable levels. Therefore, its robustness was tested by using 62 randomly selected new cases (Table 10). As shown in Table 10, the error rates for predicting the TCs on the low level and high levels are 20.00% and 21.05%. With a total error rate of 11.29%, the established BBN's prediction accuracy is generally acceptable.

Table 10. Robustness test of the BBN model using the values of TCs in 62 random cases.

TCs (Actual)	TCs (Predicted)			Error Rate (%)
	Low	Medium	High	
Low	8	2	0	20.00
Medium	1	32	0	3.03
High	0	4	15	21.05
Total error rate: 11.29%				

6. Discussion

6.1. Developers' Principle Impact on the Nature of TCs in PH through Their Attributes and Choices

Developers' attributes can be recognized as the principal determinants of TCs for the aspects of due diligence in PH projects, according to the questionnaire survey results suggesting that the PH experience and the competitiveness of the developer are the primary factors that influence the scale of due diligence costs. This study shows that the richer the experience of the developers, the lower the TCs will be, which is consistent with the argument of Coggan, Buitelaar [9]. The challenges of information searching, learning, and governance could be better addressed if stakeholders had similar experiences in their organizational memory. Moreover, developers' competitiveness indicates a significant influence on TCs due to the differences in due diligence efforts. Their reputation and operational capacity mirror their capability to respond to changes and risks; therefore, the costs related to bidding and searching for partners differ considerably.

Developers' choices of the prefabrication rate, the contract payment method, and the qualification of the general contractor reveal significant influences on the TCs arising from monitoring and enforcement. The questionnaire survey indicated that the prefabrication rate determines the technical complexity of the architectural design, the detailed design, and the design change, which directly impacts the volume of the monitoring tasks. A high prefabrication rate usually means high technical uncertainties in manufacturing, transportation, and assembly. Correspondingly, more supervision and monitoring are necessary from the developers to ensure the quality of the products. In addition, the developers' risks depend on the payment methods adopted [49]. For example, incremental costs from quality inspection and monitoring for the assembly vary between the lump-sum and unit-price projects due to the difference in developers' responsibilities. Similarly, the TCs from monitoring and enforcement are different when procuring general contractors with varying qualification levels.

6.2. Simple Strategies for PH Developers to Minimize their TCs

1. Strategies regarding attributes: minimizing the TCs by improving the experience in PH

Developers with rich PH experience have a higher likelihood of reducing TCs in PH projects. In the Chinese context, this advantage is primarily enjoyed by large-scale developers, such as the top 50 real estate companies. However, small companies often face the challenge of lacking experience, which acts as a barrier to minimizing TCs. In such cases, a sustainable development strategy for small-scale real estate companies is to learn from experienced large developers. This can be achieved through visiting large companies and successful projects, which has proven to be an effective method in other industries [21]. Another efficient strategy is to hire professionals or skilled workers who possess PH experience. Although this may increase labor costs, it reduces the costs associated with adaptation, information searching, consulting, and other aspects. The presence of experienced employees enhances a company's professionalism, improves production efficiency, reduces TCs, and enhances competitiveness in attracting potential partners [17]. Overall, gaining experience and hiring experienced employees contribute to reducing TCs, expanding the market size of developers, and leveraging the benefits of economies of scale. These strategies are not only applicable in China but can also be implemented globally to enhance the professionalism and competitiveness of developers in the PH industry across various regions and countries.

2. Strategies regarding choices

First, developers are commended to make relational choices to define the technical specificity of PH projects proactively by pursuing a reasonable prefabrication rate. The prefabrication rate is a significant explanatory factor for developers' TCs in PH. In practice, the prefabrication rate of a PH project is sometimes predetermined by the developer and specified in the bidding documents as a prerequisite for selecting general contractors. Although the BBN analysis results indicate that a high prefabrication rate leads to increased TCs, this does not imply that developers should aim for a low rate. When determining the prefabrication rate, Chinese developers are advised to consider both the local government's requirements (benchmarks) and their own company's capabilities with a long-term perspective [36]. Firstly, developers are encouraged to comply with any mandatory regulations regarding the prefabrication rate in the project's region. Secondly, in regions where no mandatory policies exist, developers should determine the most efficient prefabrication rates based on the manufacturing and assembly capabilities of the local PH market. Although private real estate companies may experience short-term TCs related to learning, procurement, and organizational adaptation when increasing the prefabrication rate, there are long-term benefits to be gained. These include reduced onsite working time, resource savings, improved integration of the production supply chain, and a decrease in the overall social cost for the local PH market.

Second, PH developers worldwide are encouraged to approach uncertainties strategically by carefully selecting appropriate contract payment methods. The contract payment method indicates how risks are allocated between the developers and the general contractor, and risks are a vital source of TCs [56]. This study indicated that the possibility of rising TCs with lump-sum contracts is lower than that with unit-price and cost-plus-fee contracts. This is because lump-sum contracts assign more risks to the general contractor rather than to the developers. In this sense, the developer's workload regarding contract monitoring and enforcement is less with lump-sum contracts than with the other types of contracts. As such, it usually is beneficial for developers to adopt lump-sum agreements for PH projects. Despite this fact, lump-sum is not always the best type of contract for construction projects. In practice, developers are suggested to use unit-price contracts in projects where the design and specifications for the prefabrication parts are not complete [49]. Moreover, the least recommended payment method is cost-plus-fee, as it places the entire cost risk on the developers while offering contractors less incentive for controlling costs in such scenarios. This nuanced approach to contract payment methods provides a global perspective on risk management in PH projects, contributing to improved efficiency and reduced TCs across different international contexts.

6.3. Integrated Strategies for Developers to Minimize the TCs of PH

Achieving high prefabrication rates presents significant technical challenges, particularly in nascent PH markets where competition and governmental regulations are stringent. In such situations, the BBN model suggests a combined strategy of selecting special-grade general contractors and unit-price contracts to effectively minimize TCs. This strategy reduces uncertainties from stakeholders and the transaction process, aligning with the core principles of TC theory [12]. High prefabrication rates signify greater technical complexity, for which the support of highly certified general contractors helps in managing uncertainties. Adopting unit-price contracts is suitable for high-uncertainty projects, in line with established construction management theory [57]. As the PH industry progresses, other critical technical challenges will emerge alongside the high-prefabrication-rate issue. Minimizing uncertainties among stakeholders and in transactions remains a prudent choice not only in the current context but also for other countries and markets experiencing rapid PH adoption. This strategic approach becomes imperative amidst challenges such as labor shortages and resource constraints, especially when developers seek to optimize production efficiency to drive profitability. These insights hold particular relevance as higher technical specificity typically correlates with increased TCs.

This study demonstrates that developers' lack of experience leads to higher TCs. However, the shift towards becoming an experienced developer cannot occur within a short period. The BBN multiple sensitivity analysis revealed that adopting the Engineering, Procurement, and Construction (EPC) method is an effective strategy for inexperienced developers to minimize TCs. This finding is consistent with the current advocacy for EPC by Chinese authorities [45]. In an EPC approach, general contractors are responsible for the entire design, procurement, manufacturing, and construction process. Some EPC contractors in the Chinese PH market now own affiliated factories to provide prefabricated components. A similar statement can be found in previous research, saying that EPC minimizes the effort required to transfer information between contractors for developers [58]. The adoption of the EPC approach has revolutionized the way information is transferred in prefabricated construction, thus reducing the burden of information-related costs for the developers. EPC contracts streamline the flow of information between the contractor, vendor, and client, leading to more efficient project delivery and thus lower TCs.

The BBN model also indicates an ideal theoretical scenario where highly experienced developers imitate a low-prefabricated project (prefabrication rate $< 60\%$) while employing lump-sum contracts, resulting in optimized TCs. However, it is important to note that this outcome can only be achieved when the assumption of non-constraints is met. As analyzed, high levels of experience and low prefabrication rates both contribute to reducing TCs in the PH industry. Furthermore, the adoption of lump-sum contracts reflects the completeness of the design, resulting in fewer TCs. Therefore, it can be concluded that developers can minimize TCs by keeping the risks in PH projects low. Consistent with these simple strategies, developers are advised to determine a prefabrication rate that aligns with their experience and capabilities rather than pushing beyond their limits to pursue a high rate. Another suggestion for developers is to enhance the completeness of the design and technical illustrations, which can minimize TCs during the subsequent construction process [59].

6.4. Policy Support for Reducing Developers' TCs to Promote PH

This study has presented the critical influence of developers' choices on the TCs of PH projects. Notably, the stakeholders' behaviors and the TCs are also highly dependent on the institutional and political environment [9]. Corresponding policy provisions are also expected to provide a supportive political environment for minimizing the developers' TCs and promoting PH.

Firstly, policies are expected to establish systemic education and certification regulations to minimize future negotiation-related TCs. The BBN analysis revealed that the costs of negotiation are a major explaining component of the total TCs in a PH project. Throughout the whole development process, it is noticed that higher negotiation costs, arising from the organizational set-up, the financing, the detailed design, and design changes, are essentially related to developers' limited knowledge and experiences regarding PH production [60]. Therefore, systemic education and certification regulations are necessary for the workers, engineers, and managers who participate in PH projects to ensure professionalism and thus remove the barriers in negotiation processes. Apart from providing training for the employed person, it would be more efficient for the immature PH market to put "prefabrication" into the education system, such as in universities and engineering qualifications, to formulate a more well-educated and efficient supply chain for the future.

Secondly, local governments are recommended to set up the required target prefabrication rate considering the practical situation of the applied region to ensure the TC scale remains at an acceptable level. As stated, a high prefabrication rate entails higher uncertainties, thus high TCs, especially for inexperienced developers. The establishment of local requirements for PH influences the assessment of developers' performance. It may result in the developers' blind pursuit of the advocated high prefabrication rate, which is eventually paid for by the overrunning of investment targets, a delayed construction period, and poor quality. Hence, rational requirements of prefabrication rates are expected by considering the differences in the local PH progress, developers' capability, and project type.

Thirdly, the government is recommended to stimulate inexperienced and small- and medium-scale enterprises to participate in the PH market. The BBN analysis showed that rich PH experience and a strong competitiveness of the developers and the general contractors bring rewards in terms of significant reductions in TCs. Yet, the current leaders pioneering the successful implementation of PH in China are primarily large-scale enterprises, whereas the small companies cannot share the benefits of PH owing to the high initial investment required for entering the market. Meanwhile, the latest analysis of Chinese policies revealed that there are not yet particular policies in place to facilitate small enterprises to promote PH [61]. In view of the above, policymakers should prioritize the needs of inexperienced and small-scale enterprises by implementing targeted incentives and policies. This includes offering financial support, loans, tax privileges, and streamlined administrative procedures for small- to medium-sized developers. The strategies devised for nurturing small- to medium-sized PH developers hold universal applicability and can be seamlessly transferred to other countries currently experiencing the diffusion phase of prefabricated building adoption. By extending support to these emerging companies, the PH market stands to expand exponentially, fostering the integration of a comprehensive supply chain and ultimately realizing economies of scale.

7. Conclusions

In the development of prefabricated housing (PH), private stakeholders, particularly developers, play a crucial role. However, the presence of transaction costs (TCs) poses challenges to stakeholders and hinders the growth of the PH industry in China. This study focused on investigating the influence of developers' attributes and choices on TCs in PH projects. The results of the questionnaire survey revealed significant relationships between developers' actions and the nature of TCs. To explore strategies for reducing TCs, a Bayesian Belief Network (BBN) model was applied to uncover causal relationships between developer-related factors and TCs, providing insights and potential strategies for developers.

(1) Developers' attributes can be recognized as the principal determinants of TCs relating to the aspects of due diligence in PH projects. Specifically, developers' PH experience and competitiveness influence TCs, indicating varying due diligence costs based on operational capacity and reputation. In terms of choices, strategic decisions regarding prefabrication rates, contract payment methods, and contractor qualifications play pivotal roles in TCs related to monitoring and enforcement.
(2) The single sensitivity analysis using the BBN identified three critical impacts of developers on TCs: choice of prefabrication rate, possession of PH experience, and choice of contract payment method. According to this analysis, simple strategies could be recommended to developers, including pursuing reasonable prefabrication rates based on local requirements, supply chain capabilities, and long-term benefits; learning from experienced enterprises and hiring skilled employees; and selecting appropriate contract payment methods to rationalize risk allocation.
(3) The multiple sensitivity analysis with the BBN model led to combined strategies for developers facing different challenges. For projects with high prefabrication rates, TCs can be controlled by procuring highly certified general contractors and adopting unit-price contracts. For developers with limited PH experience, adopting the EPC approach can significantly reduce TCs thanks to efficient information delivery under the highly integrated procurement structure of EPC.
(4) Insights into policy recommendations underscore the importance of systemic education, rational target setting for prefabrication rates, and targeted support for small- to medium-sized enterprises to foster PH market growth universally. Overall, these recommendations, based on empirical evidence and theoretical frameworks, present actionable strategies for developers and policymakers to navigate the complex landscape of PH projects with reduced TCs and enhanced efficiency.

This exploration into the intricate dynamics of TCs, with a focused lens on developers' influences and strategic interventions within the Chinese PH context, has yielded insightful contributions to both theoretical frameworks and practical applications. Theoretically, this study extends TC theory by elucidating how traders shape TCs through their distinct attributes and choices in PH implementation. We emphasize impactful factors such as experience, technical specificity, and uncertainties, thereby illuminating the mechanisms through which TCs manifest in PH development processes. This nuanced understanding enriches the existing literature on construction management, transaction cost economics, and prefabricated housing development. From a practical perspective, this research equips developers and stakeholders with actionable strategies to effectively mitigate TCs. Our recommendations, including optimizing prefabrication rates, leveraging PH experience, and refining contract payment methods, offer concrete pathways to enhance project efficiency, reduce hidden costs, and streamline the transaction process in PH development. Furthermore, the findings of this study provide valuable insights for policymakers aiming to cultivate a conducive institutional environment for promoting PH initiatives both in China and other PH markets with rapid growth characteristics.

Despite the valuable insights gained, it is essential to acknowledge the limitations of our study. First, the scope of our sample, limited geographical context, and specific methodological choices may constrain the generalizability of the findings. Future research endeavors could expand the sample size across diverse regions, incorporate multi-method approaches for a more comprehensive analysis, and delve deeper into the complexities of TCs in PH projects across different developmental stages. Second, the combined strategies recommended in this study are only derived from three typical situations. For stakeholders facing other constraints or more than one constraint, further investigations need to be carried out. Third, exploring the implications of emerging technologies such as BIM and Blockchain in mitigating TCs could also be a promising avenue for further investigation. By addressing these limitations, future studies can build upon our foundational work, delve into unexplored facets, and refine strategies to navigate the evolving landscape of PH with enhanced process efficiency and management effectiveness.

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References

1. Ji, Y.; Lv, J.; Li, H.X.; Liu, Y.; Yao, F.; Liu, X.; Wang, S. Improving the performance of prefabricated houses through multi-objective optimization design. *J. Build. Eng.* **2024**, *84*, 108579. [CrossRef]
2. Zhou, J.; Li, Y.; Ren, D. Quantitative study on external benefits of prefabricated buildings: From perspectives of economy, environment, and society. *Sustain. Cities Soc.* **2022**, *86*, 104132. [CrossRef]
3. General Office of the State Council of the People's Republic of China. Guiding Opinions of the General Office of the State Council on Vigorously Developing Prefabricated Buildings. 30 September 2016. Available online: http://www.gov.cn/zhengce/content/2016-09/30/content_5114118.htm (accessed on 17 April 2024). (In Chinese)
4. Ministry of Housing and Urban-Rural Development of the People's Republic of China. The 14th Five-Year Plan for the Construction Industry. 19 January 2022. Available online: https://www.mohurd.gov.cn/gongkai/zhengce/zhengcefilelib/202201/20220125_764285.html (accessed on 17 April 2024). (In Chinese)
5. Wu, H.J.; Qian, Q.K.; Straub, A.; Visscher, H. Stakeholder Perceptions of Transaction Costs in Prefabricated Housing Projects in China. *J. Constr. Eng. Manag.* **2021**, *147*, 04020145. [CrossRef]
6. Wu, H.J.; Qian, Q.K.; Straub, A.; Visscher, H. Exploring transaction costs in the prefabricated housing supply chain in China. *J. Clean. Prod.* **2019**, *226*, 550–563. [CrossRef]
7. Whittington, J.M. *The Transaction Cost Economics of Highway Project Delivery: Design-Build Contracting in Three States*; University of California: Berkeley, CA, USA, 2008.
8. He, Q.; Wu, J.; Wu, Z.; Zhang, J.; Chen, X. Evolutionary game analysis of prefabricated buildings adoption under carbon emission trading scheme. *Build. Environ. Behav.* **2024**, *249*, 111121. [CrossRef]
9. Coggan, A.; Buitelaar, E.; Whitten, S.; Bennett, J. Factors that influence transaction costs in development offsets: Who bears what and why? *Ecol. Econ.* **2013**, *88*, 222–231. [CrossRef]
10. Xue, H.; Zhang, S.; Su, Y.; Wu, Z.; Yang, R.J. Effect of stakeholder collaborative management on off-site construction cost performance. *J. Clean. Prod.* **2018**, *184*, 490–502. [CrossRef]
11. Shanghai Housing and Urban-Rural Development Management Committee. Calculation Guidelines for Individual Prefabrication Rate and Assembly Rate of Prefabricated Buildings in Shanghai. 27 December 2019. Available online: https://zjw.sh.gov.cn/jsgl/20191230/bdec1f18954d4538bbacbf5f5cb58343.html (accessed on 17 April 2024). (In Chinese)
12. Winch, G. The construction firm and the construction project: A transaction cost approach. *Constr. Manag. Econ.* **1989**, *7*, 331–345. [CrossRef]
13. Luo, L.Z.; Li, Y.K.; Wang, X.; Jin, X.; Qin, Z.Y. Supply Chain Vulnerability in Prefabricated Building Projects and Digital Mitigation Technologies. *IEEE Trans. Eng. Manag.* **2023**. *Early Access*. [CrossRef]
14. Wu, Z.Z.; Luo, L.R.; Li, H.; Wang, Y.; Bi, G.Q.; Antwi-Afari, M.F. An Analysis on Promoting Prefabrication Implementation in Construction Industry towards Sustainability. *Int. J. Environ. Res. Public Health* **2021**, *18*, 11493. [CrossRef]
15. Kong, A.; Kang, H.B.; He, S.Y.; Li, N.; Wang, W. Study on the Carbon Emissions in the Whole Construction Process of Prefabricated Floor Slab. *Appl. Sci.* **2020**, *10*, 2326. [CrossRef]
16. Wang, Y.; Wang, F.; Sang, P.; Song, H. Analysing factors affecting developers' behaviour towards the adoption of prefabricated buildings in China. *Environ. Dev. Sustain.* **2021**, *23*, 14245–14263. [CrossRef]
17. Mao, C.; Shen, Q.; Pan, W.; Ye, K. Major Barriers to Off-Site Construction: The Developer's Perspective in China. *J. Manag. Eng.* **2015**, *31*, 04014043. [CrossRef]
18. Simon, H.A. Administrative behaviour. *Aust. J. Public Adm.* **1950**, *9*, 241–245. [CrossRef]
19. Tadelis, S.; Williamson, O.E. *Transaction Cost Economics*; Introductory Chapters; University of California: Berkeley, CA, USA, 2012; pp. 159–189.
20. Kiss, B. Exploring transaction costs in passive house-oriented retrofitting. *J. Clean. Prod.* **2016**, *123*, 65–76. [CrossRef]
21. Mundaca, L.; Mansoz, M.; Neij, L.; Timilsina, G.R. Transaction costs analysis of low-carbon technologies. *Clim. Policy* **2013**, *13*, 490–513. [CrossRef]

22. Antinori, C.; Sathaye, J. *Assessing Transaction Costs of Project-Based Greenhouse Gas Emissions Trading*; Lawrence Berkeley National Laboratory: Berkeley, CA, USA, 2007.
23. Kamali, M.; Hewage, K. Life cycle performance of modular buildings: A critical review. *Renew. Sustain. Energy Rev.* **2016**, *62*, 1171–1183. [CrossRef]
24. Shahab, S. Transaction Costs in Planning Literature: A Systematic Review. *J. Plan. Lit.* **2022**, *37*, 403–414. [CrossRef]
25. Qian, Q.K.; Fan, K.; Chan, E.H.W. Regulatory incentives for green buildings: Gross floor area concessions. *Build. Res. Inf.* **2016**, *44*, 675–693. [CrossRef]
26. O'Connor, J.T.; O'Brien, W.J.; Choi, J.O. Industrial project execution planning: Modularization versus stick-built. *Pract. Period. Struct. Des. Constr.* **2015**, *21*, 04015014. [CrossRef]
27. Lu, W.X.; Zhang, L.H.; Pan, J. Identification and analyses of hidden transaction costs in project dispute resolutions. *Int. J. Proj. Manag.* **2015**, *33*, 711–718. [CrossRef]
28. Tam, V.W.Y.; Fung, I.W.H.; Sing, M.C.P.; Ogunlana, S.O. Best practice of prefabrication implementation in the Hong Kong public and private sectors. *J. Clean. Prod.* **2015**, *109*, 216–231. [CrossRef]
29. Shahab, S.; Clinch, J.P.; O'Neill, E. Accounting for transaction costs in planning policy evaluation. *Land Use Policy* **2018**, *70*, 263–272. [CrossRef]
30. Rajeh, M.; Tookey, J.E.; Rotimi, J.O.B. Estimating transaction costs in the New Zealand construction procurement: A structural equation modelling methodology. *Eng. Constr. Archit. Manag.* **2015**, *22*, 242–267. [CrossRef]
31. Williamson, O.E. *The Economic Institutions of Capitalism*; Free Press: New York, NY, USA, 1985.
32. Williamson, O.E. *The Mechanisms of Governance*; Oxford University Press: Oxford, UK, 1996.
33. Hong, J.; Shen, G.Q.; Mao, C.; Li, Z.; Li, K. Life-cycle energy analysis of prefabricated building components: An input–output-based hybrid model. *J. Clean. Prod.* **2016**, *112*, 2198–2207. [CrossRef]
34. Jin, R.; Hong, J.; Zuo, J. Environmental performance of off-site constructed facilities: A critical review. *Energy Build.* **2020**, *207*, 109567. [CrossRef]
35. Jiang, L.; Li, Z.; Li, L.; Gao, Y. Constraints on the promotion of prefabricated construction in China. *Sustainability* **2018**, *10*, 2516. [CrossRef]
36. Du, Q.; Hao, T.T.; Huang, Y.D.; Yan, Y.Q. Prefabrication decisions of the construction supply chain under government subsidies. *Environ. Sci. Pollut. Res.* **2022**, *29*, 59127–59144. [CrossRef] [PubMed]
37. Jobin, D. A Transaction Cost-Based Approach to Partnership Performance Evaluation. *Evaluation* **2008**, *14*, 437–465. [CrossRef]
38. De Schepper, S.; Haezendonck, E.; Dooms, M. Understanding pre-contractual transaction costs for Public–Private Partnership infrastructure projects. *Int. J. Proj. Manag.* **2015**, *33*, 932–946. [CrossRef]
39. Wu, H.; Qian, Q.K.; Straub, A.; Visscher, H.J. Factors influencing transaction costs of prefabricated housing projects in China: Developers' perspective. *Eng. Constr. Archit. Manag.* **2021**, *29*, 476–501. [CrossRef]
40. Li, L.; Li, Z.; Wu, G.; Li, X. Critical success factors for project planning and control in prefabrication housing production: A China study. *Sustainability* **2018**, *10*, 836. [CrossRef]
41. Statista. Leading Chinese Real Estate Companies on the Fortune China 500 Ranking as of 2019, by Revenue. Available online: https://www.statista.com/statistics/454494/china-fortune-500-leading-chinese-real-estate-companies/ (accessed on 17 April 2024).
42. Masood, R.; Lim, J.B.P.; González, V.A. Performance of the supply chains for New Zealand prefabricated house-building. *Sustain. Cities Soc.* **2021**, *64*, 102537. [CrossRef]
43. Liu, G.; Li, K.; Zhao, D.; Mao, C. Business model innovation and its drivers in the Chinese construction industry during the shift to modular prefabrication. *J. Manag. Eng.* **2017**, *33*, 04016051. [CrossRef]
44. Ministry of Housing and Urban-Rural Development of the People's Republic of China. Opinions on Accelerating the Development of the New Industrialization Building. 2020. Available online: https://www.gov.cn/zhengce/zhengceku/2020-09/04/content_5540357.htm (accessed on 17 April 2024). (In Chinese)
45. MOHURD. Regulations on the Qualification Management of Construction Enterprises. 2018. Available online: https://www.mohurd.gov.cn/gongkai/zhengce/zhengcefilelib/201812/20181229_774543.html (accessed on 17 April 2024). (In Chinese)
46. Carbonara, N.; Costantino, N.; Pellegrino, R. A transaction costs-based model to choose PPP procurement procedures. *Eng. Constr. Archit. Manag.* **2016**, *23*, 491–510. [CrossRef]
47. Ding, J.; Wang, N.; Hu, L. Framework for designing project delivery and contract strategy in Chinese construction industry based on value-added analysis. *Adv. Civ. Eng.* **2018**, *2018*, 5810357. [CrossRef]
48. Chen, Q.; Xia, B.; Jin, Z.; Wu, P.; Hu, Y. Choosing appropriate contract methods for design-build projects. *J. Manag. Eng.* **2016**, *32*, 04015029. [CrossRef]
49. Li, H.M.; Arditi, D.; Wang, Z.F. Transaction costs incurred by construction owners. *Eng. Constr. Archit. Manag.* **2014**, *21*, 444–458. [CrossRef]
50. Hon, C.K.H.; Sun, C.J.Y.; Xia, B.; Jimmieson, N.L.; Way, K.A.; Wu, P.P.Y. Applications of Bayesian approaches in construction management research: A systematic review. *Eng. Constr. Archit. Manag.* **2022**, *29*, 2153–2182. [CrossRef]
51. Zhou, Q.; Fang, D.; Wang, X. A method to identify strategies for the improvement of human safety behavior by considering safety climate and personal experience. *Saf. Sci.* **2008**, *46*, 1406–1419. [CrossRef]
52. Jitwasinkul, B.; Hadikusumo, B.H.; Memon, A.Q. A Bayesian Belief Network model of organizational factors for improving safe work behaviors in Thai construction industry. *Saf. Sci.* **2016**, *82*, 264–273. [CrossRef]

53. Van Der Gaag, L.C. Bayesian belief networks: Odds and ends. *Comput. J.* **1996**, *39*, 97–113. [CrossRef]
54. Norysys. Netica Help. Available online: https://www.norsys.com/WebHelp/NETICA.htm (accessed on 17 April 2024).
55. Mohammadfam, I.; Ghasemi, F.; Kalatpour, O.; Moghimbeigi, A. Constructing a Bayesian network model for improving safety behavior of employees at workplaces. *Appl. Ergon.* **2017**, *58*, 35–47. [CrossRef]
56. Dorward, A. The effects of transaction costs, power and risk on contractual arrangements: A conceptual framework for quantitative analysis. *J. Agric. Econ.* **2001**, *52*, 59–73. [CrossRef]
57. Picornell, M.; Pellicer, E.; Torres-Machí, C.; Sutrisna, M. Implementation of earned value management in unit-price payment contracts. *J. Manag. Eng.* **2017**, *33*, 06016001. [CrossRef]
58. Fan, Z.; Liu, Y.; Li, Y. Research on Collaborative Mechanisms of Railway EPC Project Design and Construction from the Perspective of Social Network Analysis. *Systems* **2023**, *11*, 443. [CrossRef]
59. Li, H.; Arditi, D.; Wang, Z. Determinants of transaction costs in construction projects. *J. Civ. Eng. Manag.* **2015**, *21*, 548–558. [CrossRef]
60. Jiang, R.; Mao, C.; Hou, L.; Wu, C.; Tan, J. A SWOT analysis for promoting off-site construction under the backdrop of China's new urbanisation. *J. Clean. Prod.* **2018**, *173*, 225–234. [CrossRef]
61. Luo, T.; Xue, X.; Wang, Y.; Xue, W.; Tan, Y. A systematic overview of prefabricated construction policies in China. *J. Clean. Prod.* **2020**, *280*, 124371. [CrossRef]