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INFLUENCE OF CONSUMER PREFERENCE AND GOVERNMENT SUBSIDY ON PREFABRICATED BUILDING DEVELOPER'S DECISION-MAKING: A THREE-STAGE GAME MODEL

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Abstract. Consumer preference and government subsidies are two of the key influencing factors in the decision-making of building developers, which plays a leading role in the development of prefabricated building market. However, the majority of the existing efforts only used empirical research methods to identify the barriers of prefabricated construction, and failed to quantitatively study the interaction mechanism, process, and trends among the influencing factors. To address this knowledge gap, this study aims to analyze and quantify the dynamic and interactive relationships among the three major stakeholders in the prefabricated building industry – the government, building developers, and consumers. A three-stage game model was developed, and an analysis of two numerical simulations was conducted. The results provided equilibrium solutions for the optimal selling price and optimal assembly rate for the building developers, as well as the optimal minimum assembly rate for government subsidy. This study provides a better understanding of the interactive behaviors among the major stakeholders, and offers meaningful insights for policy design and strategic planning for promoting the development of prefabricated buildings.

Keywords: prefabricated building, building developers, government policy and subsidy, assembly rate, consumer preference.

Introduction

Sustainable construction is crucial for creating a healthier built environment and achieving the global sustainable development goals. However, the traditional construction industry still relies heavily on the conventional cast in-situ method, which has long been criticized for "labor intensive, dangerous, and polluting", and has significantly hindered construction sustainability (Eastman & Sacks, 2008). For example, the U.S. construction industry accounts for 600 million tons of waste generation in 2018 (United States Environmental Protection Agency [EPA], 2020); and in China, 20% of the total energy consumption were consumed by the construction industry (Hong et al., 2017). With the increasing housing demand and rapid urbanization, the extent of the detrimental impacts of construction activities on the environment could be exaggerated (Gan et al., 2018a). The need for modernizing the traditional construction industry and tackling the issues of housing demand, sustainability, and innovation-driven development calls for the application and development of off-site construction (OSC) (Han & Wang, 2018).

Originated from the manufacturing industry, OSC is a radical innovation to replace conventional in-situ construction method (Kamali & Hewage, 2017; Phillips et al., 2016). In light of numerous benefits of OSC in improving construction productivity, safety, quality, and environmental performance effectively, the adoption of OSC has made considerable progress accounting for up to 30–50% prefabrication rate in countries and regions such as Japan, Denmark, Netherlands, Sweden, Germany, Hong Kong, and Singapore, etc. (Jaillon & Poon, 2010; Mao et al., 2016; Han et al., 2017). Similarly, China has also entered a new round of nationwide promotion to shift the traditional in-situ construction method to prefabricated construction since 2014, to alleviate the environmental impacts associated with the construction activities. For instance, the National Plan on New Urbanization 2014–2020 and the

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Plan on Green Building has made OSC a top development priority to upgrade traditional construction industry and facilitate human-centered, sustainable urban development in China. According to the report of China prefabricated building development in 2019 (Technology and Industrialization Development Center Affiliated to Ministry of Housing and Urban-Rural Construction, 2020), after the issue of the instructions on vigorously developing prefabricated buildings by the General Office of the China State Council in 2016, all 31 provinces across the country have presented relevant policy documents to promote the development of prefabricated buildings, with 33, 157, 235, and 261 documents respectively from 2016 to 2019, for constant improvements of supporting policies and refinements of implementation measures. In particular, various economic incentive policies were put forward to provide institutional safeguards for facilitating the development of prefabricated buildings. Taking Shanghai in China, which has issued relatively sound policy measures, as an example, the government presented an incentive of 100 yuan per square meter to prefabricated housing projects with an overall gross floor area of more than 30,000 square meters and a prefabricated assembly rate of 45 percent or more, and the maximum subsidy for a single project is 10 million yuan (Shanghai Municipal Housing Administration et al., 2014).

The effects of governmental subsidy are particularly significant in the early development stage of OSC, as evidenced by Pan et al. (2007) and Zhang (2013). However, despite the strong policy stimulus, the promotion of OSC is still challenging, and the OSC policies have often failed to attract active participation from the private sector (Park et al., 2011). In the prefabricated building market, building developers, consumers, and government are the three major market participants. Building developers are suppliers of the prefabricated building products. They are subject to restrictions and constraints of both internal factors (i.e., economic interest of enterprises) and external factors (i.e., constraints of policies and regulations, and competitive pressure from the market). Consumers are demand subject for the prefabricated building products. Prices and quality of prefabricated buildings are the main factors that influence consumers' individual preference and purchasing behaviors. Government, on the other hand, provides policy guidance and specific incentives for prefabricated construction, to encourage active participations of building developers and consumers, through the form of direct fund subsidy (Gao & Tian, 2020).

Government subsidies, enterprise competition, consumer preference, and prefabricated assembly level are important decision factors that affect decisions among the three stakeholders. The strategic choices and game decisions among the three major stakeholders play a leading role in the effective promotion of OSC adoption. Government's reasonable financial subsidy policies are highly correlated with accurate judgments of actual development progress of the OSC industry. Building developers are influenced by government subsidy policies and consumer preferences when making production and operation decisions. Therefore, a systematic analysis of these factors and their interrelationships is essential to facilitate the synergy among the three stakeholders and promote the development of the prefabricated construction industry.

However, despite the importance of existing efforts, there is still a lack of research on the interaction mechanism among government subsidy policies, consumer preferences, and developers' decisions, and many research questions still remain unanswered. For example, how should the government formulate an effective financial subsidy policy based on the actual development status of the prefabrication industry? How should building developers respond to government subsidy policies and make further decisions on production and operation? And, how do consumers' perceptions of the prefabricated buildings affect the prefabricated construction market and the decisions of real estate developers? In view of this, this study aims to analyze the dynamic behavior strategies of the three stakeholders in the prefabricated construction market [i.e., the government, two types of building developers (active and passive developers adopting prefabricated building methods), and consumers]. A three-stage game model is developed to derive the equilibrium solution of the optimal selling price, optimal assembly rate, and optimal minimum assembly rate for subsidy. Different scenarios are also numerically analyzed to illustrate the interactions and decision-making behaviors of the three stakeholders in the game, which will contribute, both theoretically and practically, to enterprise decision, policy design, and industry development of OSC.

The remainder of this paper is organized as follows: Section 1 provides an extensive literature review of the existing research efforts and identifies the knowledge gaps; Section 2 introduces the research methodology and the mechanics of the three-stage game model; Section 3 presents the results and discussion for the numerical simulation; Section 4 discusses the managerial implications. Final section summarizes the conclusions and future work directions.

1. Literature review

1.1. Government role on enterprise decision making

A number of research efforts have been conducted on government subsidy policies and enterprise decision making. "Welfare Economics", which was proposed by Pigou (1920), is the first study on government financial subsidies. According to Pigou, social welfare maximization cannot be achieved due to the externalities of economics. Government should thus intervene by adopting "extra rewards" (subsidies) or "extra restrictions" (tax). Leahy and Neary (1997) studied two types of subsidies, i.e., research and development (R&D) subsidies and production subsidies, and classified them into four game scenarios according to the commitment of government. Girma et al. (2008)

studied the effects of government subsidies in Irish, and found that government subsidies were effective in overcoming corporate financial crises and assisting new technology adoption. Mitra and Webster (2008) analyzed the importance of government subsidies in remanufacturing activities by establishing a two-stage game model between producers and remanufacturers, and comparing three subsidy scenarios (i.e., government giving subsidies to remanufacturers, to producers, or to both), and found that the introduction of subsidies could increase remanufacturing activity. Sheu and Chen (2012) developed a three-stage game model for examining the impact of government subsidies on the profits of green supply chains, and the results showed that, with green taxation and subsidization, social welfare and chain-based profits improved by 27.8% and 306.6%, respectively, compared with the case without financial intervention. Zhang et al. (2014a, 2014b) explored the impacts of different government subsidies on the profits of supply chain companies, taking the biofuel supply chain as a case study. Raz and Ovchinnikov (2015) analyzed how the government coordinated manufacturers' pricing and supply through rebates and subsidies, and conducted a numerical analysis using data from the electric vehicle industry. Miao et al. (2018) analyzed the optimal pricing and production decisions of manufacturers under the carbon tax policy and the cap-and-trade program. Ma et al. (2018) analyzed the effects of carbon tax policies on supplier wholesale prices, production quantities, as well as manufacturer procurement decisions and sales prices in a supply chain system with multiple suppliers and a single manufacturer.

Government incentives in the prefabricated construction market has also been emphasized in previous studies. For example, existing studies have found that the improvement of incentives is one of the policy recommendations for the development of prefabricated buildings (Yang et al., 2017); and the imperfect performance in OSC policy and laws is one of the main barriers at present based on an Interpretive Structural Model (ISM) analysis (Gan et al., 2019). Accordingly, it has been widely acknowledged that government is the main incentive subject for the development of sustainable construction (e.g., prefabricated construction), especially at the starting stage; and positive intervention of government has always been the driving force for the advancement of prefabricated construction (Jiang et al., 2017). For example, Wu et al. (2019a) concluded that government is the main leader in the promotion of prefabricated buildings through analyzing the influential factor model; Mao et al. (2018) regarded government policy as the original driving factor in the critical driving path revealed by a structural equation model to promote the development of OSC. In practice, both Chinese central and local governments presented varied policy measures to facilitate the wide use of prefabricated construction and to cultivate the prefabricated building market (Zhang et al., 2016). Economic incentives were proposed as the predominant methods in varied government incentives and region-specific incentive mechanisms should be established in different stages (Guo et al., 2015). As for the different stakeholders, Tam et al. (2007) mentioned that incentive policies should be introduced to encourage initiatives of developers and consumers; Li et al. (2018) surveyed the variables on construction enterprises' willingness to accept the OSC policy by means of the ordered logistic regression analysis; Shi et al. (2018) studied how the incentive policy measures issued by government influenced the effort level of prefabricated building contractors and the profit of owners in mega construction projects; Park et al. (2011) pointed out that the government could reduce the construction cost of developers by providing subsidy, which would facilitate the adoption of OSC by developers.

Some scholars have also studied the evaluation of prefabricated building policies. For example, Park et al. (2011) examined the effectiveness of alternative Singapore prefabrication policies in a qualitative and quantitative manner, considering the private sector's response and subsequent changes. Zhang et al. (2017) proposed an integration framework, including growth management model and OSC policy evaluation method. Liu et al. (2018) constructed a three-dimensional analysis framework based on policy tools to evaluate the comprehensiveness of existing prefabricated construction policy system in China. Tang et al. (2019) presented the deficiencies in OSC policy instruments in Guangzhou, including unclear preferential policies and insufficient research for the policy making.

1.2. Three-stage game model

The theoretical system of game theory was laid by Von Neumann and Morganstein's "Game Theory and Economic Behavior". Three-stage game is a special case of multistage game, which is defined as a finite sequence of standard stage games. It was first introduced to the optimal policy research domain by Spencer and Brander (1983). The model set government's policy choice as the first stage, and then extended into a three-stage game. Each of the three stages is an independent, complete, but imperfect information game (i.e., Simultaneous-Move Games). These stages of the game are sequentially performed by the same participants, and the total payment obtained from this game sequence is evaluated by a sequence of game results. After each stage, the results can be observed by all the participants, and the information becomes common knowledge.

Three-stage game is an intertemporal game that requires the discount of future earnings. The discount factor δ is determined by the patience of the participants, and its value is often assumed to be between zero and one. Let V_{it} be the expected benefits that Participant i obtained from the outcome of the game at stage t, and V_i be the total benefits obtained by Participant i in the multi-stage game. Then V_i can be defined as: $V_i = V_{i1} + \delta_1 V_{i2} + \delta_2 V_{i3}$. In the three-stage game, participants can strategically determine their behaviors in later stages based on the actions taken in earlier stages, in order to maximize benefits.

In a multi-stage game with three stages, the strategies taken by Participant i can be a list of conditional pure strategies in the following form: $S_i = \left\{s_{i1}, s_{i2}\left(h_1\right), s_{i3}\left(h_2\right)\right\}$, where h_{t-1} is the specific result obtained before Stage t (Stage t not included), and $s_{it}\left(h_{t-1}\right)$ is the action that participant i takes at Stage t. In general, the strategies of three-stage games can be defined using an extensive game structure. For example, as in extensive games, the strategies of three-stage games are defined as a complete list of strategies (mixed or pure) for each participant on each information set, and the information set of each participant is connected to the results obtained from previous stage.

Three-stage game method has widely been used in many fields, such as green supply chain management (Sheu & Chen, 2012), and financial supervision mode optimization. It provides a way to investigate the dynamic process of the game players' interactions in different game stages, and find optimal subsequent actions based on full observation of the system. It can thus provide a better understanding of the causal relationships in the internal decision processes, which is an ideal tool for solving logical causality problems in large-scale comprehensive problems.

1.3. State of the art and knowledge gaps

Although a number of research efforts have been undertaken towards discovering the impacts of government policy incentives on decisions of building developers in the prefabricated construction market, substantial knowledge gaps still exist.

First, there is a lack of study that quantitatively analyzes the dynamic and interactive relationship between the government, the developer, and the consumer. Despite the importance of the existing efforts, their research depth is relatively shallow and there is a dearth of research focusing on the prefabricated building policy. The majority of existing studies mainly identified critical barriers by literature review and expert interview, and analyzed the importance level of the influencing factors based on questionnaire survey (e.g., Mao et al., 2015), interpretive structural modeling (e.g., Gan et al., 2018b), or SWOT analysis (e.g., Jiang et al., 2017). Such approaches only investigated and analyzed the influencing factors empirically and qualitatively, which could lead to subjective conclusions. Meanwhile, existing studies only focused on certain governmental incentive behaviors, without discussing them in specific problem contexts, nor discussing how specific policies would mobilize other market players (e.g., the developers). In addition, to the best of the authors' knowledge, Shi et al. (2018) is the only existing effort that studies the similar problem as this study. In Shi et al. (2018), an incentive prefabrication model with reputational concerns from the project owner's perspective was established, and the impacts of incentives on supplier's effort and project owner's profit in mega projects were discussed. Although adopted a similar game theory approach, the planning and management of mega projects (e.g., the Hong Kong-Zhuhai-Macau Bridge in China) are led by the government, which poses significantly different features than the market-led prefabricated construction projects considered in this study. In addition, Shi et al. (2018) is carried out only from the perspective of owners. However, government, building developers, and consumers are all important market players in the development of prefabricated buildings. Therefore, it is necessary to study the interactions of the developers and consumers when facing with different government incentive policies.

Second, there is a lack of study on the impacts of a broad perspective of the barriers and their interlinkages. Existing studies mainly only focus on a limited number of factors and from a specific perspective. For example, Zakaria et al. (2018) categorized factors identified in the literature that explicitly or implicitly impact industrialized building systems (IBS) adoption decision-making and specifically focused on a framework consisting of contextual, structural, and behavioral factors. However, a more holistic review and framework of the barriers is imperative. For example, additional initial construction costs of about 300–500 yuan per m^2 may be increased compared with conventional in-situ construction according to recent studies (Mao et al., 2015; Zhang et al., 2014a, 2014b). This will dampen building developer's enthusiasm in utilizing the prefabricated construction. Based on this, particular government behaviors such as subsidy policy making, should be supportable to the principal participant of prefabricated construction initiative (Arif et al., 2012). By contrast, very few studies attempted to examine how the subsidy policy from the government influence the developer's decision behavior and the perception of stakeholders towards prefabrication and related policies (Steinhardt & Manley, 2016). Specifically, the questions, for example, how Chinese local governments decided the minimum assembly rate to determine subsidy levels and how consumers' preference on prefabricated building affect the revenue of building developers, remain to be further analyzed and studied. However, there is a lack of research on the mechanism of actions among the elements of governmental subsidy, consumer preference, and developers' decision making in the existing publications.

Therefore, to address the above-mentioned knowledge gaps, this study aims to analyze the dynamic behavioral strategies of the three stakeholders in the prefabricated construction industry: the government, two types of building developers (i.e., active and passive developers adopting prefabricated construction methods), and consumers. A three-stage game model was constructed to derive the equilibrium solution of the optimal selling price, optimal assembly rate, and the optimal minimum assembly rate for government subsidy, and analyze the influence of consumer preferences and government subsidy policies on the decisions of selling price, revenue, assembly rate level, and market share by the different prefabricated building developers.

2. Methodology

This study considers the optimization of the government subsidy level, the assembly rate, and the selling price as a three-stage game. On the one hand, developer behavior is directly affected by government subsidy policy and consumer preference. And on the other hand, the information among stakeholders is incomplete. For example, it is impossible for the government to monitor the level of efforts that building developers would spend in the development of prefabricated buildings. Therefore, the government, building developers, and consumers constitute a dynamic multi-stage, multi-player game with incomplete information. The research methodology of this paper is shown in Figure 1.

2.1. Problem description

Prefabricated buildings that are sold by building developers are required to meet the minimum assembly rate by the local government regulations or requirements during land acquisition. Assembly rate is denoted by α. A higher α indicates a higher assembly level. As defined in the Chinese National Standard, *Standard for Assessment of Prefabricated Building*, which is enacted in 2016, the assembly rate of industrial buildings is the ratio of number (or building area) of prefabricated components and building parts to the total number (or the total building area) of similar components or parts. In China's real estate market, there exist two types of building developers based on their attitude towards prefabricated buildings: passive or active. Both types of developers are large real estate companies, because in general, small and medium-sized companies are not capable of engaging in the development of prefabricated buildings. The passive developers are reluctant to develop prefabricated buildings, and they only aim to meet the minimum assembly rate. They are denoted as *Developer A*. The active developers, on the other hand, are highly innovative and motivated to apply cutting-edge technologies in prefabricated buildings. They actively take initiatives to connect with construction companies and component manufacturers, build prefabricated construction supply chains, and explore new prefabrication technologies. They are denoted as *Developer B*. Assembly rate of Developer A and Developer B are denoted by α_A and α_B, respectively. The selling prices of the buildings constructed by Developer A and Developer B are denoted by p_A and p_B, where $p_A \le p_B$, because Developer A's marginal cost of construction is lower than that of Developer B.

In the real estate market, consumers have a wide range of preferences for prefabricated buildings. Some consumers recognize the strengths (e.g., safety, comfort, and energy efficient) of prefabricated buildings. They prefer to pay additional prices for buildings with high assembly rates. Some other consumers, however, are skeptical about the performance of prefabricated buildings, and are not willing to purchase prefabricated building products. The consumer preference level for prefabricated buildings is denoted by ν, and η is the payment coefficient of consumer preference. For each unit of increase in the consumer preference level, consumers are willing to pay an extra amount of η for building products.

In order to encourage building developers to develop and construct buildings with higher assembly rate, the government provides direct subsidies for projects with assembly rate above a certain level. Government subsidy level is calculated based on building assembly rate. For example, in Shanghai, a prefabricated residential project with a total gross floor area of more than 30,000 square meters, can receive a subsidy of 60 yuan (or US$9) per square meter if its assembly rate is 15% or more, and 100 yuan (or US$15) per square meter if its assembly rate is over 25%. Let μ_i be the subsidy coefficient per unit prefabricated building product, where $i = A, B$. Then$\mu_i = t\left(\alpha_i - \underline{\alpha}\right)$, where t is the adjustment coefficient for the subsidy coefficient, and $\underline{\alpha}$ is the lower limit of the assembly rate for government subsidy ($0 \le \mu_i$, $t \le 1$). Then, μ_i can be expressed as follows:

$$\mu_i = \begin{cases} t(\ \alpha_i - \underline{\alpha}\ ) & \alpha_i \ge \underline{\alpha} \\ 0 & \alpha_i < \underline{\alpha} \end{cases}, i = A, B.$$

Accordingly, this paper develops a three-stage game model by considering government subsidies, enterprise competition, consumer preference, and assembly rate. The first stage aims to determine the subsidy coefficient per unit prefabricated building product μ_i; the second stage aims to determine the assembly rates for Developers A and B (i.e., α_A and α_B); and the third stage aims to determine the building selling prices p_A and p_B for both developers.

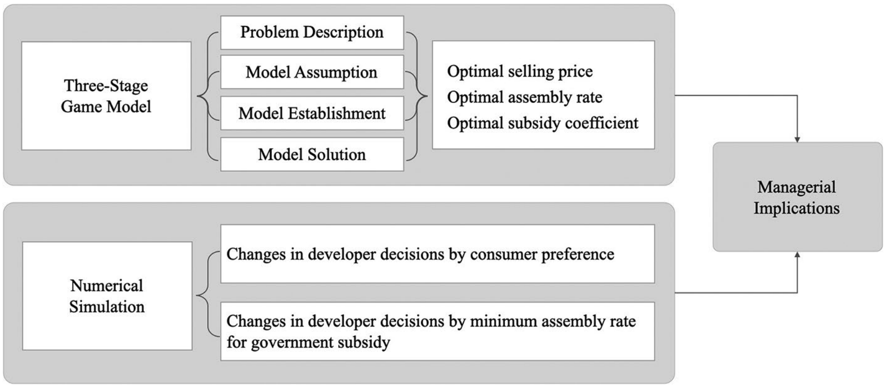

Figure 1. Research methodology

2.2. Model assumptions and notations

To simplify the complex conditions of the problem, this study considers seven assumptions:

(1) The target prefabricated construction market is a duopoly market that is composed of two large real estate companies, Developers A and B. The two companies adopt different strategies in prefabricated building development: passively or actively.

(2) Developers A and B must meet the minimum required assembly rate (denoted by α_0) set by the government at the time of land acquisition (i.e., $\alpha_i > \alpha_0$, where $i = A, B$). Due to the different development strategies adopted by the two developers, it is assumed that the assembly rate of Developer A is lower than the minimum assembly rate for subsidy (i.e., $\alpha_A < \underline{\alpha}$), while the assembly rate of Developer B is higher than the limit (i.e., $\alpha_B > \underline{\alpha}$).

(3) As the prefabrication technology is still in the evolving stage, both the developers have to bear extra costs (denoted by β_A and β_B) for the construction of prefabricated buildings, to train workers and management personnel, propagate prefabricated building products, and select prefabricated construction contractors. It is assumed that the additional cost has a quadratic relationship with the improvement of the assembly rate, i.e., $\beta_i = \varepsilon_i \left(\alpha_i - \alpha_0\right)^2$, where ε_i is an additional cost coefficient, α_0 is the minimum assembly rate required by the government, and α_i is the assembly rate of Developers A and B ($i = A, B$).

(4) Prefabricated construction technology could improve construction efficiency, save materials, and reduce labor use. Increasing assembly rate would thus reduce marginal cost. The reduced marginal cost is defined as $\delta_i = \gamma_i \left(\alpha_i - \alpha_0\right)$, where γ_i is the marginal cost reduction rate ($i = A, B$). In addition, the construction costs of Developers A and B are denoted by c_A and c_B, where $c_A \le c_B$.

(5) Consumer preference ν for the prefabricated building products is uniformly distributed, i.e., $\nu \sim \left[\underline{\nu}, \overline{\nu}\right]$, where $\underline{\nu}, \overline{\nu}$ denote the lower and upper limits of the consumer preferences, respectively. It represents the range of consumers from those who would never purchase prefabricated building products to those who are extremely inclined to building products with high assembly rate. When $p_A + \eta\left(\nu - \underline{\nu}\right) = p_B - p_B\mu_B$, there exist a purchase preference ν^*, where consumers have no purchase preference regardless of the assembly rate. Eqn (1) shows how ν^* is calculated.

$$\nu^* = \frac{p_B - p_A - p_B t(\ \alpha_B - \underline{\alpha}\ )}{\eta} + \underline{\nu}. \tag{1}$$

(6) Utilities refer to the total satisfaction received from the building products (i.e., purchasing cost saving, building function, environmental performance, etc.). The utilities obtained from Developers A and B's products are denoted by u_A and u_B, respectively. The revenue of Developer A, Developer B, and the government are denoted by π_A, π_B, and π_G, respectively. The revenue that the government obtains in the process of promoting the prefabricated construction technology is the total social welfare, i.e., the sum of enterprise income ($\pi_A + \pi_B$) and consumer surplus ($u_A + u_B$) minus the government subsidies for Developer B $\left[p_B\mu_B q_B = p_B t\left(\alpha_B - \underline{\alpha}\right)q_B\right]$.

(7) The capacity of the prefabricated construction market is assumed to be 1. Considering the market demand for high assembly rate is q_B, then the demand for low assembly rate $q_A = 1 - q_B$.

Table 1 shows a summary of all the notations that are used in this study.

Table 1. Summary of notations

Notation	Meaning	Notation	Meaning
α	Assembly rate	δ_i	Marginal cost reduction amount ($i = A, B$)
α_0	Minimum required assembly rate set by the government	γ_i	Marginal cost reduction rate ($i = A, B$)
$\underline{\alpha}$	Minimum assembly rate for government subsidy	ν	Consumer preference
α_i	Assembly rate of building developers ($i = A, B$)	$\overline{\nu}$	Upper limit of consumer preference
p_i	Building selling price by the building developers ($i = A, B$)	$\underline{\nu}$	Lower limit of consumer preference
c_i	Construction costs of the building developers ($i = A, B$)	u_i	Utilities when consumers purchase the building products ($i = A, B$)
μ_i	Subsidy coefficient per unit prefabricated building product ($i = A$, B)	π_i	Revenue of the building developers ($i = A, B$)
t	Adjustment factor for the subsidy coefficient	π_G	Revenue of the government
β_i	Extra costs for the construction of prefabricated buildings ($i = A, B$)	q_B	Market demand for high assembly rate buildings
ε_i	Additional cost coefficient ($i = A, B$)	q_A	Market demand for low assembly rate buildings
η	Payment coefficient of consumer preference		

2.3. Model establishment

The decision-making process of the government, Developer A, Developer B, and consumers considering government subsidies are modeled in three stages as follows:

- *Stage 1*: With the goal of maximizing social welfare, the government aims to choose the optimal subsidy coefficient for the development of prefabricated buildings. The total social welfare includes the consumer surplus and the revenue of the two building developers.
- *Stage 2*: Given the existing subsidy coefficient set by the government, the two building developers determine their optimal assembly rate to maximize their own revenue.
- *Stage 3*: Considering the competition between the two building developers, their difference in assembly rate, and consumer preference for prefabricated construction products, the two building developers determine their optimal selling price.

Accordingly, the utilities of consumers purchasing the building products by Developer A and Developer B can be expressed by Eqn (2) and Eqn (3):

$$u_A = \int_{\underline{\nu}}^{\nu^*} \frac{\eta(\nu-\underline{\nu})-p_A}{\bar{\nu}-\underline{\nu}}d\nu = \frac{p_B^2\left(1-t(\alpha_B-\underline{\alpha})\right)^2}{2\eta(\bar{\nu}-\underline{\nu})}+$$

$$\frac{3p_A^2-4p_Ap_B\left(1-t(\alpha_B-\underline{\alpha})\right)}{2\eta(\bar{\nu}-\underline{\nu})}; \quad (2)$$

$$u_B = \int_{\nu^*}^{\bar{\nu}} \frac{\eta(\nu-\underline{\nu})-p_B+p_Bt(\alpha_B-\underline{\alpha})}{\bar{\nu}-\underline{\nu}}d\nu = \frac{\eta(\bar{\nu}-\underline{\nu})}{2}-$$

$$p_B\left(1-t(\alpha_B-\underline{\alpha})\right)+\frac{p_B{}^2\left(1-t(\alpha_B-\underline{\alpha})\right)^2-p_A{}^2}{2\eta(\bar{\nu}-\underline{\nu})}. \quad (3)$$

The revenue of Developers A and B can be calculated by Eqn (4) and Eqn (5):

$$\pi_A = \left(p_A-c_A+\gamma_A(\alpha_A-\alpha_0)\right)(1-q_B)-$$

$$\varepsilon_A(\alpha_A-\alpha_0)^2; \quad (4)$$

$$\pi_B = \left(p_B-c_B+\gamma_B(\alpha_B-\alpha_0)+\right.$$

$$\left.p_Bt(\alpha_B-\underline{\alpha})\right)*q_B-\varepsilon_B(\alpha_B-\alpha_0)^2. \quad (5)$$

The revenue of the government can be calculated by Eqn (6):

$$\pi_G = \pi_A+\pi_B+u_A+u_B-p_Bt\alpha_B-\underline{\alpha}q_B. \quad (6)$$

The market demand for low and high assembly rate building products adds up to 1 (i.e., $q_A + q_B = 1$). This relationship can further be expressed as Eqn (7):

$$q_A = 1-\int_{\nu^*}^{\bar{\nu}}\frac{1}{\bar{\nu}-\underline{\nu}}d\nu = \frac{1-t(\alpha_B-\underline{\alpha})}{\eta(\bar{\nu}-\underline{\nu})}p_B-\frac{1}{\eta(\bar{\nu}-\underline{\nu})}p_A. \quad (7)$$

2.4. Model solution

The above three-stage dynamic game model can be solved by backward induction.

2.4.1. Stage 3: Solution for the optimal selling price for building developers

Find the first derivative of p_A and p_B for π_A and π_B, respectively, and get the optimal solutions for p_A and p_B as follows:

$$p_A^* = \frac{1-t(\alpha_B-\underline{\alpha})}{2}p_B^*+\frac{c_A-\gamma_A(\alpha_A-\alpha_0)}{2}; \quad (8)$$

$$p_A^* = \frac{\eta(\bar{\nu}-\underline{\nu})+2\left(c_A-\gamma_A(\alpha_A-\alpha_0)\right)}{3}+$$

$$\frac{\left(1-t(\alpha_B-\underline{\alpha})\right)\left(c_B-\gamma_B(\alpha_B-\alpha_0)\right)}{3\left(1+t(\alpha_B-\underline{\alpha})\right)}; \quad (9)$$

$$p_B^* = \frac{2\eta(\bar{\nu}-\underline{\nu})+c_A-\gamma_A(\alpha_A-\alpha_0)}{3\left(1-t(\alpha_B-\underline{\alpha})\right)}+$$

$$\frac{2c_B-2\gamma_B(\alpha_B-\alpha_0)}{3\left(1+t(\alpha_B-\underline{\alpha})\right)}. \quad (10)$$

Proposition 1. The enhancement of assembly rate α_i will increase the marginal cost reduction rate γ_i and reduce the marginal construction cost c_i (i = A, B). Based on Eqn (8), with the increase of p_A, the component $\frac{c_A-\gamma_A(\alpha_A-\alpha_0)}{2}$ decreases, which will lead to an increase of the difference between the selling prices of Developers A and B (i.e., $p_B^*-p_A^*$). In the actual market competition, Developer A will take actions to improve γ_A while balancing the construction cost c_A. Considering the increasing price difference, Developer A tends to adopt a low price strategy, while Developer B will rely on the advantages of their high assembly rate to maintain a higher price to win the consumer market.

Proposition 2. Equations (9) and (10) indicate that the greater the payment coefficient η, the higher the consumer preference for the prefabricated buildings, and the higher the selling prices for both developers. Therefore, taking measures to increase consumers' willingness to purchase prefabricated construction products will benefit both building developers.

Proposition 3. Further analysis of Eqns (9) and (10) indicates that the increase of the minimum required assembly rate α_0 will increase the selling price for the building products with both low and high assembly rate constructed by Developer A and B. This can be proved by finding the first derivative of α_0 for p_A^* and p_B^*, respectively.

$$\frac{\partial p_A^*}{\partial\alpha_0} = \frac{2\gamma_A}{3}+\frac{\gamma_B\left(1-t(\alpha_B-\underline{\alpha})\right)}{3\left(1+t(\alpha_B-\underline{\alpha})\right)}>0;$$

$$\frac{\partial p_B^*}{\partial\alpha_0} = \frac{\gamma_A}{3\left(1-t(\alpha_B-\underline{\alpha})\right)}+\frac{2\gamma_B}{3\left(1+t(\alpha_B-\underline{\alpha})\right)}>0.$$

The above formulas indicate that p_A^* and p_B^* are both monotone increasing functions of α_0, thus proved Proposition 3. If keeping the development status and technical level of the prefabricated construction industry unchanged, the price of building products with both high and low assembly rate will increase only by raising the minimum required assembly rate. Therefore, government decisions will have an important impact on the development of prefabricated construction market.

Proposition 4. If the minimum required assembly rate α_0 changes, the market share of Developer A and B will change accordingly. This change is related to the ratio of their marginal cost reduction rates γ_A and γ_B.

Substituting p_A^* and p_B^* into Eqn (7):

$$q_A^* = \frac{\eta(\bar{v}-\underline{v}) - c_A + \gamma_A(\alpha_A - \alpha_0)}{3\eta(\bar{v}-\underline{v})} + \frac{(1-t(\alpha_B-\underline{\alpha}))(c_B - \gamma_B(\alpha_B-\alpha_0))}{3\eta(\bar{v}-\underline{v})(1+t(\alpha_B-\underline{\alpha}))}; \tag{11}$$

$$q_B^* = \frac{2\eta(\bar{v}-\underline{v}) + c_A - \gamma_A(\alpha_A - \alpha_0)}{3\eta(\bar{v}-\underline{v})} - \frac{(1-t(\alpha_B-\underline{\alpha}))(c_B - \gamma_B(\alpha_B-\alpha_0))}{3\eta(\bar{v}-\underline{v})(1+t(\alpha_B-\underline{\alpha}))}. \tag{12}$$

Based on the first derivative of α_0 for q_A^* and *, we can obtain:

$$\frac{\gamma_A}{\gamma_B} = \frac{(1-t(\alpha_B-\underline{\alpha}))}{(1+t(\alpha_B-\underline{\alpha}))}.$$

When $\frac{\partial q_A^*}{\partial \alpha_0} > 0$ and $\frac{\partial q_B^*}{\partial \alpha_0} < 0$, $\frac{\gamma_A}{\gamma_B} < \frac{(1-t(\alpha_B-\underline{\alpha}))}{(1+t(\alpha_B-\underline{\alpha}))}$;

When $\frac{\partial q_A^*}{\partial \alpha_0} < 0$ and $\frac{\partial q_B^*}{\partial \alpha_0} > 0$, $\frac{\gamma_A}{\gamma_B} > \frac{(1-t(\alpha_B-\underline{\alpha}))}{(1+t(\alpha_B-\underline{\alpha}))}$.

The above results indicate that, when $\frac{\gamma_A}{\gamma_B} < \frac{(1-t(\alpha_B-\underline{\alpha}))}{(1+t(\alpha_B-\underline{\alpha}))}$, the minimum required assembly rate is positively related to the market share of Developer A, while negatively related to the market share of Developer B. On the contrary, when $\frac{\gamma_A}{\gamma_B} > \frac{(1-t(\alpha_B-\underline{\alpha}))}{(1+t(\alpha_B-\underline{\alpha}))}$, the minimum required assembly rate is negatively related to the market share of Developer A, while positively related to the market share of Developer B. When $\frac{\gamma_A}{\gamma_B} = \frac{(1-t(\alpha_B-\underline{\alpha}))}{(1+t(\alpha_B-\underline{\alpha}))}$, the market share of Developers A and B remains unchanged regardless of the change of the minimum required assembly rate.

2.4.2. Stage 2: Solution for the optimal assembly rate for building developers

The revenues of Developers A and B can be calculated by substituting p_A^*, p_B^*, q_A^*, and q_B^* into Eqns (4) and (5):

$$\pi_A^* = \left(p_A^* - c_A + \gamma_A(\alpha_A - \alpha_0)\right)\left(1 - q_B^*\right) - \varepsilon_A(\alpha_A - \alpha_0)^2; \tag{13}$$

$$\pi_B^* = \left(p_B^* - c_B + \gamma_B(\alpha_B - \alpha_0) + p_B^* t(\alpha_B - \underline{\alpha})\right) * q_B^* - \varepsilon_B(\alpha_B - \alpha_0)^2. \tag{14}$$

The revenue of the government is:

$$\pi_G^* = \pi_A^* + \pi_B^* + u_A + u_B - p_B^* t\alpha_B - \underline{\alpha} q_B^*. \tag{15}$$

Take the first derivative of α_A and α_B for π_A^* and π_B^*, respectively:

$$\alpha_A^* = \alpha_0 + \frac{\gamma_A}{\gamma_A^2 - 9\varepsilon_A\eta(\bar{v}-\underline{v})}\left[c_A - \eta(\bar{v}-\underline{v}) - \frac{(1-t(\alpha_B-\underline{\alpha}))(c_B - \gamma_B(\alpha_B-\alpha_0))}{1+t(\alpha_B-\underline{\alpha})}\right] \tag{16}$$

and α_B^* meet

$$\frac{2t(2\eta(\bar{v}-\underline{v})) + c_A - \gamma_A(\alpha_B - \alpha_0) + \varepsilon_B}{3\left(1+t(\alpha_B^*-\underline{\alpha})\right)^2} q_B^* - 2\varepsilon_B(\alpha_B^* - \alpha_0) = 0. \tag{17}$$

2.4.3. Stage 1: Solution for the optimal subsidy coefficient

Taking the first derivative of the adjustment factor t for Eqn (15), the optimal adjustment factor t^* can then be obtained. The optimal subsidy coefficient can thus be calculated by $\mu_i^* = t^*(\alpha_i - \underline{\alpha})$, where t^* satisfies Eqn (18):

$$\alpha_A^* = \alpha_0 + \frac{\gamma_A}{\gamma_A^2 - 9\varepsilon_A\eta(\bar{v}-\underline{v})}\left[c_A - \eta(\bar{v}-\underline{v}) - \frac{(1-t(\alpha_B-\underline{\alpha}))(c_B - \gamma_B(\alpha_B-\alpha_0))}{1+t(\alpha_B-\underline{\alpha})}\right] \tag{18}$$

and α_B^* satisfies Eqn (19):

$$\frac{2(\alpha_B^*-\alpha_0)(c_B - \gamma_B(\alpha_B^*-\alpha_0))}{3\left(1+t^*(\alpha_B^*-\underline{\alpha})\right)^2}\Big(2 - (1-t^*(\alpha_B^*-\underline{\alpha}))p_B^* + c_A - \gamma_A(\alpha_B^*-\alpha_0)\Big) - \frac{2(\alpha_B^*-\underline{\alpha})(c_B - \gamma_B(\alpha_B^*-\alpha_0))}{3\left(1+t^*(\alpha_B^*-\underline{\alpha})\right)^2} q_A^* - \frac{2(\alpha_B^*-\underline{\alpha})(c_B - \gamma_B(\alpha_B^*-\alpha_0))(p_A^* - c_A + \gamma_A(\alpha_A^*-\alpha_0))}{3\eta(\bar{v}-\underline{v})\left(1+t^*(\alpha_B^*-\underline{\alpha})\right)^2} +$$

$$\frac{\left(\alpha_B^* - \underline{\alpha}\right)\left(2\eta\left(\overline{\nu} - \underline{\nu}\right) + c_A - \gamma_A\left(\alpha_A^* - \alpha_0\right)\right)}{3\left(1 - t^*\left(\alpha_B^* - \underline{\alpha}\right)\right)^2} +$$

$$\frac{2\left(\alpha_B^* - \underline{\alpha}\right)\left(c_B - \gamma_B\left(\alpha_B^* - \alpha_0\right)\right)}{3\left(1 + t^*\left(\alpha_B^* - \underline{\alpha}\right)\right)^2} q_B^* +$$

$$\frac{2\left(\alpha_B^* - \underline{\alpha}\right)\left(c_B - \gamma_B\left(\alpha_B^* - \alpha_0\right)\right)\left(p_B^* - c_B + \gamma_B\left(\alpha_B^* - \alpha_0\right)\right)}{3\eta\left(\overline{\nu} - \underline{\nu}\right)\left(1 + t^*\left(\alpha_B^* - \underline{\alpha}\right)\right)^2} = 0. \quad (19)$$

3. Numerical simulation

Due to the complexity of the above equations, this study used Matlab software (R2014a) to approximate the solutions and simulate the dynamic decision process by assigning a value to each parameter to get further insights. Two numerical simulations are conducted to analyze the impact of ν, the consumer preference, and $\underline{\alpha}$, the minimum assembly rate for government subsidy, to provide decision support for the government and the building developers.

3.1. Impact of changes in consumer preference ν

Table 2 shows the dynamic changes of all the factors caused by changes in consumer preference. The simulation results are plotted in Figure 2. According to the results, with the increase of consumer preference ν, the adjustment factor for the subsidy coefficient t, the ratio of building selling price for low and high assembly rate p_A / p_B, and the ratio of the equilibrium revenues of Developer A and B, π_A / π_B, all show a decreasing trend. The subsidy coefficient of Developer B μ_B, the equilibrium prices p_A and p_B, the revenue of the developers π_A and π_B, the total social welfare π_G, as well as the assembly rate of Developer B α_B, are all gradually increasing. The market share for low assembly rate buildings q_A, the ratio of the equilibrium production of Developers A and B q_A / q_B, and the assembly rate of Developer A α_A, all decrease first and then increase, but with an overall increasing trend. The market share for high assembly rate buildings q_B has tendency to increase first and then decrease, with an overall decreasing trend.

Building selling price: The increase of p_A and p_B indicates that consumers are increasingly recognizing prefabricated buildings and are willing to pay more; but the decrease of their ratio p_A / p_B indicates that the price difference has an increasing trend, which means that, compared with the building products with low assembly rate, those with high assembly rate have a higher price and better market recognition. This is consistent with Proposition 1 and 2 in the Model Solution section (Section 2.4.1).

Stakeholder revenue: The increase of the revenues π_A and π_B indicates that building developers are profitable in developing prefabricated buildings, regardless of their strategies; however, the decrease of their ratio π_A / π_B further indicates that the active developer, Developer B, would increase its revenue faster. The total social welfare π_G will continuously increase, and change from negative to positive. This indicates that prefabricated construction will be gradually recognized by the market, and the total cost of society is constantly decreasing. The adjustment factor t has gradually become smaller, while the subsidy coefficient μ_B is constantly increasing. This shows that with the increase of market acceptance of building products in high assembly rate, the market income of Developer B will continue to increase, while the government subsidies will constantly decrease. This also indicates the cultivation and development to the assembly building market.

Market share: With the increase of consumers' preference for prefabricated buildings, the passive developer has a tendency to transform to active prefabricated building developers. As the ratio of the equilibrium production of the two types of developers q_A / q_B increases, the market share of the passive developer (Developer A) increases (i.e., q_A shows a gradually increasing trend), while the market share of the active developer (Developer B) decreases, and they both determine the increase in the total market share of prefabricated building products. This is consistent with Proposition 4 in the Model Solution section (Section 2.4.1).

Table 2. Dynamic changes of all the factors caused by changes in consumer preference ν ($c_A = 3$; $c_B = 4$; $\varepsilon_A = \varepsilon_B = 1$; $\overline{\nu} = 8$; $\underline{\nu} = 2$; $\alpha_0 = 1$; $\underline{\alpha} = 2$; $\gamma_A = \gamma_B = 0.5$)

ν	t	p_A	p_B	q_A	q_B	α_A	α_B	π_A	π_B	π_G	p_A / p_B	q_A / q_B	π_A / π_B	μ_B
0.5	0.5000	3.7816	4.6735	0.2680	0.7320	1.0447	2.0376	0.2135	–0.1395	–2.8605	0.8091	0.3661	–1.5299	0.0188
0.6	0.4996	3.9059	5.1450	0.2576	0.7424	1.0429	2.1213	0.2370	0.2405	–2.5483	0.7591	0.3470	0.9857	0.0606
0.7	0.4981	4.0488	5.6542	0.2548	0.7452	1.0425	2.1901	0.2708	0.6589	–2.2155	0.7160	0.3419	0.4110	0.0947
0.8	0.4946	4.2060	6.1870	0.2557	0.7443	1.0426	2.2463	0.3120	1.0994	–1.8691	0.6798	0.3435	0.2838	0.1218
0.9	0.4892	4.3736	6.7331	0.2583	0.7416	1.0430	2.2928	0.3586	1.5504	–1.5146	0.6495	0.3483	0.2313	0.1432
1.0	0.4819	4.5488	7.2853	0.2618	0.7382	1.0436	2.3321	0.4092	2.0033	–1.1565	0.6244	0.3546	0.2043	0.1600
1.1	0.4733	4.7294	7.8397	0.2654	0.7346	1.0442	2.3662	0.4629	2.4542	–0.7972	0.6033	0.3612	0.1886	0.1733
1.2	0.4639	4.9141	8.3932	0.2689	0.7310	1.0448	2.3962	0.5188	2.9004	–0.4383	0.5855	0.3679	0.1789	0.1838
1.3	0.4541	5.1017	8.9456	0.2723	0.7276	1.0454	2.4233	0.5765	3.3419	–0.0803	0.5703	0.3743	0.1725	0.1922
1.4	0.4441	5.2916	9.4949	0.2755	0.7244	1.0459	2.4479	0.6357	3.7771	0.2761	0.5573	0.3803	0.1683	0.1989
1.5	0.4341	5.4833	10.0411	0.2785	0.7215	1.0464	2.4706	0.6959	4.2064	0.6306	0.5461	0.3860	0.1654	0.2043

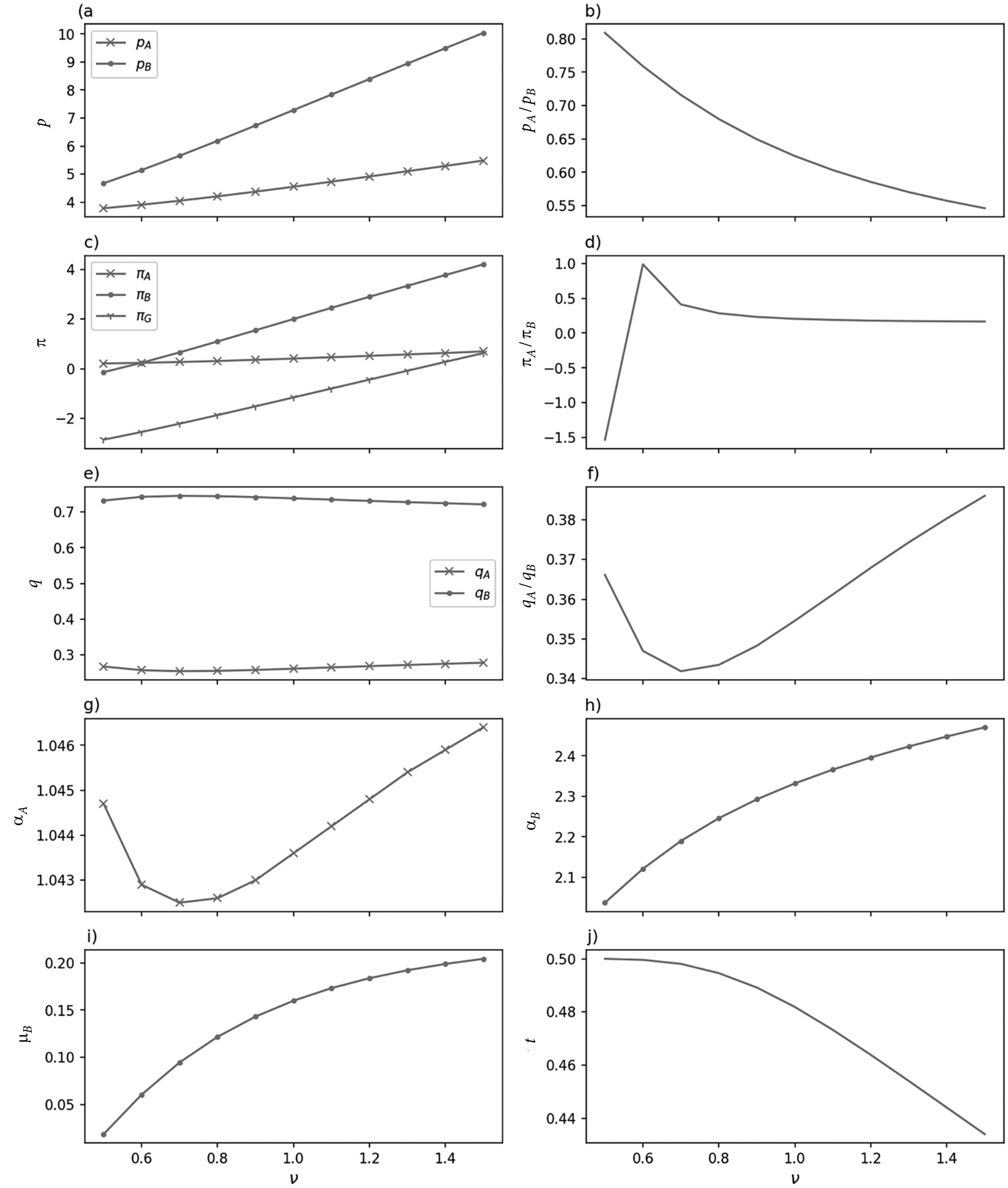

Figure 2. Plots of the dynamic changes of all the factors caused by changes in consumer preference

Assembly rate level: The assembly rate of the active Developer B is continuously increasing, which helps to promote the overall construction industrialization, thereby increasing construction efficiency and enhancing the sensational effect and public confidence for prefabricated buildings. Due to the under-development conditions in China's current OSC market, the increase in assembly rate will significantly increase stakeholder revenues (Zhang, 2019), which is consistent with Proposition 3 in the Model Solution section (Section 2.4.1). Improving assembly rate level thus has profound impacts on the development of prefabricated building market.

3.2. Impact of changes in minimum assembly rate for government subsidy $\underline{\alpha}$

Table 3 shows the dynamic changes of all the factors caused by changes in minimum assembly rate for government subsidy. The simulation results are plotted in Figure 3. According to the results, with the increase of the lower limit of the assembly rate $\underline{\alpha}$, the selling price for buildings with low assembly rate p_A, the market share for low assembly rate buildings q_A, the assembly rate of Developer A α_A, the revenue of Developer A π_A, the ratio of building selling price for low and high assembly rate p_A/p_B, and the ratio of the equilibrium production of Developers A and B q_A/q_B, are all gradually decreasing. The revenue of Developer B π_B and the total social welfare π_G showed an increasing-decreasing trend. The ratio of the equilibrium

Table 3. Dynamic changes of all the factors caused by changes in minimum assembly rate for government subsidy $\underline{\alpha}$ ($\nu = 1.5$; $c_A = 3$; $c_B = 4$; $\varepsilon_A = \varepsilon_B = 1$; $\overline{\nu} = 8$; $\underline{\nu} = 2$; $\alpha_0 = 1$; $\gamma_A = \gamma_B = 0.5$)

$\underline{\alpha}$	t	p_A	p_B	q_A	q_B	α_A	α_B	π_A	π_B	π_G	p_A / p_B	q_A / q_B	π_A / π_B	μ_B
2.0	0.2481	6.4805	12.1607	0.2921	0.7079	1.0487	2.7210	1.0213	4.9645	1.4841	0.5329	0.4127	0.2057	0.1789
2.1	0.3269	6.4489	12.5387	0.2894	0.7106	1.0482	2.7384	1.0028	5.5224	1.7490	0.5143	0.4073	0.1816	0.2086
2.2	0.4069	6.4198	12.8954	0.2870	0.7130	1.0478	2.7778	0.9860	5.9776	1.9265	0.4978	0.4025	0.1649	0.2351
2.3	0.4803	6.3942	13.2113	0.2848	0.7152	1.0475	2.8357	0.9712	6.3053	2.0070	0.4840	0.3982	0.1540	0.2572
2.4	0.5431	6.3719	13.4779	0.2829	0.7170	1.0472	2.9069	0.9586	6.5039	1.9953	0.4727	0.3946	0.1473	0.2753
2.5	0.5939	6.3525	13.6987	0.2813	0.7187	1.0469	2.9880	0.9476	6.5856	1.9012	0.4637	0.3914	0.1439	0.2898
2.6	0.6310	6.3358	13.8682	0.2799	0.7201	1.0466	3.0769	0.9381	6.5451	1.7235	0.4568	0.3887	0.1433	0.3009
2.7	0.6504	6.3216	13.9748	0.2787	0.7212	1.0464	3.1740	0.9302	6.3596	1.4482	0.4523	0.3864	0.1462	0.3083
2.8	0.6470	6.3103	13.9971	0.2778	0.7222	1.0463	3.2807	0.9238	5.9859	1.0480	0.4508	0.3846	0.1543	0.3110
2.9	0.6194	6.3016	13.9253	0.2771	0.7229	1.0462	3.3984	0.9190	5.3978	0.5037	0.4525	0.3832	0.1702	0.3087
3.0	0.5770	6.2947	13.7850	0.2765	0.7235	1.0461	3.5246	0.9151	4.6384	–0.1605	0.4566	0.3821	0.1973	0.3027

revenues of Developers A and B π_A / π_B showed a decreasing-increasing trend. And the selling price for buildings with high assembly rate p_B, the adjustment factor for the subsidy coefficient t, the market share for high assembly rate buildings q_B, the assembly rate of Developer B α_B, and the subsidy coefficient of Developer B μ_B, all shows an increasing trend.

Building selling price: The increase of p_B, as well as the decrease of p_A and the equilibrium price ratio p_A / p_B show that, on one hand, increasing the required assembly rate will increase prices of building products with high assembly rate; and on the other hand, consumers still have high preferences for prefabricated building products.

Stakeholder revenue: The decrease of π_A, as well as the rise-drop of π_B and π_G, indicate that raising the minimum assembly rate will inhibit the revenue of the companies that passively develop prefabricated buildings. For the active developer and the society, revenues will increase, but there is a turning point. Excessively increasing the minimum assembly rate will bring a revenue decrease, which will impede the development of the prefabricated industry. This finding is also confirmed by the drop-rise pattern of the equilibrium revenue ratio π_A / π_B.

Market share: The reduction of market share q_A and increase of market share q_B indicate that the increase of minimum required assembly rate can effectively expand market size of prefabricated construction industry. The decreasing trend of the equilibrium production ratio q_A / q_B indicates that with the increase of the minimum assembly rate, the market share of the passive developers tends to increase.

Assembly rate level: The assembly rate levels α_A and α_B are decreasing and increasing respectively, but compared to the moderate change of α_A, the change of α_B is significant, which indicate that the passive developers are not sensitive to the change of required assembly rate, while the active developers will continuously improve their assembly rate in order to obtain government subsidies. The increase of the adjustment factor t and the subsidy coefficient of Developer B μ_B is an objective requirement for improving the lower limit of the assembly rate.

4. Managerial implications

Based on the results of the above-mentioned model solution and numerical simulation analysis, consumer preferences and the minimum assembly rate for government subsidies have significant impacts on the selling price, revenue, building assembly rate, and market share of prefabricated building developers. Several managerial implications are thus identified as follows.

First, consumer preference can provide a fundamental driving force for the development of the OSC market, and it is necessary to guide and cultivate consumers' recognition for prefabricated buildings. The increase of consumer preference will drive the increase of the selling price of prefabricated buildings and resolve the major barrier for high costs (Rahman, 2014). This will benefit both types of developers – both of their revenues are positively increasing. Although the total social welfare is negative in the short term, the absolute negative value is constantly decreasing, which indicates the long-term benefits for all the stakeholders. In addition, increased consumer preference can also expand the scale of the prefabricated building market and improve the assembly rate level of the active developers. Three potential methods could be considered to improve consumer preference. First, government should take the lead to promote prefabricated buildings. As the largest market demander for public buildings (i.e., hospitals, libraries, and schools), government can better demonstrate the feasibility and benefits of prefabricated buildings, which would stimulate the market and consumers' preferences (Wuni & Shen, 2020). Second, cultivating leading developers and initiating pilot projects could increase the market demand for prefabricated buildings, and also better propagate the hidden value of prefabricated construction for rapid turnover and improved sustainability. And third, more education is needed to enhance public and industry awareness of the benefits of prefabricated construction. Government should cooperate with industry leaders to change the current situation of low recognition and acceptance for OSC, and stimulate the potential market demand of prefabricated buildings (Rahman, 2014).

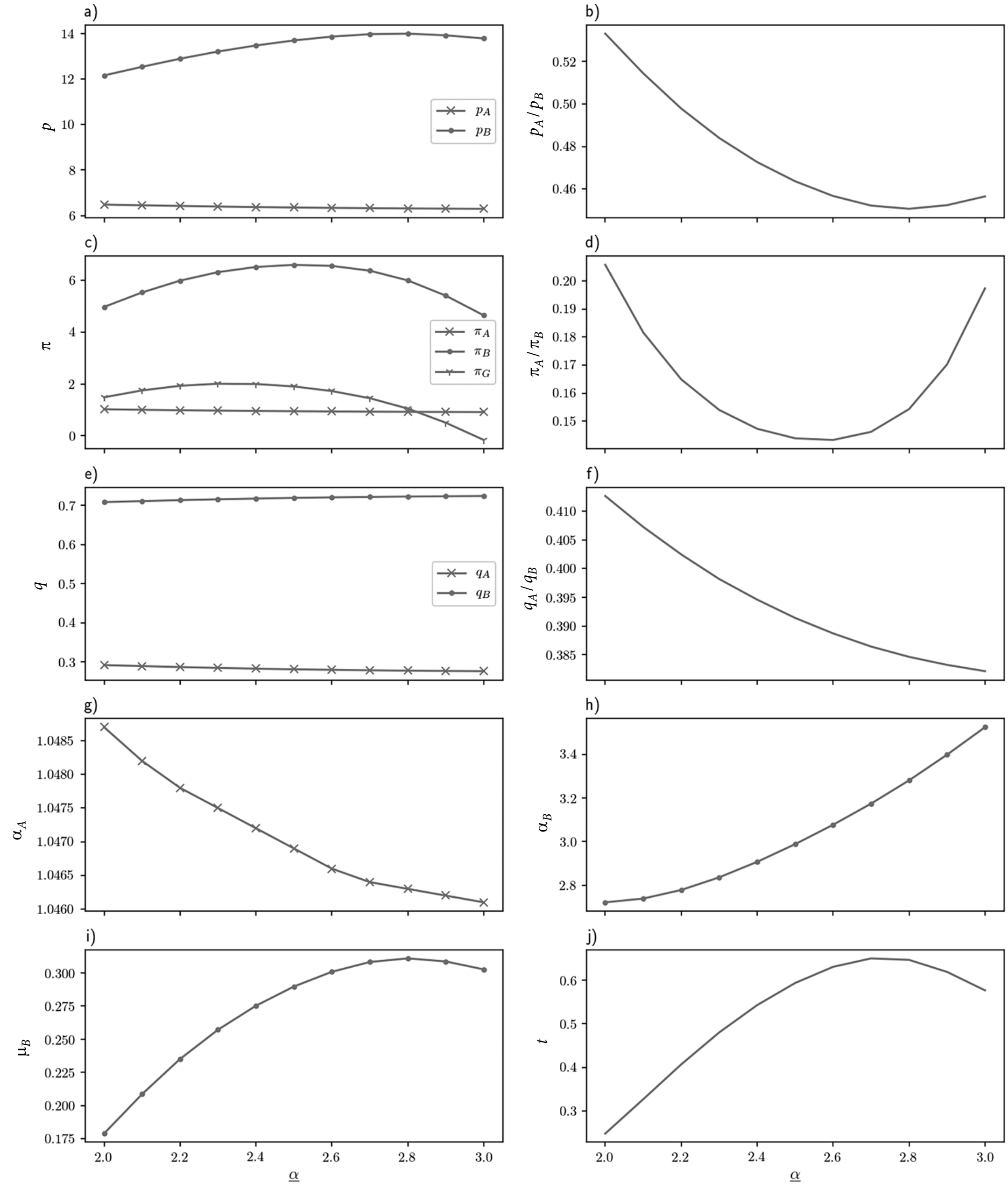

Figure 3. Plots of the dynamic changes of all the factors caused by changes in minimum assembly rate for government subsidy

Second, more efforts are needed to reduce the cost of prefabricated building developers. With the decrease of construction cost, developers' revenue will increase, and government subsidies will drop, as analyzed in Section 4.1. This is consistent with the general growth pattern for the cultivation of emerging industries. To reduce the cost for the successful implementation and construction of prefabricated buildings, system analysis and early decision-making are essential (Song et al., 2005). On the one hand, it is necessary to make early management plans. Prefabricated components and modules need to be produced before construction and assembly, the integration and coordination of different stakeholders need to be strengthened at an early stage of the prefabricated projects (Hwang et al., 2018), and all the different divisions, such as design, labor, component manufacturing and transportation, and technical assembly measures, require careful planning prior to the start of the OSC projects (Kamali & Hewage, 2016). On the other hand, building developers should actively seek collaboration with other stakeholders (i.e., construction companies and component manufacturers), to reduce marginal production cost and reduce their dependence on government subsidies and supports.

Third, the minimum assembly rate for government subsidies should be carefully selected. As indicated in Section 3.2, raising the minimum assembly rate for government subsidies can effectively increase the scale of the prefabricated construction market, the revenue of active developers, and the total social welfare. However, excessive increase of the rate will lead to a decrease in revenue.

In general, when the marginal production cost of prefabricated building developers is high, the government should appropriately lower the rate to ensure the active developers are profitable and the total social welfare is maximized; when the marginal production cost of prefabricated buildings is reduced, the government can continuously increase the rate. But this should also be within a reasonable limit, because with the increase of the rate, the total social welfare is reduced, and more government subsidies are needed. Therefore, the optimal minimum assembly rate for subsidies should be scientifically formulated and adjusted dynamically according to the cost and potential value of prefabricated buildings (Wu et al., 2019b), as well as the impact of the changes of government subsidy policies on building developers.

Conclusions

Consumer preference and government subsidies are two of the key influencing factors in the decision-making of building developers. A systematic analysis of these factors and their interrelationships is essential to facilitate the synergy among the major market participants and promote the development the prefabricated construction industry. This study aims to analyze the dynamic behavioral strategies of the three stakeholders in the prefabricated construction industry: the government, two types of building developers (i.e., active and passive developers adopting prefabricated construction methods), and consumers. A three-stage game model was constructed to derive the equilibrium solution of the optimal selling price, optimal assembly rate, and the optimal minimum assembly rate for government subsidy, and analyze the influence of consumer preferences and government subsidy policies on the decisions of selling price, revenue, assembly rate level, and market share by the different prefabricated building developers. Two numerical simulations were conducted to identify the influence of the consumers' preference and the minimum assembly rate for government subsidies from the perspectives of selling price, stakeholder revenue, market share, and assembly rate level. Further management implications are proposed according to the results of the model solutions and the numerical simulations.

This study contributes to the body of knowledge in two primary ways. First, this study offers a novel methodology to quantify the intertwined relationships of the main stakeholders in the development of prefabricated buildings. The majority of existing efforts only used empirical research methods to identify the many influencing factors or barriers of prefabricated construction, and failed to quantitatively study the interaction mechanism, process, and trends among the influencing factors. However, to the best of our knowledge, this study is the first effort to quantify how specific influencing factors are interconnected and affecting the development of prefabricated buildings. Based on a three-stage game model and numeric simulation of the model solution, this study quantifies the impacts among the major stakeholders and improves the understanding of interactions among the government, building developers, and consumers dynamically and systematically. Second, this study derives the formula for optimal selling price and optimal assembly rate for building developers, as well as the optimal minimum assembly rate for government subsidy. These results are meaningful for policy design and industry strategic planning at different stages of the development of prefabricated buildings.

One limitation of this study is its duopoly market hypothesis. This is based on the reality that the current prefabricated building market is still embryonic, with underdeveloped technology, low acceptance rate, and limited number of developers that are willingly to lead the market. However, as the market demand increases, the number of enterprises in different links of the OSC supply chain will continue to increase, and the industrial structure and organizational model will change accordingly. Therefore, it is necessary to establish a more realistic model for analysis as market grows. In addition, there is information asymmetry between the government and building developers. How to obtain real market parameter information (such as the assembly rate level) is crucial for the government to formulate of subsidy policies. Further studies considering information asymmetry is thus needed in future research.

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