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Article

Promoting the Application of Off-Site Construction in China's Residential Building Industry from the Angle of Ecosystem

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Abstract: Off-site construction (OSC) is an innovative construction method. However, OSC is not widely applied in residential buildings due to many barriers. Therefore, this paper aims to unravel this puzzle and interpret the slow development of OSC. The paper develops a new analytical lens based on the ecosystem concept. By deconstructing some ecosystem concepts, the paper conceptualizes China's residential building industry ecosystem (RBI-ECO) and proposes three hypotheses. The results show that the current structure of RBI-ECO does not support OSC development. Firstly, the performance of different types of enterprises is imbalanced. Secondly, there is a lack of cooperation between enterprises except for daily communication of projects. Moral risks, competition, and a fragmented supply chain are the primary causes. These barriers in RBI-ECO limit the implementation of OSC. In order to promote the application of OSC, the government can implement mandatory policies and concrete measures, establish a designer-led mechanism, motivate enterprises to transform into comprehensive enterprises, and enhance learning and education for OSC enterprise managers.

Keywords: off-site construction (OSC); residential building industry ecosystem (RBI-ECO); survey; semi-structured interview; recommendations

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1. Introduction

Off-site construction (OSC) is also known as prefabrication [1], industrialized building [2], prefabricated construction [3], and off-site manufacture [4], which is a new type of construction workmanship that allows building components/parts to be prefabricated off-site, and upon prefabrication, transported to the site for assembly [5–8]. OSC has various advantages over traditional construction, including increased efficiency, productivity, safety, and reduced energy consumption. To countries where unique housing provision challenges are emerging, OSC proffers the possibility of expediting the building process and addressing housing shortage issues [3,9]. After WW II, OSC techniques began to be applied worldwide. According to the report of the U.S. Department of Housing and Urban Development, Sweden, Finland, and Norway are the first-tier countries where OSC has made much progress in the housing industry by 2022, with a market share of about 45%; the second tier includes Germany (15%) and Japan (10%). Other countries such as China, Australia, UK, and US are placed at tier-three, where the percentage of OSC for housing market is no more than 6% [10] However, the latest fourteenth Five-Year Plan (2021–2025) of China mandated that at least 30% of the newly built houses have to apply OSC techniques and by 2025, this number has to reach 100% by 2035 [11]. There is no doubt that it is a great challenge for China, especially in the residential building industry, because in China, OSC is not just defined as prefabrication off the site, but also considered as a means for achieving the "modernization of building industry" which includes green

production, prefabrication and mechanization, lean construction, supply chain integration, international and professional project management, and industrial workers [12].

Manifold influencing factors, such as cost, design and manufacturing, logistics, site operation, regulation formation, supply chain, return on investment, technical standardization, personnel and upskilling, industry acceptance, etc., were be identified as the primary causes for slow development of OSC in China [6,13–15]. Mao et al. [9] argued that OSC has higher cost which consists of material cost, labor cost, machinery cost, factory cost, land cost, management cost, and mold cost. Fabrication of prefabricated modules sets a higher requirement on the use of special equipment and upskilled trade workers. For example, a lack of proper workforce upskilling may result in a downgraded level of operational efficiency and productivity of equipment [16]. OSC can inevitably increase the spending on quality-assured design, fabrication, logistics, and site operations that lie in equipment, resources, and workers [17]. A common pitfall is seen as difficulties of putting together the prefabricated modules at the construction site due to a lack of accuracy and techniques in the prefab design stage. The correlation among various problems seems to have increased the difficulty of implementing OSC. A lack of Design for Manufacture and Assembly (DfMA) standards, for instance, will lead to such consequences on stakeholders as a lack of interest, motivation, knowledge, experience, and project management capabilities on component design, manufacturing, logistics, and assembly [15,18–20]. Likewise, non-standard prefabricated components can increase the difficulty of component lifting and assembly as well as affect workers' efficiency. In addition, due to the lack of awareness of OSC, stakeholders are reluctant to embrace the change of existing corporate strategies and business models, which prevents the formation of a new-type industry chain [19,21]. Gan et al. [22] formulated a stakeholder and barrier network, in which each OSC development barrier is associated to at least four stakeholders. They also pointed out that government and property developers should become the initiators of the stakeholder alliance and take the responsibility of coordinating all the alliance members in OSC problem-solving. According to Mao et al. [23], frequent communication among OSC stakeholders is important to ensure OSC project success, especially in the project design phase. However, the level of communication seems insufficient. One of the reasons is that methods that dominate the day-to-day exchange of project information are predominantly based upon 2D drawings and such a method may hinder timely responses when changes or interruptions occur, leading to inaccurate inventory, prolonged lead time, late delivery, and misplaced assets. While the construction industry is seeking productivity growth, there is an immediate need for these issues to be tackled [24–27]. However, multitudinous measures such as tax reductions, subsidized policies, workforce upskilling, and technical norms have been put in place, and construction using traditional methods is still commonplace [28,29]. Regardless of governments and industrial participants, both of them are confused by this problem and need a reasonable interpretation. This study attempted to unravel the puzzle.

According to Geels [30], people will lose trust in existing technologies due to various problems and alter expectations of new technologies. OSC is such a new technology to solve various problems of the traditional construction method. Geels [30] also pointed out that the new technology will promote to form a new regime accompanied by wider changes, which may eventually influence wider landscape developments of a system. It means that the advent of OSC not only caused the change of construction technology but also caused wider changes. For example, OSC introduced new stakeholders such as modular designers, manufacturers, and assemblers [31]. The advent of new stakeholders changed the distribution of resources and interests of the traditional building industry. The compositions and interactions of the building industry have changed and will change continuously [32,33]. OSC as a new technique is an independent variable as well as a dependent variable because technology development is often influenced by enterprise strategies, policies, natural environment, and other factors [34]. Thus, this paper guessed that the corresponding changes of China's residential building industry did not match up with

the OSC development, which limited the application of OSC. Through literature review, this paper found that ecosystem theory is always used to study similar topics, see those by Rong et al. [35], Sagar and Frosch [36], and Decan et al. [37]. Pulkka et al. [38] have introduced ecosystem concepts into the construction industry in their article. Gulnaz Aksenova discussed why BIM adoption has not lead to a systemic evolution in the Finnish architecture, engineering, and construction (AEC) business ecosystem [39]. Their research results showed that the ecosystem concept is applicable and provides a valuable lens for understanding some phenomena in the construction industry. However, to the best of the our knowledge, there are few papers which use the ecosystem concept to analyze the development of OSC, and this paper is one of them. Although the objective of this paper is China, the research conclusion can be referred to by other developing countries.

The remaining of this paper is organized into five sections, namely, a brief introduction around OSC in China (Section 1); the methodology (Section 2); the analysis of results of surveys and interviews (Section 3); four recommendations for OSC implementers and policy-makers to develop OSC (Section 4), and the conclusion (Section 5).

2. Methodology

2.1. Research Agenda

Three distinct research phases were executed in this article: (1) conceptualizing China's residential building industry ecosystem (RBI-ECO) and proposing some hypotheses about problems of China's RBI-ECO; (2) investigating the status quo and identifying the problems, and (3) formulating effective development recommendations. Figure 1 shows the research flow adopted in this paper. Phase 1 provides the conceptual framework for understanding the RBI-ECO and helps to propose hypotheses from two aspects of structure and interaction. Phase 2 provides the direction for questionnaire designing. Finally, the results of the survey and interview are the basis for effective recommendations.

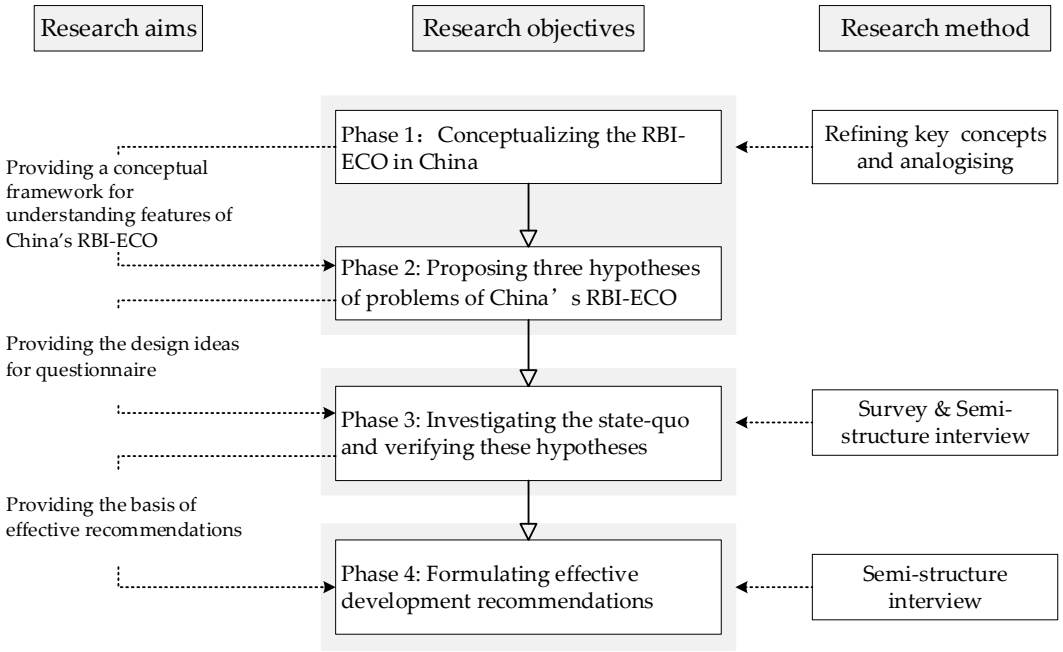


Figure 1. Research flowchart.

2.2. Conceptualizing the RBI-ECO of China and Proposing Hypotheses

2.2.1. The Key Concepts of Ecosystem

In order to better understand phenomena that are linked to multidisciplinary bodies of knowledge, Jabareen [40] proposed a new qualitative method for building a conceptual

framework. In his paper, Jabareen took a conceptual framework as a plane which integrates various concepts. Deconstructing and synthesizing these concepts can help to understand phenomena comprehensively. The opinions and methods of Jabareen are highly cited by other scholars [41–43]. Drawing lessons from these thoughts, this paper tried to deconstruct and synthesize some concepts from the ecosystem to understand China's RBI-ECO. Arthur Tansley, a British ecologist, firstly used the "ecosystem" in his publication in 1935 to emphasize the importance of interaction between organisms and their environment [44,45]. Tansley described this term as "The whole system, ... including not only the organism-complex, but also the whole complex of physical factors forming what we call the environment" [46]. As time passed, the definition of "ecosystem" became more and more corresponding. An ecosystem consists of all living organisms and physical environments in an area, and the dynamic interactions that link them [47–49]. The dynamic interactions are that organisms regulate themselves and react with the external environment, and aim to maintain a stable state [50]. Ecosystems also are depicted as networks which have certain structure and function [49,51]. Structure refers to the way that the ecosystem is organized, such as species composition, and distribution of energy and matter [49]. The function of an ecosystem, on the other hand, is the biological modification of abiotic conditions, including modification of energy flow, climate, and so forth [49]. The ecosystem structure will change due to disturbance which is a change in environmental conditions [52]. The process of change in the species structure is named succession [53]. Disturbance and succession drive the ecosystem to reach a new stable state by stimulating interaction between organisms and between organisms and environments [54]. Based on the definition of the ecosystem, some key concepts were refined to describe a general ecosystem, including composition, organisms, environment, interactions, networks, structure, function, energy flow, disturbance, and succession. According to Jabareen [40], these concepts can form a conceptual framework to understand other ecosystems, such as RBI-ECO.

2.2.2. China's RBI-ECO

- Composition

Taking China's residential building industry as an ecosystem, it also consists of organisms and their living environment. Organisms refer to various enterprises and individuals who involve in residential construction-related activities [38]. These enterprises include property developers, design companies, contractors, material suppliers, machine suppliers, consulting firms, sale agents, and so on (as shown in Table 1). In general, these enterprises have different businesses but finish buildings together. The individuals include the staff of enterprises and clients who will buy dwellings. Production activities of residential buildings need various resources, such as raw materials, capital, information, labor, technology, laws, standards, and so on. These resources have close relationships with external environments, namely, natural, social, economic, technological, and political environments. For example, the political environment influences law-making. Natural, social, economic, technological, and political environments constitute the living environments of enterprises and individuals of RBI-ECO.

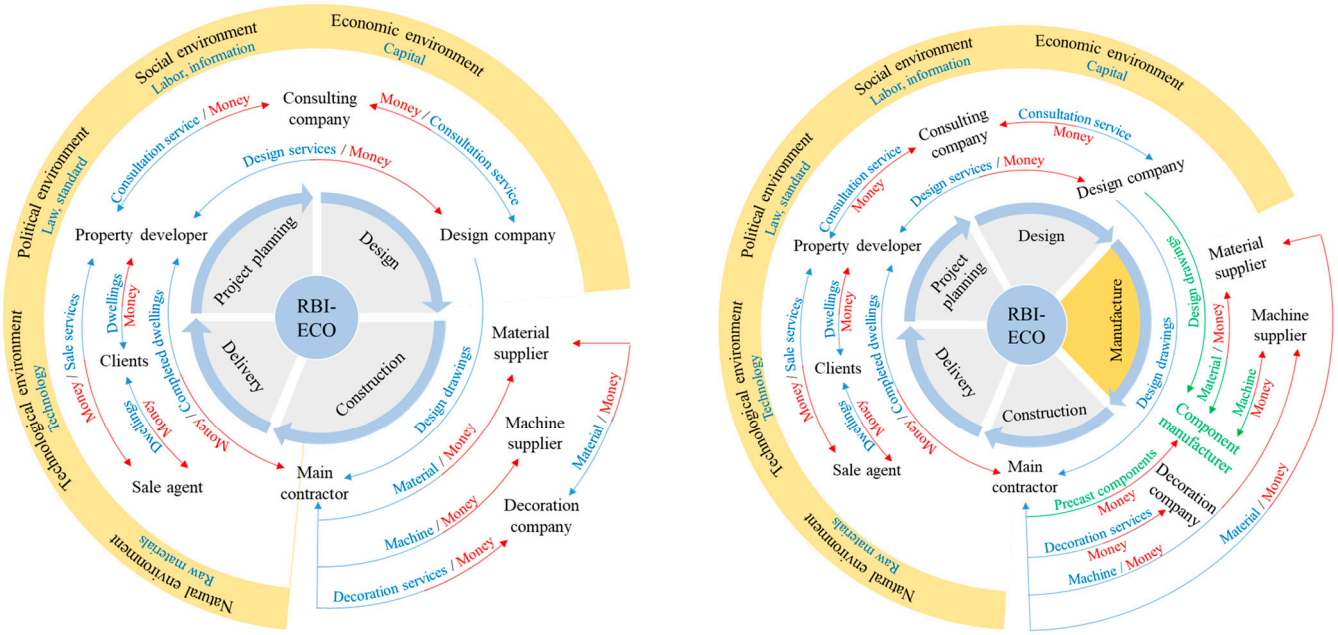
Table 1. Composition of China's RBI-ECO.

Composition	Types	Attribute
Organisms	Property developer	Buys land; plans projects; raises money; manages construction activities and sales; delivers and operates projects
	Design company	Provides design services for the property developer
	Main contractor	Is responsible for the day-to-day oversight of a construction site; management of subcontractors and employed by the property developer
	Consulting firm	Provides various consulting services for various enterprises
	Decoration company	Provides decoration services for the main contractor

Composition	Types	Attribute
	Component manufacturer	Provides precast components for the main contractor
	Machinery supplier	Sells or rents machines for the main contractor and the component manufacturer
	Sale agent	Provides sale services for the property developer
	Material supplier	Provides materials for the main contractor and the component manufacturer
	Client	Can be any customer who would buy dwellings
Environment	Natural environment	Is related to raw material, energy, land, environmental protection, geographical condition, and so on
	Social environment	Is related to social values, social stability, public security, religion, social welfare, education, and so on
	Economic environment	Is related to the labor market, consumer preference, GDP, finance, productivity, demands, and so on
	Technological environment	Is related to technological research and development, technological creation, technological progress, and so on
	Political environment	Is related to laws, standards, policies, war, civil strife, and so on

- Networks

Owing to the complexity of participants, China's RBI-ECO has equally complex networks, see Figure 2. The composition of enterprises and the flow of resources reflect the structure of networks of China's RBI-ECO. Before the application of OSC, in the entire construction cycle, China's RBI-ECO has nine core business types. The nutriment and energy of enterprises refer to the construction-related matter and services, and capital. However, since OSC as a new construction method was introduced in China, the structure and flow of resources of China's RBI-ECO has changed. OSC is an influential disturbance that affected the technological environment firstly because OSC can achieve higher production efficiency, save materials and time, and reduce more accidents than traditional construction technology [24,32]. Thus, some enterprises tried to transform towards OSC. However, the previous structure is not fit for OSC due to the lack of component manufacture which is a crucial part of OSC [28]. Therefore, a new organism named 'component manufacturer' was created. Along with this came a redistribution of construction-related matters, services, and capital. The function of networks of China's RBI-ECO made little change after implementing OSC. Enterprises still modified themselves and the external environment continually. In order to adopt OSC, enterprises redesigned the business model, made new strategies, and asked for the assistance of policy. In this process, enterprises achieve succession. In the long term, not only the technological environment but also other environments will be modified due to the continuous regulation of enterprises.



(**a**) (**b**)

Figure 2. The RBI-ECO of China before (**a**) and after (**b**) implementing OSC.

- Interactions

In China's RBI-ECO, interactions happen between enterprises and between enterprises and environments, which aim to keep a stable state of the residential building industry. A property developer is the initiator of the construction of residential buildings [23]. Generally, the property developer grasps valuable information about the market of residential buildings from the social environment, political environment, and economic environment to develop projects. At the same time, before launching projects, the property developer needs to buy land from government, raise money from financial organizations, and employ staff from the labor market. Once projects start, the design company will provide design service for the property developer to finish concept design, and construction drawing design of projects. Various consulting companies will provide various consultation services for other enterprises. The main contractor will construct buildings after obtaining the design drawings and then deliver completed projects to the property developer. The material supplier, machine supplier, and decoration company will provide materials, machines, and decoration services for the main contractor, respectively [55]. Completed dwellings will be sold to clients by the property developer or the sale agent directly and indirectly. A portion of sales revenue will be used to pay back the money of financial institutions and offset costs. The remaining sales revenue will be used to invest in new projects. Interactions between different types of enterprises are cooperation mostly. Competition often happens among the same type of enterprise which fight for similar, limited resources [56]. With the emergence of OSC, there are some new interactions [31]. The design company, material supplier, and machine supplier need to provide resources for the component manufacturer. The component manufacturer provides precast components for the main contractor. A potential competition will occur between the manufacturer and the main contractor with the development of prefabrication technology. The interactions between enterprises and environments influence the development of OSC. For instance, labor shortage leads to increased labor cost of projects which promotes the application of OSC. Due to differences between OSC and traditional construction methods, governments have to adjust current laws, standards, and policies to suit OSC.

2.2.3. Hypotheses

For China's RBI-ECO, OSC as a new construction technology is an environmental disturbance that influences the structure of RBI-ECO. However, OSC is not only a new technique but also a future development target of the residential building industry, which means that the further change of structure also needs to match up with OSC to promote OSC development. The structure change of RBI-ECO has a close link with the regulation and the modification of enterprises and the environment. At the same time, the regulation and modification result from the interactions between enterprises and environments. Although OSC was introduced to China since the 1960s, the traditional construction method still dominates the residential building industry. China's governments have enacted various policies and measures to encourage implementation of OSC, to little effect [29]. Based on the discussion above, this article has defined three hypotheses:

H1: Present structure of China's RBI-ECO is unsuitable for the development of OSC;

H2: The frequency of positive interactions between enterprises and between enterprises and environments is not enough;

H3: Existing interactions are insufficient to promote the application of OSC.

In order to verify these three hypotheses, surveys and semi-structured interviews were carried out. The results and analyses of the questionnaires and interviews were discussed in the next section.

2.3. Survey and Semi-Structured Interviews

In this paper, the data were mainly derived from surveys and semi-structured interviews. Surveys and interviews are the most suitable methods to gain data in the context of a lack of official databases of OSC in China. Governments sometimes published news or official documents to report the status quo of OSC, but this was less and fragmentary. Hence, it is difficult to collect much useful information related to the focus of this study by the news and official documents. Surveys and interviews help to overcome this defect on account of diverse data sources and targeted topics. Surveys and interviews are widely adopted in construction engineering and management research to collect professional and valuable views [57]. Holstein and Grubium [58] regarded the interview as a tool that can trigger and guide a meaning-making conversation. The survey and interviews were conducted in Chongqing which is one of the core cities in western China. Chongqing is experiencing rapid urbanization and has enormous construction projects. Chongqing government expected that OSC would be widely adopted in these construction projects. However, OSC was unpopular, especially in residential projects, and launching the OSC projects was still difficult. Both governments and enterprises hoped to change the current dilemma.

The questionnaire contains a total of 13 questions (Appendix A, Table A1). Q1 and Q2 were used to investigate the basic information of respondents; Q3 was designed to ensure the reliability of interview results; Q4 to Q13 were used to investigate the current status of OSC. From July to August 2019, questionnaires were widely distributed to the people who work in ACE (architecture, engineering, and construction) enterprises, R&D institutes, and engineering and construction departments by a snowball technique. A total of 199 questionnaires were recovered, of which 99 were valid questionnaires according to Q3. Among the 99 questionnaires, 83 respondents were from enterprises, 8 were from research institutions, and 8 were from government departments. In the questionnaire, Q7 is a five-point Likert-type scale which should be measured by internal consistency among the variables to evaluate the reliability. The SPSS 21 was selected as the analysis tool. The Cronbach's Alpha was 0.937, suggesting that the items have relatively high internal consistency. In general, Cronbach's Alpha of 0.7 or higher is considered "acceptable" [49]. Although the remaining questions are not Likert-type scale and hard to be conducted statistical tests, Q3 helped to exclude unreliable respondents by requiring related experience

of OSC. It is believed that the results of these questions are reliable. To develop a more scientific understanding of the research issue, the researchers also conducted semi-structured interviews (Appendix A, Table A2) to explain and validate the conclusions of questionnaires. A total of 10 interviewees (6 from enterprises; 2 from R&D institutes; 2 from government departments) were selected for the semi-structured interviews (Table 2). All of them were engaged in OSC-related businesses or research for more than five years; that is, they have relatively rich professional knowledge and practical experience. The researchers collated, reviewed, and synthesized the results of questionnaires and the answers of semi-structured interviews, which are given in Appendix B.

Table 2. Profile of the interviewees from different entities.

Interviewees	Position	Years of Working	Authority	Attribute
Li YG	Engineer	8	CMCU Engineering Co., Ltd.	Design company
Liu CM	Manager	7	Chongqing Construction Engineering Group Corporation Limited	Manufacturer
Ma YH	Engineer	8	Greatech	Contractor
Xiao ZZ	Professor	15	Chongqing University/CCETG Chongqing Engineering Co., Ltd.	Academy/ Design company
Yang YX	Engineer	9	Broad Group	Consultancy
Liu A	Officer	5	Ministry of Housing and Urban-Rural Development of Chongqing	Government
Fu Y	Associate professor	9	Chongqing University	Academy
Ding ZZ	Manager	8	Vanke	Property developer
Chen WK	Engineer	13	Chongqing Huirui Construction Technology Co., Ltd.	Contractor
Zhang YW	Officer	6	Ministry of Housing and Urban-Rural Development of Chongqing	Government

3. Analyzing Results and Discussing Hypotheses

3.1. The Status Quo Analysis of the Structure of China's RBI-ECO to Verify H1

In China, an OSC enterprise will receive an honorary title called "Prefabrication Base" if the enterprise has mature technology, product quality control systems, sufficient funds and resources, good reputation, and fewer security incidents. However, only 18 enterprises in Chongqing have received this title, accounting for less than 1% of the total number of AEC-related (architecture, engineering, construction) enterprises in Chongqing. The lack of OSC companies could lead to few professionals, which can be verified in Q3 (Figure A1, Table A3): no more than 50% of respondents are deeply involved in OSC projects or researches (the sample size for analysis of Q3 was 199). Among approved enterprises, 50% are component manufacturers, 27% are comprehensive enterprises, 11% are main contractors, and 6% are design companies. According to Q4 (Figure A3, Table A3), there are similar proportions: 52% are component manufacturers, 22% are comprehensive enterprises, 9% are main contractors, 11% are design companies, and 7% are property developers. The data showed that our sample-based results are almost identical to the government's statistical results, so we can infer that our sample size and structure are reasonable. Meanwhile, it also showed that the number and proportion of various types of enterprises of OSC in Chongqing are imbalanced. When asked about what is the driving force for enterprises to implement OSC in Chongqing in Q5 (Figure A2, Table A3), 70% of respondents chose "Enterprises' expectation of becoming a leader in OSC field"; 55% of respondents chose "The encouragement and requirement of the government"; only 17% of respondents chose "There are abundant OSC projects in the building market". Q6

(Figure A3, Table A3) revealed that the property developer, the design company, the component manufacturer, the comprehensive enterprise (refer to the enterprise involved in all of the links of OSC project) and the main contractor are considered to be the five most critical for promoting OSC. The property developer had received the most support, about 84%. Q7 (Figure A3, Table A3) aims to grade the development level of each type of OSC enterprise. The component manufacturer, the main contractor, the property developer, the design company, and the comprehensive enterprise had received 3.04 points, 2.59 points, 2.72 points, 2.51 points, and 2.49 points, respectively. The data suggest that in addition to the component manufacturer, other critical OSC populations are actually developing poorly.

According to I1 (Table A4), all interviewees indicated that the lack of OSC projects in Chongqing led to insufficient capacity of OSC enterprises and limited enterprises in implementing OSC. This view is consistent with the results of Q5. Meanwhile, interviewees from enterprises also pointed out that different enterprises have different expectations for OSC. The property developer hopes OSC can shorten the project period and save costs; the design company hopes OSC can reduce design difficulty; the main contractor hopes OSC can reduce the complexity of site construction and improve the building quality. However, OSC cannot meet these KPIs currently and this caused enterprises' low acceptance of OSC. According to I2 (Table A4), 80% of interviewees revealed the reason why the component manufacturer grows fast. They said enterprise managers and policy-makers generally believe that the business of prefabricated component production is a prominent opportunity to involve in OSC projects. In order to enter the OSC field quickly, enterprises are more willing to engage in the business of component manufacturing. Different from the results of Q6 and previous literature, interviewees from the R&D institutes believed that the design company should be given more attention, rather than the property developer. They pointed out that the design company plays a vital role in OSC projects because the design phase is closely related to the subsequent links, such as component manufacturing, material selection, and component assembly on site. If the design company can take on the role of project manager simultaneously, technical obstacles and extra costs will be reduced, and the project quality will be improved and the schedule can be well-controlled. In the meantime, the property developer should convert the current project investor, organizer, and manager roles to a single project investor role. Nevertheless, interviewees lamented that most OSC design companies do not have awareness and intention to implement OSC projects actively because of many uncertainties, such as the lack of design specifications, material norms, structural safety regulations, and other issues.

In sum, the H1 can be verified in light of the results from questionnaires and interviews. Currently, the number of OSC enterprises is much less than that of traditional enterprises. The scale of each type of OSC enterprise is imbalanced. Resources shifted to component manufacturer easily, which led to discordant development of OSC enterprises. These facts are enough to prove that the present structure of China's RBI-ECO goes against OSC application.

3.2. The Status Quo Analysis of Interactions between Enterprises to Verify H2

Q8 and Q9 (Figure A4, Table A3) were designed to investigate the current state of interaction between enterprises. Each option of Q8 received 0%, 14%, 38%, 31%, 5%, and 12%. This result revealed a lack of cooperation between OSC enterprises within the same business. The result of Q8 verified the opinion of literature: competition is widespread among enterprises from the same population and the lack of observable interaction reflects the intensity of competition [56]. Regarding the frequency of cooperation between different types of enterprises (Q9), 2% of respondents chose "always", 16% of respondents chose "often", 42% of respondents chose "occasionally", 27% of respondents chose "rarely", 2% of respondents chose "never", and 11% of respondents chose "do not know". The results indicated that cooperation between different types of enterprises is also

uncommon except for daily communication of projects. However, cooperation is very significant for OSC enterprises within different businesses. According to Bar-Yam [59], a cooperative relationship can help different enterprises achieve a win-win outcome.

According to I3 (Table A4), interviewees said that rare cooperation between enterprises resulted from enterprise managers' concern of moral hazard. Enterprise interviewees pointed out that enterprises often invested in R&D and project experiments in the early stage of OSC. It is hard for enterprises to make ends meet in the early stage. There is no doubt that cooperation is good for sharing costs and risks. However, the effect of cooperation may be disadvantageous. For example, enterprises need to share profits and technologies with partners despite partners who slack off in their tasks. The investment of enterprises aims to develop core competencies and dominate the OSC market in the future. However, enterprises may lose the possibility of becoming a leader of OSC businesses due to cooperation. Hence, enterprises are more willing to offset current costs through future potential profits rather than co-operate with other enterprises, especially the same kinds. On the one hand, 85% of interviewees pointed out that the traditional building industry is too fragmented and different types of enterprises have independent business systems. These facts lead to rarely active cooperation between different types of enterprises. However, OSC has a higher coordination requirement for different types of enterprises [60]. On the other hand, an interviewee from the R&D institution said that almost all decision-makers of enterprises and the government pin their hope on the property developer to resolve conflicts and problems of OSC implementation. Therefore, other stakeholders are not proactive in optimizing the processes of the OSC supply chain, solving the problems of OSC projects, and promoting cooperation between stakeholders. The interviewees believed that active cooperation between enterprises is conducive to change RBI-ECO to suit OSC, especially in the early stage, because closed cooperation can help enterprises reduce investment risks, overcome technical difficulties, and share practical experience. For the whole industry, the advantages of cooperation outweigh its disadvantages.

From the results of Q8, Q9, and I3, this paper found that cooperation as a positive interaction is not popular among enterprises, which confirmed H2. On the one hand, there are competitions and moral risks between the same types of enterprises. On the other hand, although there are many unavoidable communications of projects between the different types of enterprises, enterprises still have rare cooperations due to the independent business systems.

3.3. The Status Quo Analysis of Interactions between Enterprises and Environments to Verify H2 and H3

In China's RBI-ECO, if enterprises want to change the living environment, the simplest method is to look for help from governments. The policies issued by governments have a significant influence on the economy, society, technology, and natural resources. According to Q10 (Figure A4, Table A3), 82% of respondents said that enterprise managers once asked governments for help to address OSC barriers. Barriers of cost and investment, design/construction technology, experience and skills of workers, standards and norms, and market demand were focused on by respondents (Q11) (Figure A5, Table A3). These barriers mainly occurred in the practice of OSC projects. Half of the OSC policies issued by the Chongqing government since 2013 are technical standards and norms, which responded to the results of Q12 (Figure A5, Table A3): most respondents believed that technical standards and norms work. Additionally, no less than 66% of respondents believed that governments had not solved the barriers of cost, enterprise cooperation, experience and skills of workers, supply chain, design/construction technology, and market demand. These results are in line with the surveyor's guess. In existing policies of Chongqing, only three policies have provisions of the economic subsidy and the tax reduction; only two policies are issued to organize the workers' upskilling; there is no concrete measure promoting the enterprise cooperation and optimizing the supply chain process. The

results of Q13 (Figure A6, Table A3) echo the results of Q12. To find shortcomings of the OSC policies, Q13 was designed and each of the answers received 67%, 49%, 24%, 48%, 31%, and 27%. These results showed that the enterprises yearn for concrete measures and sufficient incentives.

I4 (Table A4) revealed why project barriers (mentioned in the Q11 result) gain more attention from enterprises. From 75% of interviewees, the reason is that enterprises cannot finish ongoing projects and survive in the competitive market due to these project barriers. The interviewees also pointed out that enterprises have less ability to overcome other barriers by themselves, such as defective supply chain structure and unbalanced enterprise types. When asked about why policies issued by the government cannot effectively solve barriers (I5) (Table A4), 75% of interviewees believed that lacking concrete measures and insufficient incentives are the primary causes. This opinion is consistent with the results of Q12. The R&D institute interviewees added that governments had not given enough consideration to the supply chain, enterprise cooperation, and enterprise transformation. However, these barriers have negative impacts on project barriers. For example, incomplete supply chain causes superfluous costs. In response to R&D institute interviewees, government interviewees said that governments have to solve project barriers firstly to alleviate enterprises' concerns and build enterprises' confidence. Governments thought that if project barriers are solved, the supply chain structure will be optimized, and enterprises will transform to OSC and co-operate with others spontaneously. The guess is reasonable, but governments overestimate their abilities to cope with project barriers. The R&D institute interviewees recommended that governments ought to pay more attention to optimize the supply chain structure, strengthen the enterprise cooperation, and innovate enterprises' transform method.

The results of the questionnaires and interviews showed that interactions between enterprises and the environment are frequent but inefficient. It is to say that positive interactions are limited. By now, governments have taken some measures to help enterprises to overcome barriers of OSC projects. However, these measures are not enough to help enterprises to get them out of trouble due to many defects. Thus, H2 and H3 can be verified.

4. Towards a Sustainable RBI-ECO for OSC

The advent of OSC stimulated the technological environment first and further influenced the structure and interaction of China's RBI-ECO. With the development of OSC, the structure and interaction of China's RBI-ECO still keeps changing. However, the further change of structure and interaction did not match up with OSC requirements, which can be verified by surveys and interviews. This means that some measures should be made to direct the change of structure and interaction of China's RBI-ECO. In addition to verifying hypotheses, this paper also concluded four recommendations from surveys and interviews (Figure 3). These four recommendations are conductive to coordinate the RBI-ECO with OSC.

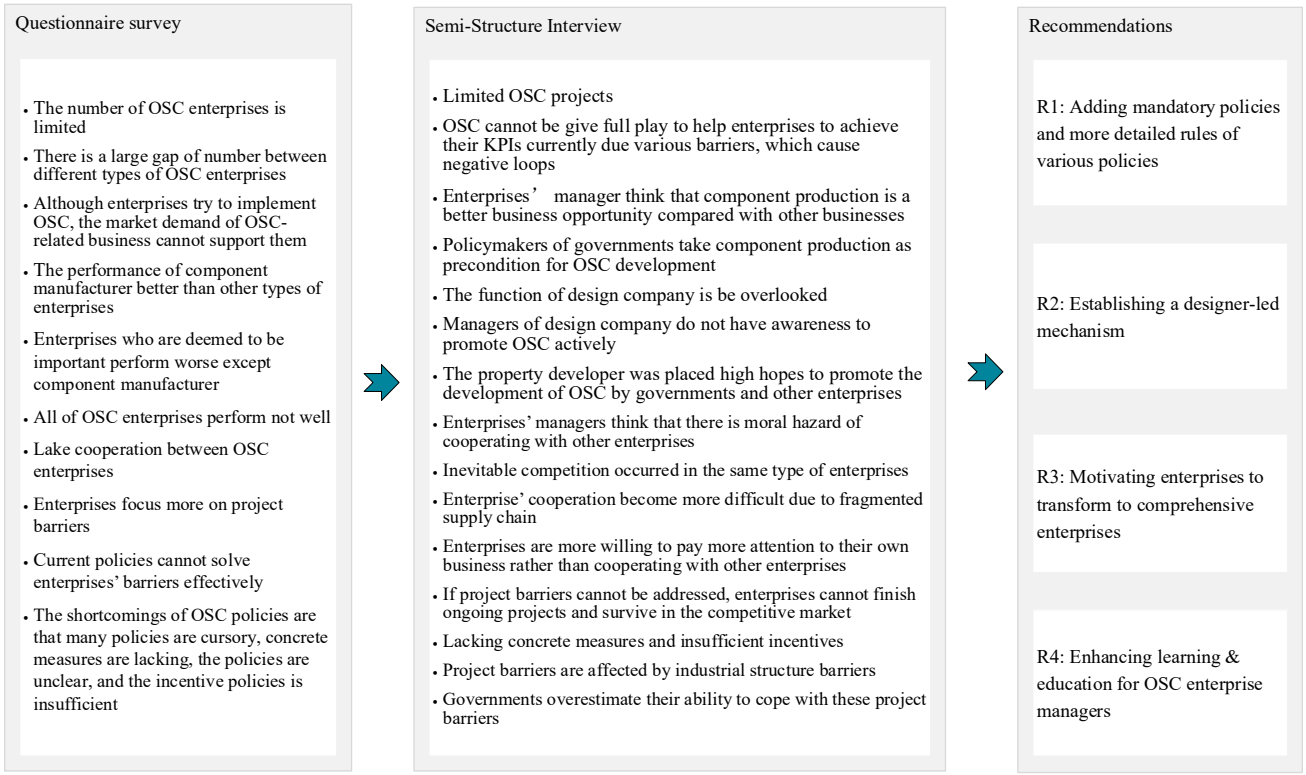


Figure 3. The recommendations derived from the surveys and semi-structured interviews.

4.1. Add Mandatory Policies and Concrete Measures (R1)

In the early stage of OSC implementation, the advantages of OSC were unobvious compared with the traditional construction method because there were few OSC projects. Enterprises were reluctant to take the initiative to implement OSC, which resulted in a limited number and capacity of OSC enterprises. However, the existing policies failed to increase the number of OSC projects and stimulate enterprises to involve in OSC projects [13]. Therefore, governments need to add some mandatory policies. For example, in Chongqing, the government ought to stipulate the types of land and buildings which adopted the OSC method, the minimum prefabricated rate of each OSC project, and the number of OSC projects of each enterprise. The purpose of these stipulations is to increase the market share of OSC in the residential building industry. When the OSC market share grows, OSC enterprises have to actively overcome barriers of cost, technology, workers' skill, design, transportation, etc. Thus, OSC enterprises will not pin all their hopes on the government to address these project barriers. Then, governments can focus on optimizing the supply chain structure and innovating the development model of OSC. Meanwhile, governments should increase penalties for environmental pollution which can force enterprises to implement OSC. Compared with traditional construction, OSC is more environmental-friendly. Moreover, the government should detail the implementation rules of the existing policies. For example, for the economic subsidy policy, the concrete measures should include who can apply the economic subsidy and how to apply the economic subsidy.

4.2. Establishing a Designer-Led Mechanism (R2)

When enterprises implemented OSC projects, they still play the role that they played in traditional construction methods before. That is, in China's residential building industry, the property developer always plays a leadership role and needs to integrate and manage all production links and other stakeholders. In the short term, this situation is difficult to be changed. However, OSC has a higher coordination requirement for different

types of enterprises [54]. In the OSC supply chain, the property developer does not have the core technology of OSC. Therefore, the property developer is difficult to quickly and effectively solve problems of each process of OSC projects. On this occasion, governments can establish a designer-led mechanism and require the design company to undertake the project management functions. Thus, the design company serves the property developer and other stakeholders serve the design company. The activities and duties of the design company have an important influence on all subsequent work processes. The design scheme determines 70% of the project cost. The materials selection during the design stage has a long-term impact on building quality. The delayed risks can be reduced if the schedule is taken into consideration in a design stage. Now, most design companies do not have awareness and capability to become the manager of OSC projects. Hence on the one hand, governments should arrange project management courses for designers and require designers to gain a professional project management qualification. This measure could help designers to master project management knowledge. When they design projects, they can balance multiple goals of projects. On the other hand, governments can require design companies to set up a project management sector to promote the designer-led mechanism. This measure could solve the temporary shortage of designers with project management experience.

4.3. Motivating Enterprises to Transform to Comprehensive Enterprises (R3)

Based on surveys and semi-structured interviews, this paper found that most enterprises rarely cooperate with other enterprises. One of the reasons is that the processes of the supply chain in the traditional residential building industry are fragmented and enterprises are more likely to devote to their own business. Another reason is that enterprise managers express concern about the moral risks of cooperation. If enterprises transform to comprehensive enterprises or integrate some links of the supply chain, the cooperation problem could be avoided or overcome, because all of the tasks will be tackled with the same goal. When enterprises become comprehensive enterprises, the possibility of information loss and schedule delay could be minimized, and the communication barriers and extra costs could be reduced. In order to motivate enterprises to transform into comprehensive enterprises, governments ought to stipulate some provisions. For example, "the comprehensive enterprises can prior gain OSC projects or construction land", "the comprehensive enterprises can prior get financial help or economic subsidies", "the comprehensive enterprises can get discounts of the loan interest rate", etc. These provisions are conducive to release the capital and resource burdens from comprehensive enterprises and encourage more enterprises to become comprehensive enterprises.

4.4. Enhancing Learning and Education for OSC Enterprise Managers (R4)

At present, governments have arranged skill training for construction workers and technical engineers. However, there is a lack of OSC knowledge lectures for enterprise managers. The knowledge and attitude of managers often have a significant influence on enterprise strategy and enterprise development [61]. Therefore, governments ought to enhance learning and education of enterprise managers. Governments can arrange some lectures and regular OSC development seminars. These lectures should include at least the following aspects: 1) the development and application of OSC technology; 2) the changes of supply chain structure when RBI-ECO updates towards OSC; 3) the conditions of changing RBI-ECO to OSC, and 4) governments' development strategy of OSC. Thus, governments can collect opinions on policies, introduce new provisions and measures of OSC, and update OSC development strategies. At the same time, enterprises can exchange experience and communicate with other enterprises to innovate the business model. In addition, governments can invite R&D institutes to participate in seminars. The researchers can assist enterprise managers in formulating strategies with consideration of the city's OSC planning. These methods are conducive to resource allocation, industrial structure optimization, and the prevention of ineffective competition.

5. Conclusions

This paper conceptualized China's residential building industry ecosystem (RBI-ECO) by refining some important concepts from the ecosystem and proposed three hypotheses to explore why OSC cannot be widely implemented in China's residential building industry. Surveys and interviews were used to verify these three hypotheses. The results showed that the emergence of OSC is a disturbance of the environment of China's RBI-ECO in nature. Before and after OSC entered China's RBI-ECO, the structure of China's RBI-ECO was changed, which has continuous impacts on China's RBI-ECO by interaction. However, the current changes of structure and interactions were not matched up with the development of OSC. The number of OSC enterprises was limited and different types of enterprises developed inharmoniously. The performance of the component manufacturer was much better than other types of enterprises. In addition, there is rare cooperation between enterprises except for daily communication of projects. Potential moral risks, fierce competition, and fragmented supply chain are key causes. Although enterprises often interacted with governments, the problems of OSC still hindered enterprises from implementing OSC, because the government cannot publish the new policies to solve these problems immediately. For forming a sustainable RBI-ECO, the government can adopt some measures from four aspects, respectively, which are enacting new policies, changing the responsibility of designers, encouraging transformation of enterprises, and enhancing skill training.

However, this paper also has some limitations. Precise data are important for this research. As of yet, there is no official data about enterprises' information of OSC. Moreover, the sample size of the questionnaire and interview is limited. Thus, the data may have some deviations compared with the actual data and the findings might be uncomprehensive. Additionally, the RBI-ECO built by this paper only considers several types of enterprises and other stakeholders such as R&D institutes; labor suppliers were not considered. Finally, this paper analyzed the current status of OSC enterprises, but did not analyze the dynamic transformation process of enterprises.

In the future, researchers can intend to construct more integral RBI-ECO by considering more stakeholders and richer interaction among the stakeholders. On the other hand, surveying and interviewing more people from different cities and different stakeholders should be carried out. Thus, more valued information could be obtained to optimize the research findings. In addition, the researchers can try to discover the transformation process of different enterprises from driving forces, barriers, strategies, and performance. Thus, much more useful recommendations could be proposed for different stakeholders and government.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Questionnaire and Interview

Table A1. Questionnaire Sample.

This survey invites you to respond to the following questions. Your answers could help the research team to find the problems of OSC development in Chongqing. There are 13 questions in the questionnaire, which will take 10–15 min to finish. Your personal information will not be disclosed.
Q1: Your affiliation: □ Enterprise □ R&D institute □ Government department
Q2: Your role: □ Manager □ Engineer □ Researcher
Q3: You have involved, managed, or researched some OSC projects: □ Yes □ No
Q4: You are working for: (respondents who have chosen "Enterprise" in Q1 should answer this question) □ Property developer □ Design company □ Component manufacturer □ Decoration company □ Consulting company □ Main contractor □ Comprehensive enterprise □ Machinery supplier □ Sale agent □ Material supplier □ Other _____
Q5: The driving force for enterprises to implement OSC: (multiple choice) □ Enterprises' expectation of becoming a leader in OSC field □ The encouragement and requirement of the government □ There are abundant OSC projects in the building market □ Various advantages of OSC compared with the traditional method □ Other _____
Q6: The most important type of enterprise for promoting OSC: (multiple choice) □ Property developer □ Design company □ Component manufacturer □ Decoration company □ Consulting company □ Main contractor □ Comprehensive enterprise □ Machinery supplier □ Sale agent □ Material supplier
Q7: Grading the development level of different types of OSC enterprises: (The development level means that the number and ability of enterprises, score from 1 to 5, 1 = the lowest level, 5 = highest level) □ Property developer □ Design company □ Component manufacturer □ Decoration company □ Consulting company □ Main contractor □ Comprehensive enterprise □ Machinery supplier □ Sale agent □ Material supplier
Q8: The frequency of cooperation between the enterprises of the same type in forms of joint bidding, researching and developing new technologies, and building factories, and so on □ Always □ Often □ Occasionally □ Rarely □ Never □ Don't know
Q9: The frequency of cooperation between different types of enterprises in forms of joint bidding, researching and developing new technologies, and building factories, and so on □ Always □ Often □ Occasionally □ Rarely □ Never □ Don't know
Q10: The frequency with which enterprises ask the government for help to address OSC barriers □ Always □ Often □ Occasionally □ Rarely □ Never □ Don't know
Q11: The barriers that enterprises reported to the government include: (multiple choice) □ Cost and investment □ Design/Construction technology □ Supply chain □ Market demand □ Standards and norms □ Enterprise transformation □ The experience and skills of workers □ Enterprise cooperation □ Other _____
Q12: The barriers which can be effectively solved by current policies published include: (multiple choice) □ Cost and investment □ Design/Construction technology □ Supply chain □ Market demand □ Standards and norms □ Enterprise transformation □ The experience and skills of workers □ Enterprise cooperation □ Other _____
Q13: The shortcomings of OSC policies published by the government are: (multiple choice) □ Many policies are cursory and concrete measures are lacking □ The policies are unclear □ Unbalanced support for different types of enterprises □ The incentive of policies is insufficient □ Ignoring the barriers about enterprise transformation, co-operation, and supply chain structure □ Lack of policies to increase the market demand □ Other _____

Table A2. Interview Sample.

This survey invites you to respond to the following questions. Your answers could help the research team to explain, validate, or refute the conclusions of the questionnaire. Each interview will last for circa 30–40 min. Data collected will be used for the research team to conduct a deep analysis of the status and problems of implementation of off-site construction (OSC) in Chongqing and formulate some recommendations. Your personal information will not be disclosed.
Name: ..... Affiliation: ..... Title/Role: .....
I1: The results of the questionnaire show that the number of OSC enterprises is limited and the capacity of OSC enterprises is poor. What caused this situation?
I2: The results of the questionnaire show that the development of different types of enterprises is uncoordinated, and the development of the component manufacturer far exceeds other types of enterprises. What do you think about this phenomenon?
I3: The results of the questionnaire show that there is rare cooperation between enterprises, whether they are the same type of enterprise or different types of enterprises. What caused this problem?
I4: According to the results of the questionnaire, why do enterprises pay more attention to the barriers about cost, construction/design technology, the experience and skills of workers, standards and norms, and market demand?
I5: According to the results of the questionnaire, why cannot government's policies effectively solve these barriers frequently reflected by enterprises?

Appendix B. The Results of Questionnaire

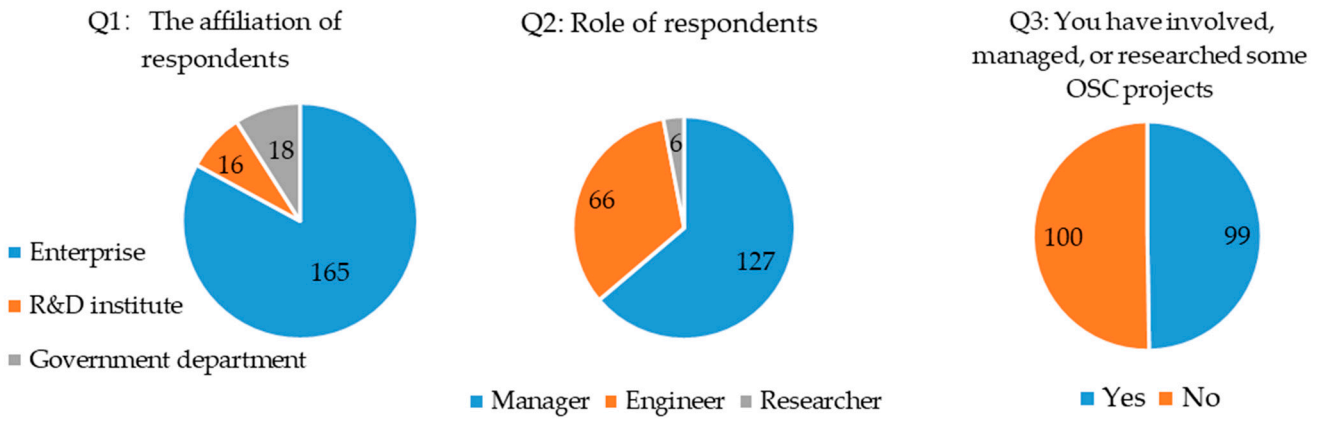

Figure A1. The basic information of respondents of the questionnaire survey.

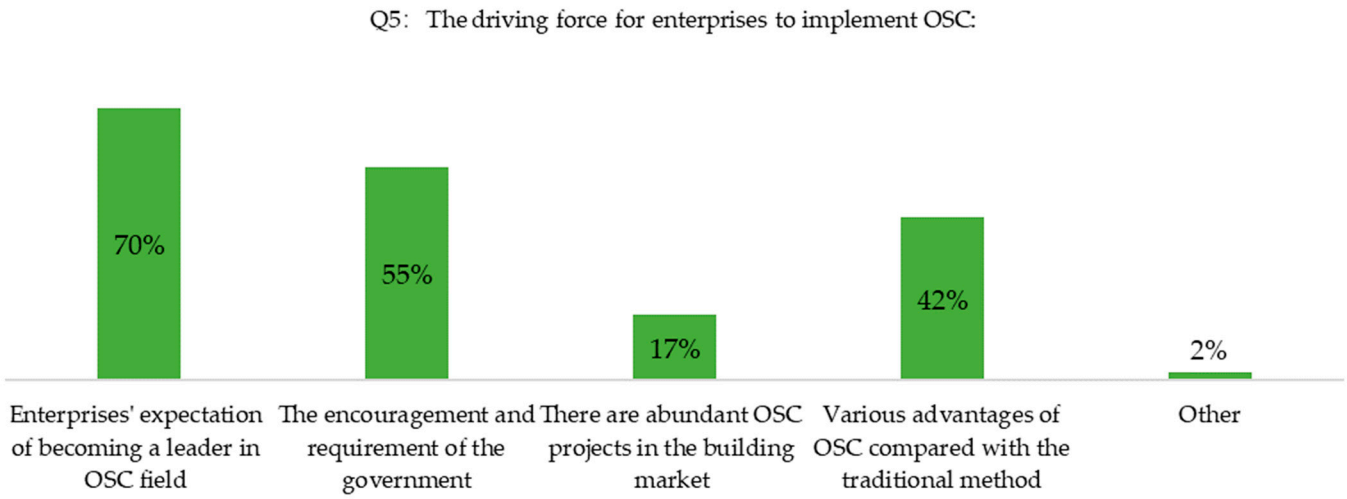

Figure A2. The results of Q5.

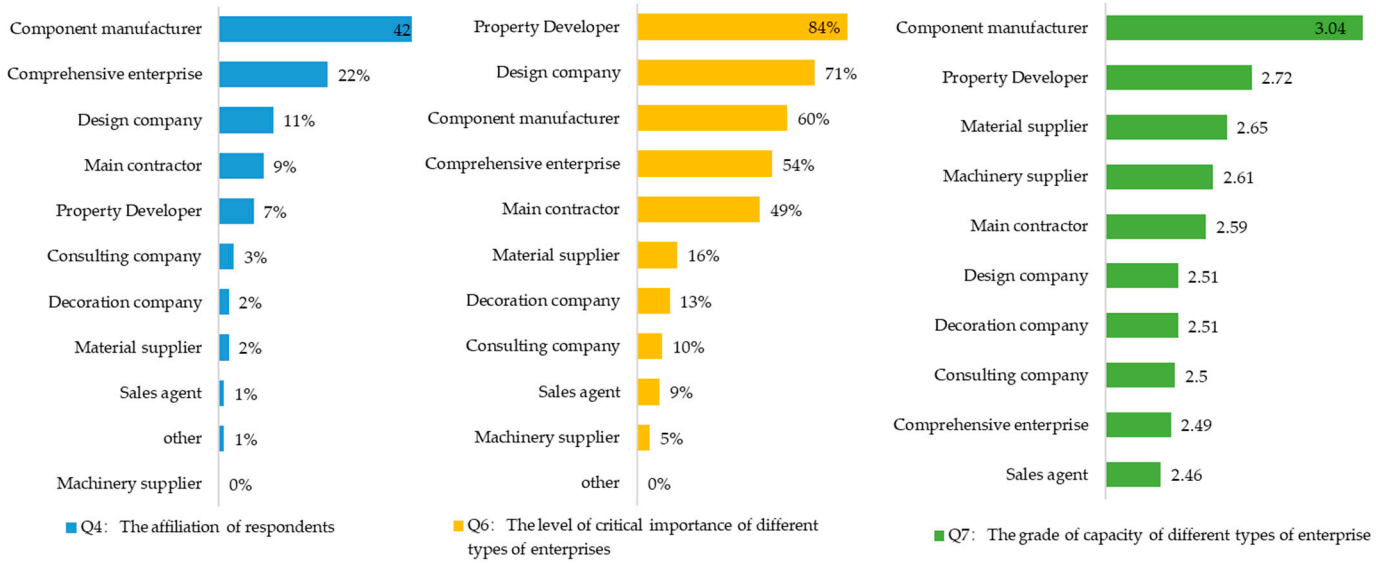

Figure A3. The results of Q4, Q6, and Q7.

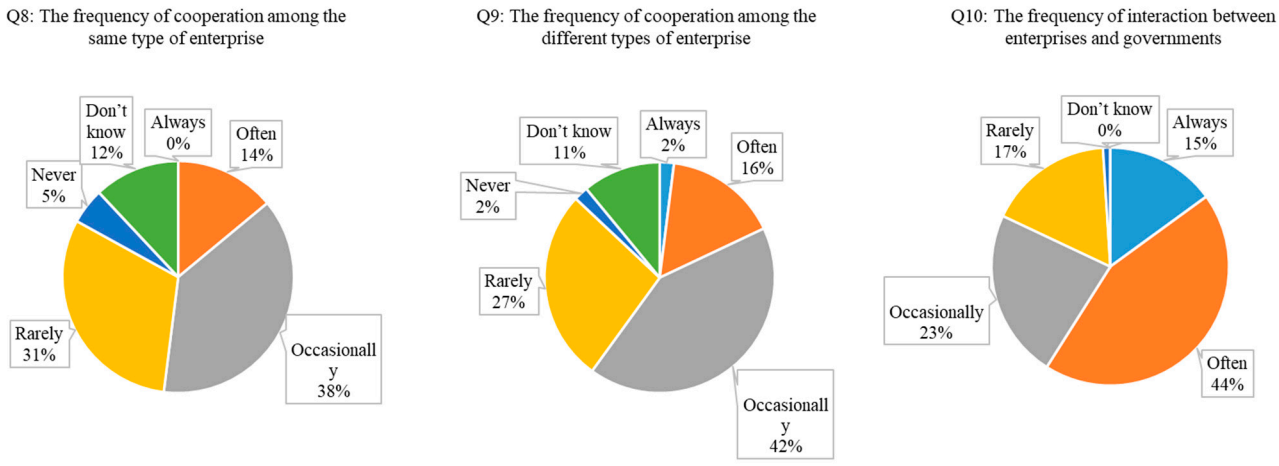

Figure A4. The results of Q8, Q9, and Q10.

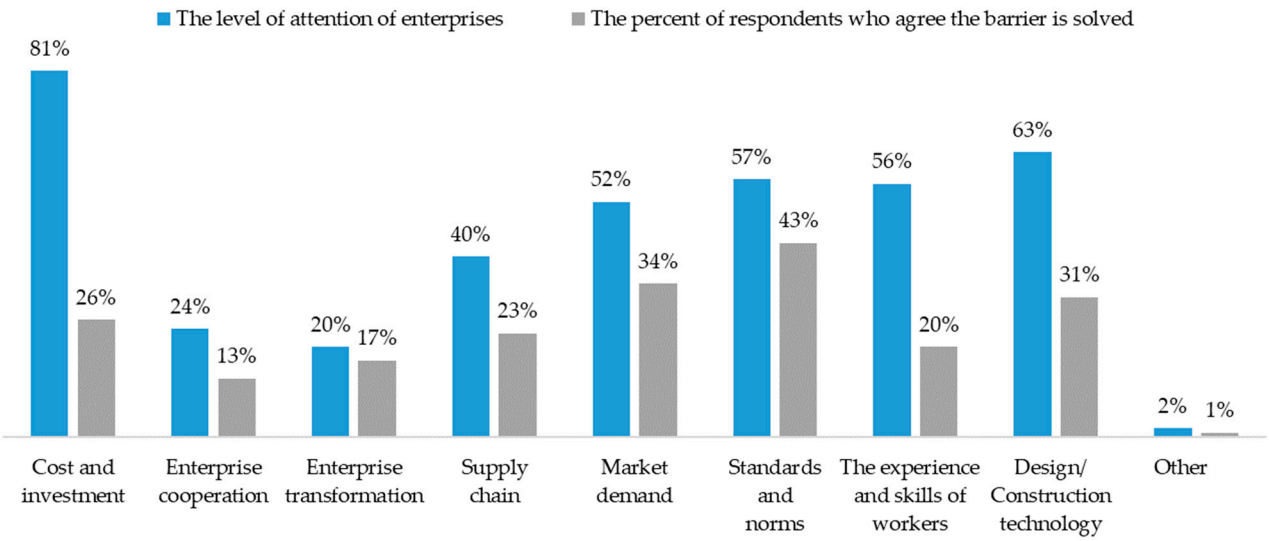

Figure A5. The results of Q11 and Q12.

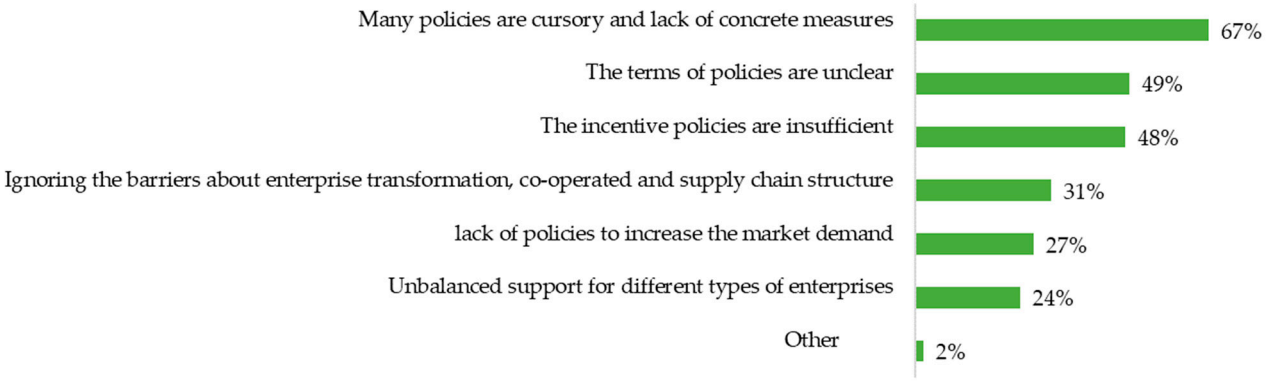

Figure A6. The results of Q13.

Appendix C. The Findings of the Questionnaire and Interviews.

Table A3. The findings of the questionnaire.

Questions	Findings
Q3	• more than half of respondents have not experienced OSC projects • the number of OSC enterprises is limited
Q4	• most respondents were from component manufacturer • there is a large gap of number between different types of OSC enterprises
Q5	• although enterprises try to implement OSC, the market demand of OSC-related businesses cannot support them
Q6	• property developer, design company, component manufacturer, comprehensive enterprise, and main contractor are deemed to be important for OSC development
Q7	• the performance of component manufacturer was better than other types of enterprises • enterprises who are deemed to be important perform worse except for component manufacturer • all of OSC enterprises do not perform well
Q8	• lack of cooperation between OSC enterprises within the same business
Q9	• lack of cooperation between different types of OSC enterprises except for daily communication of projects
Q10	• most enterprises have looked for help from governments to address their problems

Questions	Findings
Q11	• enterprises focus more on project barriers such as cost and investment, design/construction technology, standards and norms, the experience and skills of workers, and market demand
Q12	• current policies cannot solve enterprises' barriers effectively
Q13	• the shortcomings of OSC policies are that many policies are cursory, concrete measures are lacking, the policies are unclear, and the incentive policies are insufficient

Table A4. The findings of interviews.

Questions	Findings
I1	• limited OSC projects • OSC cannot be given full play to help enterprises to achieve their KPIs currently due to various barriers, which cause negative loops
I2	• enterprise managers think that component production is a better business opportunity compared with other businesses • policy-makers of governments take component production as a precondition for OSC development • the function of the design company is overlooked • managers of design company do not have the awareness to promote OSC actively • the property developer was placed on high hopes to promote the development of OSC by governments and other enterprises
I3	• enterprise managers think that there is a moral hazard of cooperating with other enterprises • the inevitable competition occurred in the same type of enterprises • enterprises' cooperation is difficult due to the fragmented supply chain of China's RBI-ECO • enterprises are more willing to pay more attention to their own business rather than cooperating with other enterprises
I4	• if these barriers cannot be addressed, enterprises cannot finish ongoing projects and survive in the competitive market
I5	• lacking concrete measures and insufficient incentives • project barriers are affected by industrial structure barriers • governments think that industrial structure barriers will be solved if project barriers are solved • governments overestimate their ability to cope with these project barriers

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