Evolution Mechanism of Off-site Construction Ecosystem Based on the Lotka–Volterra Model: A Case Study

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ABSTRACT
Off-site construction (OSC) is an alternative method to conventional construction for solving problems of high energy consumption, high pollution, and poor efficiency. OSC is a reform trend for the global construction industry. The emergence of OSC can influence the production relations in traditional construction industry chain, thereby changing the roles of stakeholders in such new construction sector. Given that most developing countries at present are still in the initial stage of adopting OSC, their construction industry is far from forming healthy and symbiotic ecosystem and highly efficient industry chain. Therefore, the scientific and rapid development of OSC becomes restricted. This study analyzes the mechanism of OSC ecosystem, reduces the vague understanding of OSC by stakeholders, and provides a reference for the strategy planning of stakeholders. From the perspective of bionics, this study aims to (1) establish an OSC ecosystem based on the theory of ecology and delimit the role of stakeholders in the OSC ecosystem, and (2) establish a Lotka–Volterra model for the OSC evolution. The OSC development in Beijing is used as an example. Data are collected and models are verified to discuss the state, trend, and turning point of the OSC evolution. The findings of this study can help stakeholders in comprehensively understanding the inherent historical development of OSC and provide a reference for the government decision making.

KEYWORDS
Off-site construction; Bionics; Ecosystem; Evolution mechanism; Lotka–Volterra model

INTRODUCTION
The concept of off-site construction (OSC) has been applied in China for more than 30 years; however, the productivity of building construction and sustainable construction industry in the county significantly lags behind those of the European and American countries, such as Denmark, Sweden, the United States, and other countries with building prefabricated rate of up to 70% above (Jallion et al., 2009; Ying Bo Ji, 2011). These countries completed the structural adjustment of large-scale industrialization in building industry through policy, technology, market, law, and other ways; these countries have also entered the maturity phases of automatization and intelligentization (Richard, 2005; Chiang et al., 2006; Ge Guo, 2009). Many cities in China, such as Beijing, Shanghai, Shenzhen, and Shenyang, have adopted OSC and have made a few achievements in building construction, building material production, and industry standards. However, the development of industry and participant in the entire building industry chain are still on a low and small-scale level. Some problems, such as extensive production, low level of standardization, lack of complete sets of technology, and limited understanding on OSC still exist. The construction industry is also far from

forming healthy and symbiotic ecosystem and highly efficient industry chain. Therefore, the transformation and upgrading of the construction industry become limited.

The development and transformation problems of construction industrialization in China have been investigated from the technical, cost, policy standard, and participant perspectives. Considerable research discussed the performance of OSC based mainly on construction industrialization. The advantageous performance of OSC and its evolution mechanism and development rules locally and internationally are rarely investigated. With the establishment of the industrial alliance and base, the OSC development has been analyzed from the systematization and integrity perspective. Zhongfu Li (1998) described the OSC industry chain integration from the industrialization perspective and believed that OSC makes the residential design, component production, and construction and sales as a complete industrial system. Yinghua Shan (2015) proposed that OSC refines and specializes the social division of labor in the construction industry and that the collaborative development of the participants is an important way of integrating technology and resources. The OSC modular feature determines the development of OSC as the "network industry chain" model. The research shows the importance to analyze the OSC development by the systematic method. However, they did not discuss the main reasons. Research on the OSC ecosystem and its general development rule is scarce. According to the theory of ecology, the natural ecosystem is organized by different creatures with different characteristics. Such ecosystem also has a complex organic connection among the various population, communities, creatures, and the natural environment. Under the effects of the natural environment, ecological communities evolve continually and then form an ecosystem. Similar to the natural ecosystem, the OSC ecosystem is also an open dynamic system and suggests many similarities in selection mechanism, environment, and evolution. This study aims mainly to build the OSC ecosystem, analyze the evolution process by referring to the theory of natural ecosystem evolution, predict the development trend of OSC ecosystem, and provide suggestions to help participants of industry transformation.

LITERATURE REVIEW

Natural ecosystem

Tansley, a British scholar, is the first to propose the ecosystem concept. Through constant evolution and development, a unified understanding of the natural ecosystem has been obtained. Specifically, the natural ecosystem is a natural system formed by the material circulation and energy flow interaction among various creatures and the bioinorganic environment in a certain space and time. The natural ecosystem connotation includes four aspects: (1) space and time limits, (2) basic composition of the system, (3) basic functions of the system, and (4) unified structure foundation and development trend on function (Guozhu Du, Botao Wang, 2007). The natural ecosystem is composed of producers, consumers, decomposers, and abiotic components. The producers play a major role in maintaining the stability of the ecosystem by transforming the energy of inorganic environment to organic biology. The consumers are consumer and deliverer of energy. The consumers obtain energy by consuming other organisms instead of producing on their own. The decomposers reuse the complex organic matters (corpses, feces) of natural system by decomposing them. In the natural ecosystem, the biont and its environment influence and limit each other. The natural ecosystem keeps a stable state of dynamic equilibrium in a certain period of time, and then becomes an organism in itself with some specific functions.

Lotka–Volterra model

The Lotka–Volterra (LV) model is widely used for investigating the natural ecosystem evolution. The LV model can analyze the interspecific competition, coevolution, density changes, and interspecific relationship among species. This model is an extension of the logistic model (block growth model), which is one dimensional and cannot describe the development law of single species. The LV model can be used to reflect a competitive state between two or more species. The two-dimensional LV model is expressed as follows:

$$\frac{\mathrm{d}N_1}{\mathrm{d}t} = a_1N_1 - b_1N_1^2 - c_1N_1N_2, \quad (1)$$

$$\frac{\mathrm{d}N_2}{\mathrm{d}t} = a_2N_2 - b_2N_2^2 - c_2N_1N_2, \quad (2)$$

where N_1 and N_2 represent the number of species of the two species in time *t*. N_1^2 and N_1^2 indicate the internal interaction of species. N_1N_2 represents the interaction between the two species. "*a*" is the growth parameter when species exist singly and is equal to intrinsic parameter "*r*". "*b*" is the limit parameter of species. "*c*" is the interaction parameter between two species, and is used to define the relationship between the two species (Table 1).

The LV model describes the development process of the biological field and is widely used in other fields. Lee (2005) applied the LV model to dynamically analyze the South Korean stock market. Bi-Huei Tsai and Yiming Li (2009) explored the electronic circuit industry development of Taiwan and its mainland by using the LV and Bass models to study the relationship between manufacturers, packaging manufacturers, and designers on the industrial chain. Chen Yu (2012) introduced the LV model to discuss the photovoltaic industry evolution and explored the relationship among the various components in the photovoltaic industry ecosystem. Xinrui Kang (2013) adopted the LV model to investigate the logistics industry. In summary, the LV model can analyze the competition and evolution in various fields. Thus, this model is suitable to determine the production relations of stakeholders during the OSC development process.

Table 1. Relationship between the two species in ecosystem

Number	Types	c_1	c_2	Feature
1	Symbiosis	-	-	Close and often long-term interaction between two different biological species
2	Competition	+	+	A contest between two or more organisms
3	Predation	-	+	A biological interaction where a predator (an organism that is hunting) feeds on its prey
4	No effect	0	0	No effect on each other
5	commensalism	-	0	A class of relationships between two organisms where one organism benefits from the other without affecting it
6	Amensalism	+	0	an organism inflicts harm to another organism without Any costs or benefits received by itself

In adopting the LV model, the solution of model parameters must be first obtained. Haijun Chen (2011) suggested that the least square method or the gray model fitting method can be used to calculate the parameters of the model. Kloppers P.H. and Greeff J.C. (2013) collected empirical data and calculated the model parameters using the integral and well logging integration models. The calculated solution of the present study is mainly used in the former.

METHODS

Establishment of OSC ecosystem

On the basis of the value stream, the related enterprises, customers, and construction environment constitute the OSC ecosystem in a certain period of time and space.

Definition of biological components of the OSC ecosystem

The OSC ecosystem is composed of three biological components, namely, producers, consumers, and decomposers. The producers are the raw material suppliers, designers, and labor suppliers. The raw material suppliers obtain raw materials from the natural environment and make these materials available to the developers or contractors. The designers provide the design drawing to the developers and contractors. The labor suppliers search labors from the social environment and provide them to the contractors. The producers keep living by relying on environment energy or producing energy on their own. The producers do not need to consume product or services of other companies to gain energy. The consumers are the supervisors, contractors, developers, owners, component manufacturers, and material manufacturers. The contractors need to rely on the designers' drawings, raw material suppliers' materials, and labor suppliers' labor to complete the project construction. The supervisors need to rely on the construction process to accomplish the task of supervision. Moreover, the developers need to rely on the designers' drawings, construction process, supervision services, and materials to obtain residential products. The owners need to rely on the developers' residential products to meet their need for living. The consumers' survival and development are based on the production or service provided by the producers or other consumers. The decomposers refer to the removal of recycling companies. When houses reached a certain life or can no longer be used because of other special reasons, the decomposers demolish and recycle houses and then recycle the material back into the production cycle.

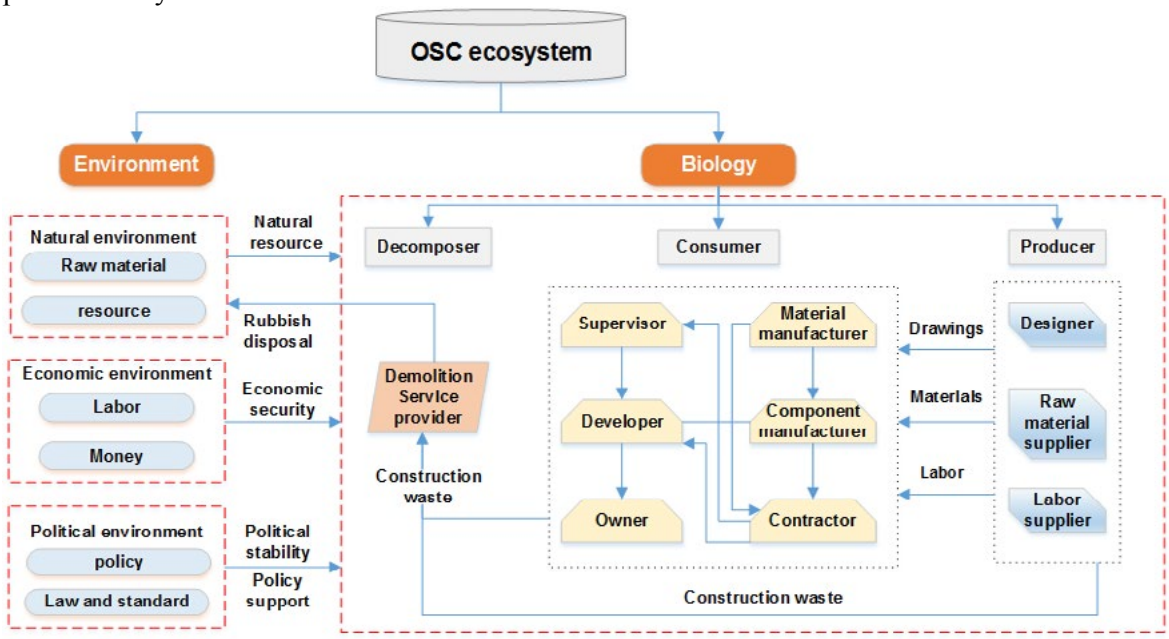

Figure 1. OSC ecosystem

Definition of environment components of OSC ecosystem

The environmental system of OSC includes the natural, social, and economic environments. Among them, the natural environment consists of the raw materials, land, resources, and

climate. The natural environment also provides the initial energy for residential construction. The changes in the natural environment, such as climate, can influence the schedule, cost, and quality of residential construction. The social environment includes the labor supply, policy support, technical standards, and so on. The stability of the social environment ensures the completion of the construction process. The economic environment mainly refers to the economic status, the situation of the construction market, and the economic environment. The economic environment provides the corresponding funds and market to the ecosystem. These biological and non-biological components form the OSC ecosystem.

LV model of the OSC ecosystem

Comparing the OSC ecosystem and the natural ecosystem emphasizes the similarity between the two. Thus, the LV model can be used in the construction field to analyze some related issues. However, the LV model still has some differences in structure and function between the two types of ecosystem. Accordingly, the following assumptions are adopted: (1) the construction industry is a closed system, which cannot be disturbed by the external system; (2) the traditional construction method (TCM) and OSC do not have internal competition. According to the above assumptions, the LV model is adjusted and thus Equations (3) and (4) are obtained. "N_1" indicates the population or community scale of the OSC ecosystem. "N_2" indicates the population or community scale of the TCM ecosystem.

$$\frac{\mathrm{d}N_1}{\mathrm{d}t} = a_1 N_1 - c_1 N_1 N_2 \qquad (3)$$

$$\frac{\mathrm{d}N_2}{\mathrm{d}t} = a_2 N_2 - c_2 N_1 N_2 \qquad (4)$$

Equations (3) and (4) are divided to yield Equation (5) as follows:

$$\frac{\mathrm{d}N_1}{\mathrm{d}N_2} = \frac{N_1(a_1 - c_1 N_2)}{N_2(a_2 - c_2 N_1)}. \qquad (5)$$

The allelic lines are the system along the rail line Function (7) (shown in Figure 3).

$$\mathrm{H}(N_1, N_2) = c_1 N_2 - c_2 N_1 + a_2 \ln N_1 - a_1 \ln N_2 \qquad (6)$$

The "*M*" point as an equilibrium in Figure 2 represents the stable coexistence state between TCM and OSC. However, the figure also shows a trajectory that can reach the equilibrium. Therefore, the equilibrium can be attained. Through the collection of data and analysis of the current location in the figure, the evolution trend of the OSC and TCM ecosystems can be obtained.

The residential area is selected as a typical area and represents the OSC ecosystem. Furthermore, this study chooses the accumulated starting area to reflect the change of the OSC and TCM population. The residential occupies the important position in the construction industry, that is, residential investment generally occupies approximately 70% of Chinese annual investment in real estate development. Residential construction investment accounts for GNP of nearly 10%, accounting for the total fixed capital formation of more than 20%. The accelerated process of urbanization in China and the influx of rural population into the city have increased the demand for housing. Thus, the scale of residential can reflect the scale of the construction industry. Given that the promotion of OSC is concentrated mainly in the residential construction, considering other types of buildings into the analysis is unreasonable.

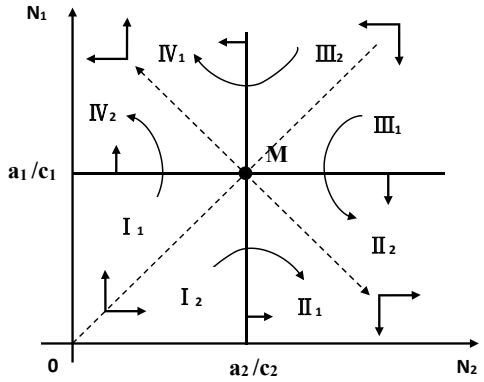

Figure 2. Function image of Equation (7)

Case study

The case study method is applied in this study for in-depth comprehension of the development trend of OSC and Beijing was selected as a typical case. Unlike other cities in China, Beijing as a first-tier city has practiced the OSC early and has gained a few achievements. Beijing can represent the advanced and perfect level of OSC development in China. The construction scale is expressed in the accumulated starting area of OSC and TCM. Data from the first OSC residential construction in 2008 in Beijing up to 2014 are collected and accumulated. However, 1978 is chosen as the base period for the data of TCM. Then, the annual completion of the area up to 2007 is accumulated. The data indicate the total residential area in Beijing by the end of 2007. Then, the operating area of OSC and TCM from 2008 to 2014 is accumulated. The specific data are presented in Table 2.

Table 2. Accumulated operating area of OSC and TCM

year	Accumulated operating area of OSC (hectare)	Accumulated operating area of TCM (hectare)
2008	0.81	33739.1
2009	5.5754	35119.38
2010	32.0954	37182.78
2011	72.6354	39779.23
2012	89.8179	41406.73
2013	224.8733	43143.27
2014	338.7797	44425.55

RESULT AND DISCUSSION

The data are input into the model to calculate the parameters using a previous solution method. The values of each parameter are obtained and shown in Table 3. The parameter results show that c_1 and c_2 are both negative. This result reflects a competitive relationship between the current OSC and TCM in Beijing. In addition, the "r" value of OSC is higher than that of TCM. This result shows that the current internal growth momentum of OSC in Beijing is higher than that of TCM. Moreover, OSC has a strong development potential. Judging from the competition coefficient "c" of the two methods, the number of competitive factors of

Beijing City is very small. This condition shows that the TCM in Beijing City has insignificantly limited OSC.

Table 3. Lotka–Volterra parameter results in Beijing

Parameters	Results
a_1	3.906619312
c_1	−7.8915E-05
a_2	0.05478183
c_2	−8.7814E-05
M	（623.84;49504.1）

The results show that the development trend of OSC in Beijing is better than that of TCM. This result is in line with the actual situation. Since 1996, China has begun to implement measures to promote the OSC development. However, OSC still maintains the slow pace in the country before 2006 and cannot make a substantial breakthrough. In 2007, the first OSC building was completed in Shanghai. Beijing also launched an OSC building practice. Under the policy guidance, Beijing strengthens the local OSC development and management actively. Since 2010, the number has gradually increased and continuously improved based on the national policy standards and Beijing policy standards. This condition provides a good environment for the progress of OSC and accelerates the development of OSC in Beijing.

At present, the OSC is well developed in Beijing and may grow as the main construction method in the city. However, the OSC ecosystem must be strengthened continuously. Referring to the evolution mechanism of the natural ecosystem, three ways are present in the evolution of the OSC ecosystem: replication mechanism, cooperation–competition mechanism, and recombination mechanism. The replication mechanism means that, in the OSC ecosystem, the new company learns development characteristics, development model, and product structure from the developers, contractors, component manufacturers, and other stakeholders to achieve rapid growth and development in the OSC ecosystem. Cooperation competition mechanism refers mainly to the stakeholders in the OSC ecosystem establishing the industry alliances and promoting the technical exchanges and resource sharing. Thus, vicious competition can be avoided and the internal symbiosis of the OSC ecosystem can be achieved. The recombination mechanism means that the upstream firms in the OSC ecosystem, such as developers, can use its location advantage and resource advantage to integrate the downstream industry chain and establish a construction industry group including the developers, contractors, designers, and other stakeholders. This method can help reduce the design change, communication cost, and unnecessary waste. Consequently, the quality management and supervision, technology innovation, and resource utilization maximization can be positively affected. The overall competitiveness of the construction industrialization can be enhanced accordingly.

CONCLUSION

OSC is the inevitable direction of Chinese construction industry and is the focus of the global construction industry in the future. This study discusses the development and evolution trend

of OSC. In Chinese construction market, competition relation exists between TCM and OSC. At present, TCM holds the leading position in the competition. However, the competitive advantage of OSC is increasingly becoming obvious and the development motive force is sufficient. With the continuous improvement of policies, standards, and norms and when the scale of OSC building reaches the balance point, the OSC can gain market advantage. Although the theory of ecology is adopted to analyze the development and trend of OSC and leads to some conclusions, the article still has several rooms for improvement. The analysis can be further developed and refined. Given that the Beijing case only reflects the domestic advanced level and not the average level, a large number of cases can be collected for future analysis. Further excavation or introducing other ecological theories can be conducted to study the OSC development.

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REFERENCE

Jaillon, L. & Poon, C. S. (2009). The evolution of prefabricated residential building systems in Hong Kong: A review of the public and the private sector. *Automation in Construction*, 18(3), 239-248.

Ji Yingbo. (2011). Research on the development of construction industrialization. China Building Industry Publishing House.

Richard, R. B. (2005). Industrialized building systems: reproduction before automation and robotics. *Automation in construction*, 14(4), 442-451.

Chiang, Y. H., Chan, E. H. W., & Lok, L. K. L. (2006). Prefabrication and barriers to entry—a case study of public housing and institutional buildings in Hong Kong. *Habitat International*, 30(3), 482-49

Ge Guo.(2009). Research on the development of housing industrialization. (dissertation Doctoral, Tongji University).

Guan Ke, & Li Zhongfu (1998). Interpretation of the concept of housing industrialization. *Modernization of construction management* (4), 19-21.

Yinghua Shan. (2015) research on the integration mechanism of the residential industry chain (dissertation Doctoral, Harbin Institute of Technology).

Guozhu Du & Botao Wang. (2007) Comparative Study of business ecosystem and natural ecosystem. *Journal of Beijing University of Posts and Telecommunications: Social Science Edition*, 9 (5), 34-38.

Green K. Industrial ecology and spaces of innovation. Edward Elgar Publishing; 2006.

Lee S J.Lee & DJ, Oh.H.S. Technological forecasting at the Korean stock market: A dynamic competition analysis using Lotka-Volterra model[J]. *Technological Forecasting and Social Change*,2005,72 (8) : 1044-1057.

Tsai B, Li Y. Cluster evolution of IC industry from Taiwan to China[J]. *Technological Forecasting and Social Change*, 2009, 76(8): 1092-1104.

Yu Chen & Fuji Xie. (2012). Based on lotka-volterra model of photovoltaic industry ecological innovation system evolution path of bionics research. *Research and development management*, 24 (3), 74-84.

Haijun Chen, Xijuan Lou, Jie Liu,Lifeng Wu. (2011) the grey estimation method and its

application of Lotka-Volterra model parameters. *The practice and understanding of mathematics*, 41 (23), 108-113.

Kloppers P H, Greeff J C. Lotka–Volterra model parameter estimation using experiential data[J]. *Applied Mathematics and Computation*. 2013, 224: 817-825.