Searching for an optimal level of prefabrication in construction: An analytical framework

Weisheng Lu[1], Ke Chen[2], Fan Xue[3], and Wei Pan[4]

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Many countries or regions, in recent years, show a rising interest in prefabrication as a "cleaner" production strategy to meet their enormous construction demand, e.g. for housing and infrastructure. Along with this trend is the observation that many governments tend to set forth a high level of prefabrication as a part of their ambitious construction plan. This paper argues that unnecessarily a higher level of prefabrication is better and develops an analytical framework for questing the optimal level of prefabrication adoption in a certain PEST (political, economic, social and technological) background. This framework contains thirteen PEST factors affecting the prefabrication adoption, including policy, supply, labor, social attitude, user acceptance, and so on. These factors in combination will determine the optimal prefabrication adoption level from 0 to 4, which was defined by Gibb 2001 to represent the range from entire cast-in-situ construction to complete prefabricated building, respectively. The framework was substantiated by using Hong Kong's prominent offshore prefabrication construction as a case. It was identified that Levels 2 and 3 are the optimal level of prefabrication adoption subject to the current PEST background in Hong Kong. This paper helps to clarify the prevailing misconception that "the higher the prefabrication level, the better". The developed framework can be used by other economies to devise their proper prefabrication roadmaps.

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Keywords: prefabrication; construction; analytical framework; Hong Kong

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1. Introduction

Great challenges caused by the rising construction demand, sharp cost pressures, and increasingly acute environmental problems have attracted extensive attention to prefabrication in the global construction industry. In a traditional and still popular way, construction work was built on site using “cast-in-situ” technologies characterized by fixed jobsite, formwork and falsework, wet trades, scaffolding, and extensive waste. It was delivered by using projects, which are a temporary organizational form that has a designed beginning and end (Turner and Müller, 2003; Bakker et al., 2016). The basic idea of prefabrication is to transfer a certain proportion of the construction work from the traditional sites to factory or other manufacturing sites (Tatum et al., 1986), so it favors the way of massive production as seen in the manufacturing industry. A construction project is considered as prefabrication if it either uses individual prefabricated building components (e.g. façade, staircase, and slab) or is entirely based on the assembly of prefabricated building modules.

Particularly, prefabrication is widely considered as a way of 'cleaner production', which is “a concept that aims at preventing the production of waste, while increasing efficiencies in the uses of energy, water, resources, and human capital” (JCLP, 2018). Many studies have unanimously discovered that prefabrication is a ‘cleaner’ strategy of production by having the following benefits:

- More controlled conditions for weather, quality control, improved supervision of labor, easier access to tools, and fewer material deliveries (Construction Industry Institute, 2002);
- Fewer job-site environmental impacts because of reductions in material waste, air and water pollution, dust and noise, and overall energy costs (Lu and Yuan, 2013; Jaillon and Poon, 2014; Tam et al., 2015; Hong et al., 2016);
- Increased worker safety through reduced exposures to inclement weather, temperature extremes, and ongoing or hazardous operations; better working conditions (e.g. components traditionally constructed on-site at heights or in confined spaces can be fabricated off-site and then hoisted into place using cranes);
- Compressed project schedules that result from changing the sequencing of work flow

(e.g. allowing for the assembly of components off-site while foundations are being poured on-site; allowing for the assembly of components off-site while permits are being processed);

- Fewer conflicts in work crew scheduling and better sequencing of crafts persons; and
- Reduced requirements for on-site materials storage, and fewer losses or misplacements of materials (Tam et al., 2015).

In view of the promising benefits of prefabrication, policy-makers (e.g. governments, authoritative institutions) in many countries or regions have recognized prefabrication to be a matter of course in their construction strategies. The Central Government in China, for example, has recently set forth a ten-year goal to apply prefabrication to 30% of the domestic newly constructed buildings (General Office of the State Council, 2016). In Singapore, prefabricated prefinished volumetric construction (PPVC) is mandatory for selected non-landed residential government land sale sites from 2014 onwards (Building and Construction Authority, 2015). In Malaysia, a public project that costs over Malaysia Ringgit (MYR)10 million or a private venture over MYR50 million is required to obtain a minimum Industrialized Building System (IBS) score of 70 (The Edge Property, 2016). Likewise, the Government of Hong Kong also has aggressively promoted the use of prefabrication.

In this context, a general observation is that the governments tend to stipulate a high level of prefabrication as part of their ambitious construction plans; similar to a prefabrication “race”. There should be an optimal level of prefabrication rather than being “the higher, the better”. Differences in policies, regional economic developments, social or cultural background, and technological factors all could be either enablers or barriers to the prefabrication adoption in different economies (Murtaza and Fisher, 1994; Pan et al., 2012; Liu et al., 2017). The combinational effects of these factors could suggest an optimal level of prefabrication that is not necessarily high but suitable for a certain PEST (political, economic, social and technological) context. Nevertheless, there is no such analytical method in place to articulate the PEST factors and to examine how they will determine the optimal prefabrication level.

The aim of this paper is to develop a framework for comprehensively analyzing the optimal level of prefabrication adoption which is suitable for a certain PEST background. In this paper, an ‘optimal level of prefabrication adoption’ represents the level at which prefabrication implementation has the optimum, overall suitability towards a certain PEST context, and in turn, its implementation will allow achieving the optimal performance measured by time, quality, cost, safety, environment or a combination thereof. The framework considers thirteen factors from political, economic, social, and technological perspectives. To offer an intelligible description of its applicability, the developed framework will be applied to the context of Hong Kong to discuss the prefabrication adoption status therein. By doing so this study can provide information to construction stakeholders regarding their either grudging adoption behaviors or essentialism about prefabrication. This study is also of relevance to policy-makers as they are keen to know the impacts a prefabrication-related policy would exert on the regional or national development of the construction industry.

The rest of this paper is structured as follows. The research methods are outlined in Section 2. Factors affecting prefabrication adoption in construction projects are reviewed in Section 3. Section 4 presents a review of indicators that depict the level of prefabrication adoption. Section 5 describes a framework for identifying the optimal level of prefabrication adoption. Section 6 shows the analytic results of the optimal level of prefabrication adoption in Hong Kong. The last section presents conclusions and recommendations for future research.

2. Research methods

This study follows a four-step research design and adopts the hybrid research methods that consist of the literature review, survey studies, focus group meetings, and interviews. In the first step, a literature review was conducted to provide a comprehensive understanding of the recognized factors affecting the prefabrication adoption. The authors searched representative papers from relevant journals and conference proceedings by using the Google Scholar search engine. Keywords used for searching included “prefab*”, “precast*”, “modular*” and “off-site”. The title and abstract of each paper were screened to check if it is related to the target topic. In addition, relevant white papers and industrial reports were also collected by using the Google search engine. By doing so, a total of 35 papers and reports were qualified for review in this study. Based on the authors’ perusal of these selected papers and reports, factors affecting the prefabrication adoption were summarized and analyzed.

Secondly, the authors reviewed existing measurements of the level of prefabrication adoption. Different from the literature searching process, the information search at this step was mainly based on the authors' knowledge due to the relatively small amount of papers that offer the required information. The authors comparatively analyzed both quantitative and qualitative measurements in order to select the one suitable for this study. Debates on the definitions of prefabrication and its measurements, as will be shown later on, are pluralistic. The authors joined in some of the debates in conferences, writing, or other occasions meanwhile bearing in the mind the operability of such measurements for the analytical framework to be developed in this study. As a result, Gibb's (2001) taxonomy and measurement is adopted.

Integrating the analytic results from the first two steps, the third step was to develop a framework that helps to identify the optimal level of prefabrication adoption. This was gradually shaped through three focus group meetings facilitated by the authors. The first one was held in the Headquarters of the Hong Kong Housing Authority (HKHA), as the biggest user and promoter of prefabrication in Hong Kong. One Swedish professor and two frontline Swedish project managers and three senior officers from the HKHA joined the meeting. This provides an excellent comparative perspective to developing the framework. The second meeting was held in one of the largest precast yards in Huizhou, China, with the general managers and engineers from the factory and academics from Hong Kong joined for a whole afternoon discussion. The offshore factory only provides prefabricated products for construction projects in Hong Kong. The third meeting was held in another large precast factory in Dongguan, China, with general managers, engineers, project managers from the main contractor, transporters and academics joined. That also provided an interesting lens through which PEST factors and their effects on prefabrication adoption were effectively examined.

In the fourth step, the developed framework was applied to Hong Kong to analyze the optimal levels of prefabrication adoption in Hong Kong with particular PEST background. The data for analysis consisted of both first- and second-hand data. The second-hand data was sourced from the official statistics published by governmental organizations. The first-hand data was collected through the authors' site surveys on a public housing project operated by the HKHA. During the site surveys, the authors conducted interviews with a number of stakeholders including one government staff member, two staff members from a main contractor, and two knowledgeable retired experts who claimed to familiar with the whole history of prefabrication development in Hong Kong. Both first- and second-hand data were then provided to a group of experts to evaluate the optimal levels of prefabrication adoption in Hong Kong by using the Delphi method. Although they are discussed in sequence here, Steps 2, 3, and 4 are actually blended together when the study was conducted. This concurrent conduction of research activities allows an on-going triangulation of data from different sources and finally a robust, operable analytical framework to be developed. We have purposely "jumped out" from the specific contexts in analyzing the general factors and developing the framework, although a close link to the specific PEST context has never been disconnected.

3. Factors affecting prefabrication adoption

Many researchers have initiated studies about the identification and analysis of factors affecting the prefabrication adoption. In this study, a factor that has been mentioned by at least two papers was deemed as a major one. Based on the literature review, a total of thirteen factors were identified as the major ones affecting the prefabrication adoption in an industrial setting (See Table 1). These are broad factors falling into political, economic, social and technological categories.

Table 1 Summary of factors affecting prefabrication adoption

	Factor	**Times being mentioned**
Political	Policy	18
	Standards, codes and guidelines	10
Economic	Supply	22
	Schedule	15
	Type and scope	11
	Repetitive components	10
Social	Labor	15
	Social attitude	9
	User acceptance	14
Technological	Resources	12

	Familiarity	15
	Construction tolerances	7
	Site logistics	12

Political factors

The political factors include *Policy* and *Standards, codes and guidelines*. *Policy* has been regarded as the major factor that would directly raise the incentive of the prefabrication adoption (e.g. Blismas, 2005; Jiang et al., 2017). Murtaza and Fisher (1994), Kamar et al. (2009), and Liu et al. (2017) have found that, under some circumstances, *Policy* can effectively encourage the prefabrication adoption by offering financial incentives if a project has achieved certain requirements in using prefabrication. In addition, the authoritatively designed *Standards, codes and guidelines* are important in the sense of guiding clients, designers, contractors, and suppliers to fluently practice their prefabrication adoption processes (Smith, 2016).

Economic factors

The major economic factors include *Supply*, *Schedule*, *Type and scope*, and *Repetitive components*. The demand and supply of prefabricated components and associated materials affect prefabrication adoption as they are the necessary condition for maintaining a smooth process of production and on-site construction (Pan et al., 2012; CII, 2012). The adoption of prefabricated components would unavoidably change the project *Schedule* as well as logistics (Li et al., 2017). Thus, when making decisions on the prefabrication adoption, one would consider the supply- and schedule- related issues (e.g. the need of a long lead time when the manufacturing factories are far away from the construction site) (Pan et al., 2007).

Type and scope of projects directly determine what type of and how many prefabricated components could be used (Gerth et al., 2013). Whether projects use *Repetitive components* is also important because, if it is the case, the use of prefabrication in such projects can gain benefits from the "economy of scale" than projects falling in the otherwise case and do not have bulk orders if using prefabrication (Chen et al., 2010; Bildsten, 2011). Similarly, for small-scope projects or uniquely designed buildings, as they generally involve a quite small number of repetitive components, it could be difficult and infeasible for them to adopt prefabrication.

Social factors

The major social factors include *Labor*, *Social attitude*, and *User acceptance*. *Labor* is a major factor that affects the prefabrication adoption (e.g. Chiang et al., 2006; Wong et al., 2017). While it might reduce the required traditional manpower, particularly carpenters and concreters, the use of prefabrication generally would lead to the demand of skilled labors for the machine operation, transporting, lifting, on-site assembly of prefabricated components, connecting the prefabricated components with the in-situ ones, etc. (Chiang et al., 2006). The lack of expertise of these trades in the market would significantly impede the prefabrication adoption.

About *Social attitude*, prefabrication has long been considered as monotonous design without much flexibility (Alinaitwe et al., 2006), which may reduce end-users' enthusiasm toward prefabrication. As a result, prefabrication has been traditionally adopted in social housing, wherein end users have no much choice unfortunately. The market for prefabricated construction could be affected if there is no continuous improvement and innovation of prefabrication technology to satisfy diversity and personality requirements of consumers (Luo et al., 2015).

User acceptance refers to the attitude of client. Researchers generally agree that the client's opinion on prefabrication would practically determine the final level of prefabrication adoption in a project (e.g. Gibb and Isack, 2003; Zhai et al., 2013). The clients' less confidence in prefabrication or misinterpretation on its benefits and risks has been found to constrain the prefabrication adoption (Kamar et al., 2009). For example, Liu et al. (2017) have found that the clients' higher awareness of the potentials of prefabrication is positively related to the actual prefabrication adoption in their projects.

Technological factors

The technological factors include *Resources*, *Familiarity*, *Construction tolerances*, and *Site logistics*. *Resources*, such as production and installation machines, have a close relationship with the quality of the prefabricated components (Song et al., 2005). *Familiarity* refers to the experience that organizations have learned from its previous project using prefabrication (Azhar et al., 2013). Some studies point out that some contractors are reluctant to adopt prefabrication since they are already familiar with the conventional method of in-situ construction (e.g. Azhar et al., 2013; Rahman, 2014).

Construction tolerances refer to the tolerances of quality for the project. Luo et al. (2015) pointed out that, in situations where there is a lack of skilled workers, the risks such as sealing joints might come along with the assembly of prefabricated components. Thus, for projects that only the high installation precision is acceptable (i.e., with small construction tolerances), stakeholder might be inclined to the traditional construction methods instead of using the prefabrication (Luo et al., 2015).

Finally, compared with the traditional cast-in-situ method, the prefabrication construction seems to be facing greater challenges in *Site logistics*. A congested site could constrain the use of prefabricated components, especially for those large-sized, heavy ones (Azhar et al., 2013). In addition, when planning the site arrangement in a prefabricated construction project, it should be considered that the lifting of prefabricated components would need heavy lift and the site transport equipment with higher capacities than before (Pan et al., 2012).

4. Measuring the level of prefabrication adoption

Measuring the level of prefabrication adoption is largely inconclusive in terms of definitions, approaches, and results. The measurements can be perceived from two generic categories: quantitative and qualitative. Quantitative measurements are employed by both scholarly papers and regulations in some economies. For example, Alinaitwe et al. (2006) suggested that the level of prefabrication adoption can be measured by the ratio of value of work done on site to off site. Wong et al. (2008) used the approximate percentage of the off-site production among all construction components. Hong et al. (2016) proposed a “prefabrication rate” that is derived from the adopted prefabrication volume over the total volume of building materials. The Construction Industry Development Board (CIDB) of Malaysia also introduced a scoring mechanism of the IBS to measure the level of prefabrication adoption. An IBS score is calculated by summing up the score of structural systems, the score of wall systems, and the score of all other simplified construction solutions (CIDB, 2004).

Quantitative measurements could offer a clear, index-style understanding of the portion of prefabrication in overall construction. They can also be an independent variable to produce the quantitative links to other construction-related variables, e.g., to measure how much energy consumption can be saved when using prefabrication to a certain extent (Hong et al., 2016). However, using the value or volume relating to prefabrication alone as the measurements could be problematic in some situations. For example, consider two prefabricated projects, one using a certain volume of precast façades and the other using the same volume of precast bathroom. If the total volume of the materials used in these two projects were the same, they would have the same prefabrication rate. However, this rate clearly cannot reflect the real situation.

Qualitative measurements also prevail. Gibb (2001), for example, proposed a five-level taxonomy of prefabrication adoption. In Gibb's (2001) taxonomy, Level 0 means a project does not use any form prefabrication at all, e.g. fully cast-in-situ; Level 1: Component and sub-assembly (e.g. lintels); Level 2: Non-volumetric assembly (e.g. 2-dimensional precast concrete wall panels, precast components with no usage space enclosed); Level 3: Volumetric assembly (e.g. volumetric bathrooms, kitchens with usable space enclosed); and Level 4: Modular building (e.g. 3-dimensional modules which form the fabric of the building structure). Similarly, Steinhardt et al. (2014) introduced a six-level taxonomy, in which Levels 0 to 5 represent none, prefabricated trusses and beams, prefabricated structural panels, specialized pods, modules, and fully completed houses delivered to site respectively. Likewise, Goodrum et al. (2009) and Sierra and Zamora (2013) introduced their qualitative measuring taxonomies in different levels, and in different terms.

Qualitative measurements cannot represent the amount of prefabrication used, but they can tell what kind of prefabrication is adopted. Hence, qualitative measurements are more suitable than their quantitative counterparts to describe which type of prefabrication is fitting into a certain PEST background. The taxonomy proposed by Gibb (2001) is used as the measurement of prefabrication adoption in this study owing to two reasons: (1) it is a widely-known qualitative measurement that has been introduced to the industry for over 15 years; (2) it helps to clearly identify the level of prefabrication adoption that has been achieved based on the types of prefabricated components used.

5. The framework to search for the optimal level of prefabrication adoption

Each level of the prefabrication adoption has its own strengths and weaknesses in comparison with the conventional construction method subject to a certain context. Given a context in which only a low level of prefabrication adoption would be suitable, the use of prefabrication at a high level might be confronting a loss due to that constrains from the contextual factors as listed above. Therefore, it is proposed that there should be an optimal level of prefabrication suitable to a certain context that is characterized by various PEST factors. This is the major proposition of this paper (See Figure 1), which is based on reflections from the three focus meetings described in Section 2. The horizontal axis is the different levels of prefabrication adoption, in this particular study, adopting Gibb's (2001) taxonomy. The vertical axis is the suitability of adopting a certain level of prefabrication. The inverted U-shaped curves mean that for a certain context there is an optimal level of prefabrication adoption. A too low or too high level means the overall performance of prefabrication implementation could be negatively affected owing to the supports and constraints imposed by the PEST factors associated with the particular context. For example, for Context A, to pursue a Level 3 prefabrication (i.e. volumetric assembly, such as volumetric bathrooms, kitchens with usable space enclosed) needs strong design expertise, manufacturing capability, and also the sufficient hoisting power that might not be readily accessible. Instead, a Level 2 (i.e. non-volumetric 2-dimensional precast concrete wall panels, precast components) might be more suitable.

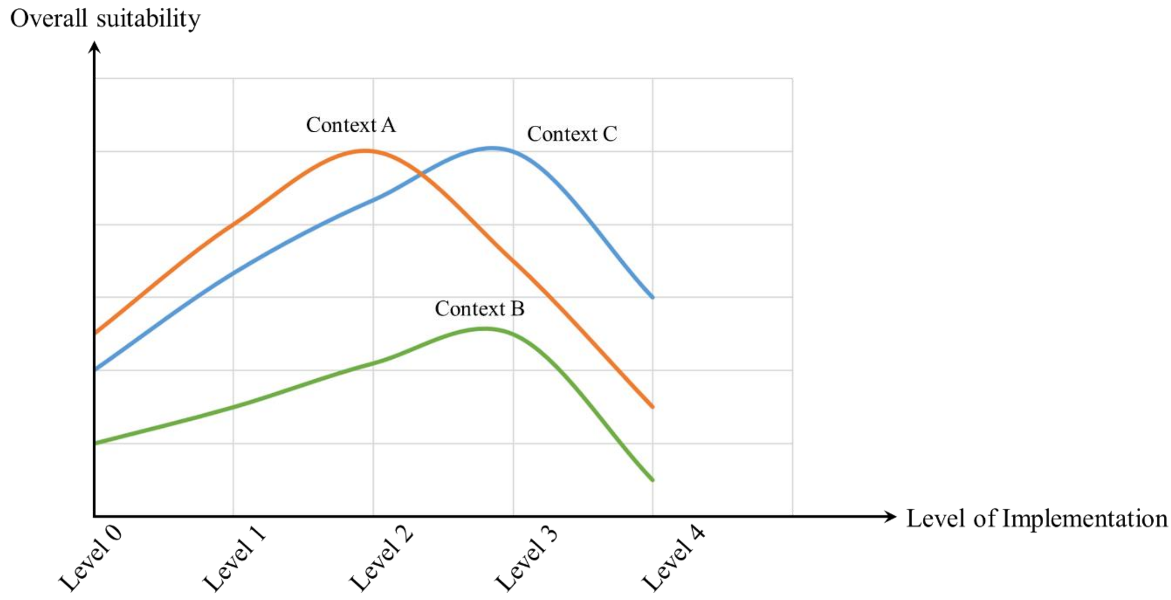


Figure 1 A conceptual illustration of the optimal level of prefabrication adoption in different contexts

Based on the proposition, the analytical framework for determining the optimal level of prefabrication adoption is developed (See Figure 2). The left-hand side of the framework illustrates that the PEST factors altogether affect a certain level of prefabrication to perform. The right-hand side of the framework illustrates how the framework can be applied in real-life scenario analyses. Subject to a given Context X, the application of the analytical framework involves three steps. At the first step, the Delphi method is adopted to ask a group of experts to give an evaluation of potential support or constraint of each factor to a certain level of prefabrication adoption. The Delphi method used the first step, in a sense, is to remap these experts' knowledge from their mind. This is because, from the focus group meetings as introduced in Section 2, the authors found that experienced experts tended to put the PEST context as an overall background and were more aware of the supporting or constraining influence of the entire context, instead of individual PEST factors, on levels of prefabrication adoption. Thus, in Round 1 Delphi, the experts are asked to mark "++", "+", "0", "-", "--" for each PEST factor regarding individual prefabrication adoption levels by using the form in Figure 2. These five signs denote "strong support" (scores 2), "moderate support" (scores 1), "neutral" (scores 0), "moderate constrain" (scores -1), and "strong constrain" (scores -2) respectively. For example, marked "++" to P1 for Level 4, it indicates that this expert considered the current policy strongly supporting the use of module building (i.e., Level 4). Then, in Round 2 Delphi, experts are asked to reassess their evaluation in the light of the consolidated results from Round 1. The statistical technique of Kendall’s coefficient of concordance could be used to assess the degree of consensus arrived by all experts (Ameyaw et al., 2016). With significant consensus, the ‘correct’ evaluation results, i.e., the signs of individual PEST factors, were regarded as being attained (Rowe and Wright, 1999).

At the second step of framework application, the overall suitability of individual prefabrication adoption levels for that given Context X is measured by summing up the signs of all PEST factors. At the third step, values of the overall suitability of the five prefabrication adoption levels are plotted and linked to form the curve. Based on the curve, the optimal level of prefabrication adoption fitting Context X can be identified.

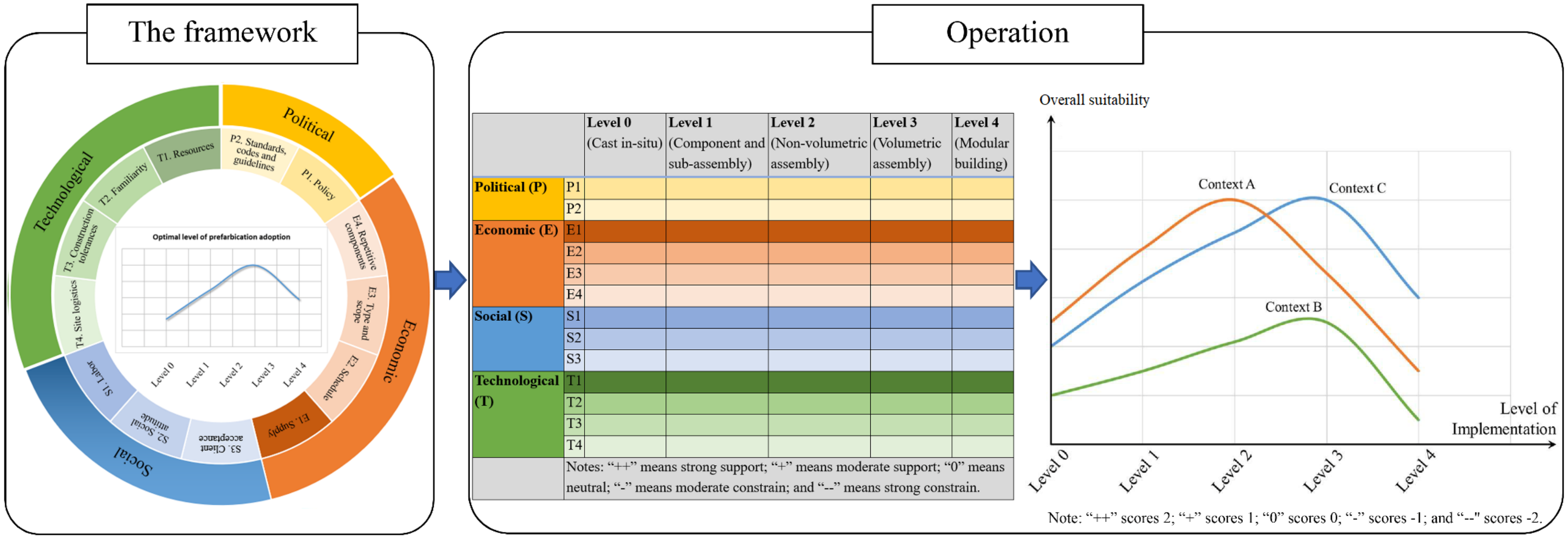


Figure 2 The analytical framework for questing the optimal level of prefabrication adoption

6. A case of Hong Kong

To illustrate how the analytical framework is implemented, and to add to the debates on an optimal prefabrication level, a case study was conducted in Hong Kong. Prefabrication is hardly new to the construction industry in Hong Kong. With a 30-year's development under the Government's strong promotion, prefabrication has been widely implemented in buildings, especially public housing projects. By the end of March 2016, there were 1.5 million units of private housing, 0.79 million units of public rental housing, and 0.40 million units of subsidized housing (Transport and Housing Bureau, 2016a). Prefabricated components are widely used in the construction of public housing blocks for better workmanship and quality control and to maximize construction efficiency (HKHA, 2017a).

Data about the Hong Kong's PEST factors were collected from the official statistics, publications, reports, and site surveys. For some factors, such as user acceptance and resources, the officially-published data is triangulated with data collected from site surveys for corroboration. The data were then analyzed by a group of 6 local experts (See Table 3) using the Delphi method as introduced in Section 5. For simplified and concise presentation, the sign of each PEST factor for a certain prefabrication adoption level is the one marked by most experts rather than the mean value from all experts. The results are summarized in Figure 3(a) and plotted to form the curves in Figure 3(b). The Kendall's coefficient of concordance of 0.779 (p_value=.000 for the significance level of 0.05) indicates that the statistically significant agreement among the experts has been arrived. As shown in Figure 3(b), Levels 2 and 3 are the most optimal level of prefabrication adoption in the current PEST background of Hong Kong.

Table 3 Profile of the experts participated in the evaluation

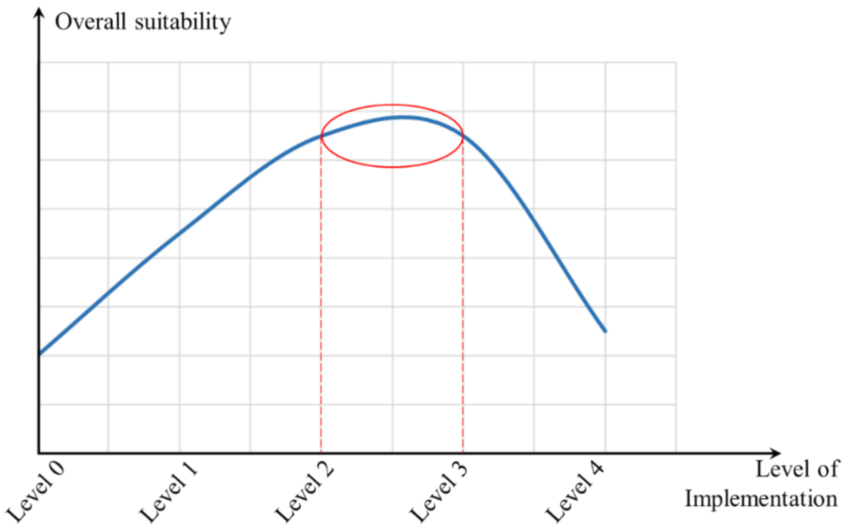
No.	Position	Years of experience in prefabrication
1	Project manager of a government agency	21
2	Senior engineer of a private developer in Hong Kong	15
3	Senior engineer of a leading main contractor in Hong Kong	16
4	Technical director of a leading main contractor in Hong Kong	13
5	Professor of a Hong Kong local university	19
6	Associate Professor of a Hong Kong local university	9

		Level 0 (Cast in-situ)	Level 1 (Component and sub-assembly)	Level 2 (Non-volumetric assembly)	Level 3 (Volumetric assembly)	Level 4 (Modular building)
Political (P)	P1	-	+	++	++	++
	P2	++	++	+	+	-
Economic (E)	E1	-	-	+	+	+
	E2	0	0	+	+	+
	E3	-	+	++	++	++
	E4	-	+	++	++	++
Social (S)	S1	--	-	0	+	-
	S2	+	0	0	0	0
	S3	+	+	+	+	0
Technological (T)	T1	+	+	+	+	+
	T2	+	+	+	+	0
	T3	++	++	+	0	0
	T4	++	+	-	-	--
Total scores		4	9	12	12	5

Kendall’s coefficient of concordance = 0.779;
p_value = .000;
significance level = 0.05.

Notes: “++” means strong support (scores 2); “+” means moderate support (scores 1); “0” means neutral (scores 0); “-” means moderate constrain (Scores -1); and “--” means strong constrain (scores -2).

(a)



(b)

Figure 3 Evaluation results of the optimal level of prefabrication adoption in Hong Kong

The evaluation results can be better interpreted by connecting them with qualitative discussions on the PEST factors in Hong Kong.

P1: Policy

Figure 3(a) shows that P1 strongly supports the prefabrication adoption in Hong Kong. Such evaluation results are consistent with the fact that the Hong Kong Government has been taking an active role in promoting the use of prefabrication through public policies. In the 2016 Policy Address, the Government highlighted that prefabrication will enhance the standardization of project design, promote mechanization and construction. The HKHA has introduced the use of precast secondary members such as secondary beams, slabs, and external facades in its public housing projects since the mid-1980s. Precast façade has been a mandatory requirement for all standard domestic blocks of public housings (Construction Industry Review Committee, 2001). For private sector projects, the Government of Hong Kong promotes the use of prefabrication by providing the gross floor area (GFA) concession. Specifically, in 2001 and 2002, Joint Practice Notes (JPN) 1 and 2 were issued by government departments, respectively. According to the JPNs, building developers could receive GFA concession if they adopt prefabrication or other green building technologies. JPNs indeed have provided incentives to private developers about adopting prefabrication in their projects.

P2: Standards, codes and guidelines

Prefabricated construction projects, like other construction projects in Hong Kong, must obey the Buildings Ordinance (CAP 123) and several complementary regulations. To provide particular information about the design, construction and quality control in prefabrication projects, the Building Department (BD) published the “Code of Practice for Precast Concrete Construction” (hereafter called “the CoP”) in 2003 and an updated version in 2016 to (BD, 2016). The Hong Kong Institution of Engineers (HKIE) also published a precast concrete construction handbook to elaborate the Code on major concerns and adopts the same paragraphing of the Code for easy referencing (HKIE, 2015). The existence of standards, codes, and guidelines is particularly important for construction, including prefabrication, which will be bewildering if without such. However, guidelines for implementing prefabricated volumetric units are currently in absence in the context of Hong Kong.

Therefore, P2 is assessed to exert moderate constraints to the Level 4 of prefabrication adoption in Hong Kong.

E1: Supply

Most precast concrete suppliers to construction projects in Hong Kong have set up their fabrication yards in the Pearl River Delta (PRD) such as Huizhou and Shunde in Guangdong Province, China (Lu, 2013). The considerable number of public housing projects in Hong Kong helps to maintain a stable demand for prefabricated components. The highly efficient road and water transportation network between Hong Kong and the PRD facilitate the delivery of prefabricated components. Figure 4 shows one of the major transportation route, about 130 miles, from fabrication yards to Hong Kong. A 2.5m width limit of the prefabricated components to be transported is set based on the capacity of trucks (Mak, 2013). The transportation is generally carried out by third-party logistics companies which own trucks, trailers (See Figure 5) and even transshipment warehouses. The relatively long distances between suppliers and construction sites require much attention about preventing the prefabricated components from damages.

Figure 4 One of the major transportation routines from fabrication yards to Hong Kong

Figure 5 The truck and trailer

E2: Schedule

The public housing projects of HKHA follow a six-day cycle (Mak, 2013). Although the interviewed government staff member admitted that a four- or five-day cycle could be achievable, a six-day cycle is suitable for the current practice due to the availability of tower crane and other resources. The six-day cycle also allocates time in advance for the production of the prefabricated components until they can be accumulated to sufficient numbers for delivery to site for installation. Comparatively, the private sector projects normally do not follow a six-day cycle; they accomplish a cycle as fast as possible. Combined the difference in the schedules of public and private sector projects, E2 is assessed to moderately support the prefabrication adoption in Hong Kong.

E3: Type and scope

The public housing project in Hong Kong generally has a standardized layout with symmetry in design. Such standardized layout is suitable for the adoption of prefabricated components. In comparison, the private sector projects are unique in design and could face more design changes during the construction process. The feature of design in private projects could hinder the use of prefabrication for maintaining design flexibilities. However, Hong Kong has been operating a prominent public housing sector for decades. Recently, the Government set a housing supply target of 460,000 units for the next ten-year period from 2016-17 to 2025-26, with a public-private split of 60:40 (Transport and Housing Bureau, 2016b). The considerable stock of public housing units could be an important reason why E3 is considered to strongly support the prefabrication adoption in Hong Kong's construction industry as a whole.

E4: Repetitive components

Explanations for the strong support of E4 shown in Figure 3(a) are similar to those for the positive effects of E3. In 2008, in line with the principle of "functional and cost-effective" design, the HKHA has developed a new library of "modular flat design" covering several types of flat units for mass production in public housing projects (See Figure 6). Designers of the selected public projects can follow these standard modular flats to draw building blocks that are suitable for different site configurations. The module flat design results in the use of may repetitive components in the public housing projects. Thus, the benefit of mass production can be leveraged.

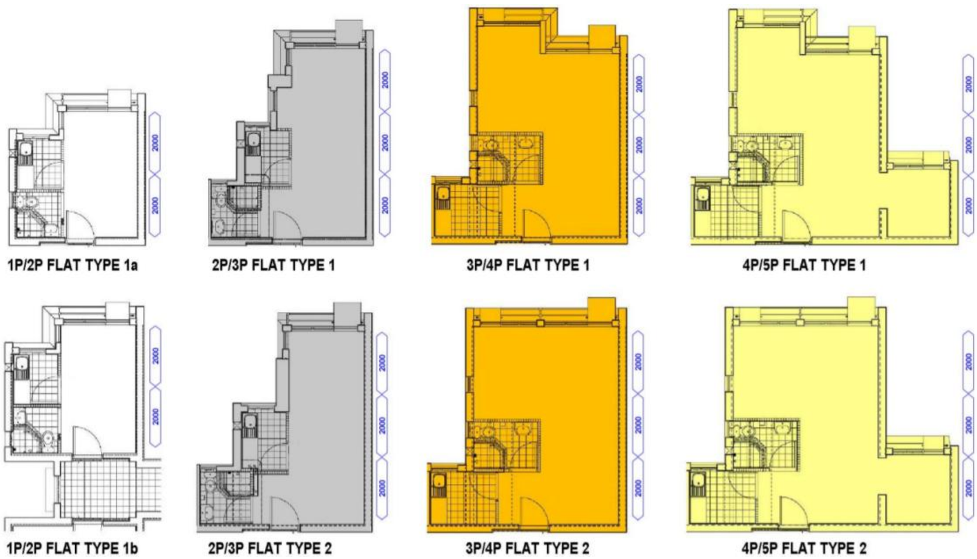


Figure 6 Standardized flat units of public housing in Hong Kong (LegCo 2015)

S1: Labor

The labor shortage is a problem plagued Hong Kong's construction industry for long. The Construction Industry Council (HKCIC) (2016) has forecasted a shortage of up to 15,000 skilled workers for the next few years in Hong Kong. Actually, one of the initial thoughts about promoting prefabrication is to alleviate the labor shortage in several trades such as formwork and bar bending, by exploiting the relatively cheaper manpower, material, and land in adjacent cities such as cities of the Pearl River Delta in Mainland China. The prominent economic development in Mainland, however, have raised challenges to the development of prefabrication in Hong Kong. For example, the labor costs and land prices in the PRD have increased greatly, making the set-up of precast yards gradually unaffordable. On the top of these labor issues, there is always a lack of skilled workers on the erection of prefabricated building structures, making it difficult to transfer to the complete use of prefabricated modular units in one step (Li et al., 2017).

S2: Social attitude

The effects of S2 on Levels 2 and 3 of prefabrication adoption are assessed to be neutral. These results imply the importance of the general education to the public about the benefits of prefabrication. In Hong Kong, the public used to have limited understandings about the promotion of prefabrication. This might cause an unfavorable impression of prefabrication to the public of Hong Kong. If the public could be more aware of the potentials of prefabrication, such as allowing the sustainable design, construction, and operation of buildings, they may become more willing to consume buildings constructed by prefabricated components.

S3: User acceptance

S3 is assessed to moderately support the prefabrication adoption in Hong Kong. The HKHA has been the pioneer in adopting prefabrication and contributed to the major prefabrication innovations. Various types of prefabricated components such as precast façade, precast staircase, precast panel wall and semi-precast slab are widely-adopted in public housing projects. Precast ground floor water tank and volumetric precast bathroom are also accepted in some of these projects (HKHA, 2017a). For the public sector, facades units are the most common prefabricated components used in Hong Kong's construction industry. In addition, the non-structure prefabricated wall is more acceptable to private sectors since its usage can receive GFA concession.

T1: Resources

The moderate support of T1 to the prefabrication adoption in Hong Kong is related to the particular structure of the local construction industry. Hong Kong's construction industry is structured by a few number of large contractors and a great number of small companies working as subcontractors. The large contractors in Hong Kong own heavy machines and are financially resourceful in adopting prefabrication in their projects. In Contrast, most of Hong Kong's subcontractors are small in size (Hong Kong Trade Development Council [HKTDC], 2016) and in a lack of recourses for adopting prefabrication. In addition, some large contractors have a tight bond with subcontractors who are afraid of losing their jobs after shifting construction process to prefabrication (Mak, 2003). These issues are believed to be the obstacle for increasing the prefabrication adoption in Hong Kong construction projects.

T2: Familiarity

Explanations for the effects of T2 on Hong Kong's prefabrication adoption are similar to those for the effects of T1. In Hong Kong, a few large contractors have been adapting their skills and expertise to the use of prefabrication, especially those participating in public housing projects. With the gained experience, these contractors can more effectively arrange the installation and handle the collaboration between prefabrication and in-situ concreting components (Tam et al., 2015). However, prefabrication is still technologically unfamiliar to the majority of local contractors. Most of them might have experienced projects using a few types of prefabricated components such as precast slabs, facades, and staircases, but have less experience in more complex prefabrication system that could be more complicated in arrangement and installation.

T3: Construction tolerances

In order to meet the requirements of construction tolerances, the quality of both production and installation must be controlled. The Housing Department follows the Buildings Department's requirements on quality control and supervision of prefabrication production in Mainland (Legislative Council [LegCo], 2017). However, when more complicated prefabricated components (i.e., Levels 3 and 4) are used, it is relatively difficult to control the quality of installation since there is no much regulative mechanism on controlling the standard and quality of workmanship. In addition, since technical issues about structural supporting have not been fully addressed, the prefabricated structural components may not able to be effectively used in construction projects. Thus, effects of T3 on the Levels 2 and 3 of prefabrication adoption are assessed to be moderate support and neutral, respectively

T4: Site logistics

Hong Kong is known to have a high density of construction work. Most of the construction site in Hong Kong is in the congested urban area and will become even congested since both storage and pre-installation handling of prefabricated components require extra working space. The congested environment makes access and delivery of heavy prefabricated components to the work spot become difficult (Jaillon and Poon, 2014). Workers have to conduct installation at high altitude under very congested floor layout. The limited space for site logistics generally constrains the use of heavy prefabricated components, such as precast water tank and bathroom, in many construction sites in Hong Kong.

7. Discussions and conclusions

Prefabrication has great potential to overweigh conventional construction methods in many aspects. Nevertheless, prefabrication is not a cure-all solution that automatically promises shortened construction time, lower construction cost, as well as other benefits, without due consideration paid to a PEST context that supports or constrains its implementation. This study argues that the optimal level of prefabrication is produced by bounded up forces from PEST factors. This argument, however, has not been well recognized by some strategic decision-makers, particularly of emerging construction markets, in devising their prefabricated construction development plans. These strategic decision-makers often intend to make ambitious plans about setting forth high, sometimes unrealistically high, levels of prefabrication adoption in construction markets of cities, regions, or countries.

In espousing this argument, this study developed an analytical framework to analyze a PEST background and determine the optimal level of prefabrication under this background. Thirteen PEST factors, including *Policy*, *Standards, codes and guidelines*, *Supply*, *Schedule*, *Type and scope*, *Repetitive components*, *Labor*, *Social attitude*, *User acceptance*, *Resources*, *Familiarity*, *Construction tolerances*, and *Site logistics*, were identified based on the literature review and interviews with the industrialists. These PEST factors provided sound directions for determining the optimal level of prefabrication adoption in a certain context. It is also suggested to use the analytical framework periodically to examine the dynamic changes in PEST factors in a certain context and their implications on the appropriate prefabrication adoption level. This is because that the PEST conditions of an economy would rarely be static but change as time elapses, though the change may not be radical within a short term (e.g. 3-5 years). These changes will subsequently impact the optimal levels of prefabrication adoption.

To illustrate the applicability of the proposed framework, the framework was substantiated in Hong Kong, a place known for a high-rise, high-density built environment, as a case. This case vividly showed that Levels 2 and 3 of prefabrication adoption are the most suitable to Hong Kong's current PEST context. The framework can also be used by cities, regions or countries that have low-rise construction projects for rationalizing their prefabrication construction strategies. That is, the framework is not meant to be a closed system and its included factors should not be considered unchangeable. More studies are encouraged to further refine the PEST factors and evaluation tools of the framework.

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