Determining the Level of Prefabricated Module Requirements in Offsite Construction

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Abstract

Offsite construction technique presents substantially speedier construction processes whilst lowering construction wastes. The level of prefabricated for offsite construction projects depends largely on the amount of complexity and the level of prefabricated components, which can be classified into two levels such as 2D penalized and 3D volumetric construction. However, there is often no specific method adoptable for determining the level of prefabrication construction. This research aims to determine the level of prefabrication requirement for offsite construction and their significance. An online database collected for offsite construction projects was analysed with decision making models. The results revealed that the building volume, i.e., the building footprint and height were the most influential factors. Furthermore, three other factors related to timber material, low-income target user, and residential function of prefabricated projects were also identified as crucial in deciding the prefabrication level. The research concluded with certain guidance recommended for choosing the appropriate prefabrication level for building construction. For example, penalized construction generally had a higher level of implementation than volumetric construction in prefabrication.

Keywords Building performance, Offsite construction, prefabrication level, Determining factor and Penalized construction.

1. Introduction

Prefabricated construction , also known as off-site construction or modern method of construction (MMC), is a modern construction approach consisting of two working sites, i.e., the off-site manufacturing site and construction site (Wuni and Shen, 2020). The prefabricated components are built in an offsite once the design is completed, then delivered to a construction site for assembly (Jiang et al. 2018). Offsite construction is an important trend in building industrialization, as it helps enhance the characteristic of the construction industry which has been largely dependent on traditional on-site construction (Young et al. 2020). The prefabricated construction method provides substantial advantages, such as reducing environmental effects, shortening project duration and improving productivity (Mostafa et al., 2020). Bertram et al. (2019) claimed that offsite construction can reduce project duration by 20% to 50 % and construction costs by 20 %. However, the term ‘prefabrication element’ covers a range of different approaches, systems, and forms (Bertram et al.2019). It can be any component/s, sub-assemblies, volumetric pre-assembly, or modular building (Apaydın 2011).

The levels of prefabrication can be different according to the degree of complexity and the scale of the prefabricated component. Mostafa et al. (2020) stated that not every design is suitable for the highest level of prefabrication and assembly technique (i.e., 3D volumetric modules) as certain situations could make it less competitive. Therefore, in order to maximize the benefits of prefabrication, finding the suitable prefabrication level to fit different situations is crucial. This study examines the benefits and challenges of different levels of prefabrication in construction. The study also adopts a wide-ranging qualitative approach by analysing project samples collected from the industry. Utilizing a decision-making model for investors to decide prefabrication level, the study defines inputting features of projects in terms of key factors that could influence the prefabrication level of a given construction project. Suggestions are presented to provide guidance when deciding the most suitable prefabrication level for offsite construction projects.

2. Background

The significant features of prefabricated buildings include reducing construction cost and material waste. Hence, most prefabricated projects are perceived as more economical compared to traditional site construction using cementitious materials. However, the problems associated with long-term return on the initial prefabrication factory investment increase the investment risk to project sponsors. Moreover, building performance and maintenance is an important determining factor on the prefabrication level of projects, which is strongly related to all stakeholders' interests, especially the building users. The review compares the two different prefabrication levels, i.e., volumetric and penalized construction, in terms of building performance during the operation and maintenance stage.

Building Performance

Thermal performance: Volumetric buildings usually adopt light materials such as Phase change material (PCM) boards as insulation, which are easy to transport and suitable for use. However, these materials with low density have less capability to store heat which can be absorbed and released easily causing overheating in some building areas (Rodrigues et al., 2016). Yoo et al. (2012) interviewed over 20 residents of shipping container houses, and detected that 14 out of 23 residents were dissatisfied with the insulation of their houses. In the penalized buildings, they can use rigid insulation (e.g., concrete) with better thermal performance. The panel connection design can also offer a high thermal resistance and an airtight envelope to prevent heat losses (Lopeza and Froesea, 2018). Hence, penalized buildings can perform better than the volumetric modules in terms of thermal performance.

Ease of maintenance and replacement: According to Lee et al. (2018), the volumetric module is manufactured as one room and each part of it can still be replaced separately during the maintenance phase, and the module is composed of bundles of individual components. The construction materials in volumetric projects can be repaired as units. For instance, the roof can be replaced as a whole module which includes the coating, waterproofing and roofing (Lee et al., 2018). The advantage of 3D volumetric construction lies in that the module or its components can easily be changed or repaired. In contrast, as penalized buildings are not fully constructed by the standard modular elements, the maintenance and replacement is more difficult compared to volumetric buildings which are based on standardized modular systems. Penalized buildings use large masses of materials and are able to utilize rigid materials as insulation which can be more resistant to mould growth and insect infestation (Lopeza & Froesea 2018). Their components have longer duration, and can prevent future maintenance issues whilst the volumetric components usually need to be repaired as a whole unit causing significant increase in the cost (Seidu et al. 2021). Due to the differences in their replacement approach and material duration between volumetric and penalized methods, the cost of maintenance and replacement for penalized components is less than for volumetric elements. Table 1 summarizes the comparison between the two different prefabrication levels in the operation stage.

Table 1. Comparison of two levels of prefabricated construction.

Criteria			Level of prefabrication	
Aspects	Project stage	Project events	Penalized	Volumetric
Building Performance	Operation	Thermal performance	√	
		Ease of maintenance and replacement		√
		Cost of maintenance and replacement	√	

Overall, the penalized construction appears to be more cost-saving and better-performing than volumetric construction. However, the above result does not necessarily mean that it is better to implement penalized construction in all prefabrication projects. Since the project condition varies from one to another, there are lots of critical factors that can contribute to the selection of an appropriate prefabrication level for an offsite construction project. The majority of existing studies focuses on comparing conventional and offsite construction approaches, but with limited comparisons between different levels of prefabrication within offsite construction. Thus, it is still unclear how to decide the most suitable prefabrication level for offsite construction projects. In fact, suitable level of prefabrication and assembly technique varies, depending on multiple factors such as the life span of the building (e.g., temporary or permanent), the desired space layout and the technical (e.g., heating, electricity, etc.) equipment to install (Rakotonjanahary et al.m2020). By deciding the proper prefabrication level for offsite construction projects, the overall benefits of the prefabrication projects can be improved. Therefore, choosing the appropriate level of prefabrication becomes critical for the effective implementation of offsite construction technologies.

3. Research Methods

The study aims to offer a direct decision-making tool for investors to effectively derive the suitable prefabrication level for construction projects. A Random Forest Classification Model is used as an enabler to predicate the prefabrication level of a project based on the identified critical input factors of the project (Breiman 2001). The nature of the Random Forest Model is a form of decision tree, i.e., a predictive model. According to Biau and Scornet (2016), the decision tree starts from observations about an item (e.g., the critical factors) to output conclusions about the item's target value, e.g., prefabrication level of construction projects in this study.

The dataset used to construct the decision-making model is a sample of 80 projects' information collected from ArchiDaily (2021), which is a project dataset with recent and recognised construction project information worldwide. The critical factors (e.g., building height, function, target user, number of floor, and structural material) in this case is used as the input features or attributes, and the prefabrication level (i.e., volumetric and penalised construction) in this case is used as the target value or output conclusion. In order to develop a more efficient decision-making model, the dataset used in model development was required to be optimised.

The forest model is developed by using Python script which is one of the commonly adopted programming languages. Following the model construction, it was evaluated for its accuracy of prediction for decision making, i.e., deciding the proper prefabrication level in this study. The most efficient way to verify the usefulness of the decision-making model is to apply real-world cases to evaluate its prediction performance (Pezhman et al. 2018). In this study, eight hypothetical construction projects were designed to investigate the applicability of the model.

4. Research Findings and Analysis

Input dataset was created from the database, and the value of output set (i.e., prefabrication levels of projects) was either volumetric or penalised. Initially based on the database, four major input factors were identified as attributes that could influence the decision of the level of prefabrication in offsite construction projects. They were: building footprint & height, building function & target user, construction material, and project location. The aforementioned four major input factors may not be equally important for deciding the prefabrication level of projects. The random forest model was used to compute the significance of these factors. The model was operated by constructing a multitude of decision trees at training time. The model was considered a powerful tool to rank the importance of variables in a classification scenario (Mistikoglu et al. 2015).

The ranking presented in Figure 1 indicated that building footprint is the dominant factor for deciding prefabrication level. This result supported the findings that the structural nature of modular building made building footprint a focal factor for deciding the prefabrication level. The second most important factor was the number of floors. Based on the analysis of building height, it was discovered that the number of floors was essential in deciding the prefabrication level, especially for super-low or super-high prefabricated buildings. The building footprint and height were the horizontal and vertical measurements of a building volume, respectively. As a result, the building volume played the most essential role in deciding prefabrication level for construction projects.

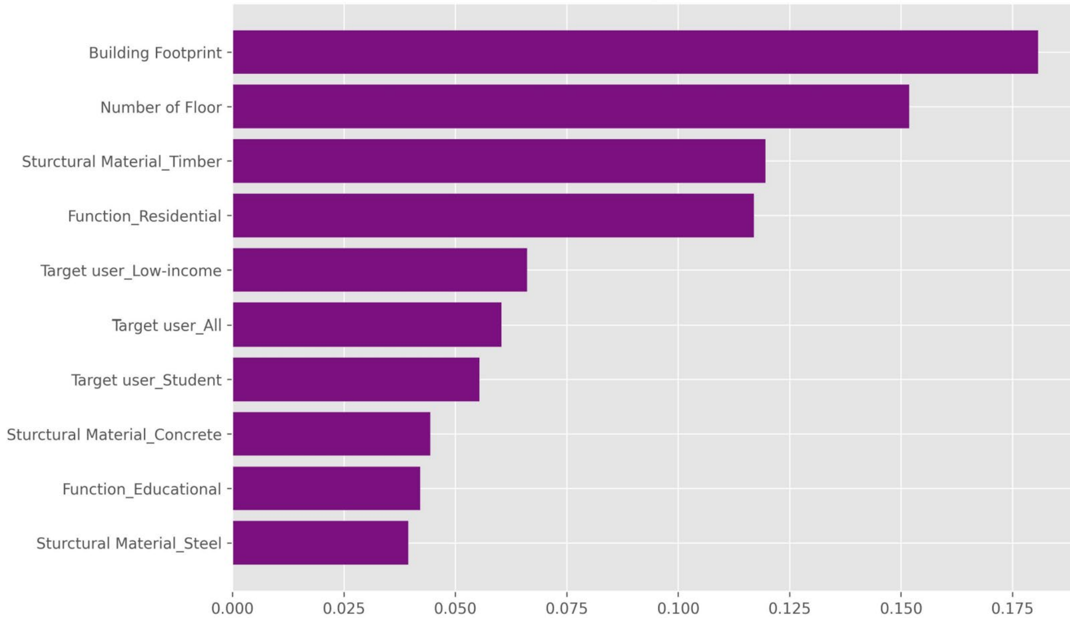

Figure 1. Importance ranking of top ten most critical factors

For the input dataset, the optimization was further performed by trimming the attributes (i.e., input factors) down into the most critical features. Building footprint and height were identified as the most critical factors engaging the three attributes related to timber material, low-income target user, and residential function of prefabrication projects. The other factors that may affect the prefabricated level are considered not important and will be ignored. The categories of structural material, building function, and target users were all reduced to binary values, i.e., timber or non-timber, residential or non-residential, and low-income or others, respectively. Table 2 shows the project attributes (i.e., the critical factors) and the target value (volumetric or penalised level) for the model.

Table 2. Features and target value of data used in the model.

Project Name	Building Footprint	Number of Floor	Sturctural Material	Target user	Function	Volumetric (1) Panelized(2)
New Casa Triângulo	230.000000	2	NonTimber	Others	Nonresidentail	2
Dreamland	1350.000000	2	NonTimber	Others	Nonresidentail	2
HOMB	182.500000	2	Timber	Others	Residential	1
Homes for All - Dortheavej Residence	1360.000000	5	Timber	Low-income	Residential	1
1000m2 Prefabricated Housing	499.000000	2	NonTimber	Others	Nonresidentail	2
...	...	...	...	...	...	...
Arizona Courtyard House	465.000000	1	NonTimber	Others	Residential	2
Tammsaare Park Pavilion	1230.000000	1	Timber	Others	Nonresidentail	2
Library and Seminar Centre BOKU Vienna	1250.000000	4	Timber	Others	Nonresidentail	2
65 Degree Group Housing	926.666667	3	NonTimber	Others	Residential	2
The Climber's Refuge	222.500000	4	Timber	Others	Residential	2

The most efficient way to verify the usefulness of the decision-making model is to apply real cases to validate its predicted results. Thus, eight hypothetical construction projects were adopted to investigate the applicability of the model. In order to ensure the quality of the virtual project data, the attributes of each hypothetical project were designed to the standard of real prefabrication projects as presented in Table 3.

Table 3. Features of hypothetical projects.

	Building Footprint	Number of Floor	Sturctural Material	Target user	Function
Project1	630.0	1	NonTimber	Others	NonResidential
Project2	343.0	2	NonTimber	Others	Residential
Project3	19600.0	3	Timber	Others	NonResidential
Project4	8826.0	6	NonTimber	Low-income	Residential
Project5	490.0	1	Timber	Others	NonResidential
Project6	3000.0	3	Timber	Others	NonResidential
Project7	4485.0	17	NonTimber	Others	NonResidential
Project8	665.0	2	NonTimber	Others	Residential

By inputting the input factors as attributes of eight hypothetical projects, the model generates the predicated prefabrication level for each project. Table 3 shows the comparison between predicated and real prefabrication level of the eight virtual projects. Since every hypothetical project is based on a real prefabrication project, the true prefabrication level of the eight projects can be obtained and compared with the predicated values. The results show that the predication levels of Projects No.2 and No.3 contradict real prefabrication level. It means that two out of eight projects are misclassified by the decision- making model. The model accuracy achieves 65%. The accuracy is not close to 100%, because a project may contain various attributes. In this decision-making model, only the most critical ones are considered, so that the accuracy may be affected. Overall, the results still verifies the usefulness of the model as a reference for investors and other stakeholders in deciding the proper prefabrication level of an offsite construction project.

Table 4. Comparison of predicted and true prefabricated level.

Prefabricated level Modular(1) Penalized(2)	True	Predicated
Project1	2	2
Project2	1	2
Project3	2	1
Project4	1	1
Project5	2	2
Project6	2	2
Project7	2	2
Project8	1	1

5. Results and Discussion

When it comes to offsite construction projects, it requires investors and designers to make decisions including selection of an appropriate level of prefabrication in the early stages of a project. According to Wuni et al. (2019), implementing offsite construction techniques is associated with a host of investment risks compared to that in conventional construction. In order to reduce the risks caused by inappropriate prefabrication techniques, it is necessary to provide reference for decision makers to decide the appropriate prefabrication level. The study offers a decision-making tool for people to predicate prefabrication level of construction projects based on their attributes by applying the model, stakeholders including investors and designers can have the recommended prefabrication level of an offsite project.

These attributes or critical input factors were initially identified from the 80 real off-site projects found. Each factor for deciding prefabrication level was analyzed in terms of the importance ranking. Five recommendations for deciding suitable prefabrication level were provided: 1) For the 'building footprint and height' factor, it was suggested to choose volumetric construction for the projects that had a less than 2500 ㎡ footprint with 3-8 stories. Meanwhile, for the projects that were more than 2500 ㎡ in footprint and more than eight-floor in height or the super-low projects with no more than 2 stories, the penalized construction might be more suitable for economic benefits; 2) regarding factor of building function and target user, it was not that essential to impact the decision of prefabrication level.

However, when it came to residential projects or projects for low-income people, such as affordable housing and temporary shelter for the homeless, it was suggested to adopt 3D modular construction; 3) as for the attribute of construction material, the utilization of timber structure in volumetric construction should be carefully considered, because it could lead to poor building thermal condition. However, the new material and technology had been emerging rapidly. Via working with new material, the building constructed by timber modules could significantly reduce the occurrence of poor thermal condition. The wide utilization of CLT (i.e., cross-laminated timber) guarantees the insulating qualities of massive wood. The construction material was no longer a constraint in deciding prefabrication level of construction projects.

However, the timber structure could still be considered an essential factor that could decide the prefabrication level; 4) in terms of project location, since the development of the offsite construction differ among countries; for these countries with insufficient technologies and immature market for higher level of prefabrication, it was suggested to utilize penalized construction instead of volumetric block system; 5) the importance ranking of all the factors indicated that the building volume (i.e. building footprint and height) was the most influential factor deciding the prefabrication level of construction projects. Besides the building footprint & height, the construction material, function and target user of a building could also impact the prefabrication level of an offsite project. Overall, the timber material, residential function and low-income target user were the three most influential elements next to building footprint & height. The project location was the least important factor among all.

By using the given suggestions and the decision-making model, it would be possible to reduce the problems and risks caused by unsuitable prefabrication levels. Nevertheless, the decision-making tool is relatively a simple model which was constructed by inputting only the most critical factors in this study. Future research can focus on conducting a more comprehensive analysis of critical input factors affecting the prefabrication level. These factors would contain more attributes such as the life span of the building (e.g., temporary or permanent) and the technical equipment to install so that a more accurate decision-making model can be delivered in more effectively deciding the prefabrication level.

5. Conclusion

The purpose of this paper is to help stakeholders including investors and designers decide the most suitable prefabrication level for construction projects. The volumetric construction and penalized construction were compared based on building performance in the operation stage. The results reveal that the penalized construction seems a better choice for offsite construction projects. Whereas, without considering the differences of projects, the suggestion cannot be conclusive. Since various factors can affect the prefabrication level of a modular building, the study adopts the decision tree model for analysing the identified critical input factors, and their significance.

The analysis suggests that building height & footprint should be emphasized as top priority for deciding prefabricated level. Additionally, the construction material, target user and building functions are also relatively important factors. Specifically, the three attributes related to timber material, low income target user, and residential function of prefabricated projects should be highlighted as more critical factors. Moreover, the specific suggestion is that the volumetric construction should be utilized more in projects with these attributes: having less than 2500 ㎡ footprint with 3-8 stories, low-income user, timber material, and residential function. Instead, penalized construction can be applied to projects with these attributes: more than 2500 ㎡ footprint, over 8 stories or low rise projects, no more than 2 stories, non-low-income user, non-timber material, and non-residential function.

For construction projects utilizing offsite technique, the decision for its prefabricated level is vital. This study provides useful suggestions and a simple decision-making tool to facilitate investors, designers and other stakeholders in deciding the prefabrication level for an offsite construction project.

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