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DECIDING BETWEEN PREFABRICATION AND ON-SITE CONSTRUCTION: A CHOOSING-BY-ADVANTAGE APPROACH

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ABSTRACT

Several academic and industrial studies have documented the benefits of prefabrication compared to on-site construction. However, key construction project actors find it difficult to analyse whether prefabrication would be beneficial for their project with specific circumstances and targets. This research aims to develop a process to evaluate the impact of prefabrication in projects. First, based on the literature review and focus group discussion, we define the impact factors of prefabrication. Second, we apply Choosing by Advantage (CBA) approach together with Cost-Benefit-analysis to define a process for prefabrication impact measurement which considers various impact factors and their importance in the project. Finally, we validate the process with the industry experts. The paper contributes to knowledge on robust decision-making processes about production methods in situations in which all impact factors are not easily comparable but require a subjective valuation.

KEYWORDS

Prefabrication, on-site construction, choosing-by-advantage, lean construction

INTRODUCTION

How could the construction project actors decide whether to use prefabricated products in their project? It is widely assumed in the construction industry that the adoption of prefabrication is the next step towards the industrialization of construction (Lu et al. 2018). However, making a decision between the prefabricated products and on-site construction is often complicated as several direct and indirect factors need to be considered (Antillon et al. 2014).

The impact of prefabrication is a debated topic. For example, Hong et al. (2018) discuss the impact of prefabrication on construction project costs. Prefabrication is argued to lower

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the project costs due to faster project delivery, cheaper labour rates, minimal waste, and the avoidance of construction site hindrances. On the other hand, prefabrication is argued to increase project costs due to the requirements of highly skilled workers, high costs of prefabricated products, and additional transportation costs (Hong et al. 2018).

Previous studies have tried to define and evaluate the impact factors of prefabrication. For instance, Antillon et al. (2014) applied a value-based cost-benefit analysis when analysing prefabrication in hospital projects. Pasquire et al. (2005) illustrated the factors and sub-factors to be considered for the detailed evaluation in a proposed prefabrication impact measurement business toolkit. However, research is scant on transparent algorithms and processes, which could guide in the decision-making concerning whether to apply prefabrication in a single project context.

In the lean construction community, Choosing By Advantage (CBA) has been suggested as a method when comparing alternative options with different impact factors. CBA is a Multi-Criteria Decision making (MCDM) system based on the advantages of alternatives. The CBA method separates value and cost (Arroyo, 2014). CBA process has been successfully applied in several cases, for example, choosing the appropriate water treatment technologies (Arroyo & Molinos-Senate, 2018), choosing the bidder (Schöttle and Arroyo, 2017), or selecting the contract type for the road maintenance (Haapasalo et al. 2015).

The purpose of this research is to apply CBA method to develop a tool to evaluate the impact of prefabrication in a construction project. To achieve this purpose, the following research questions are answered:

RQ1: What are the impact factors of prefabrication and how to measure them?

RQ2: How could the 'Choosing by advantage' method be applied for deciding on the use of prefabrication in construction projects?

The first research question about impact factors will be answered based on the literature review, its synthesis and validation in focus group meetings. The focus group involves the consortium of Aalto University and 16 leading Finnish construction companies aimed at developing a vision of 2030 for the Finnish construction industry. The literature study first shortly introduces the literature on prefabrication in general and the major impacts of prefabrication. The impact factors of prefabrication and their measurement methods are validated with an industry expert focus group. After that, we focus more on analysing existing measurement and evaluation tools when deciding between prefabrication and on-site construction. To answer the second research question, we will first review the literature on choosing by advantage and then apply it in a prefabrication context with multiple impact factors. As a conclusion, an evaluation process which combines the CBA method and cost-benefit analysis will be presented.

THEORETICAL BACKGROUND

PREFABRICATION

Prefabrication means a practice of manufacturing the components of building or structure in factory circumstances and then transporting and assembling them onsite (Goodier & Gibb, 2007). Prefabrication can be understood at different levels, considering the production of small parts and components of a building or entire house or volumetric building block which can be manufactured in the factory (Neil and Deli, 2016). Later, Piroozfar & Farr, (2013) have defined modularization, industrialized building, mass production, and prefabrication as separate concepts. The industrialized building is a higher level concept, under which modularization enables the mass production and prefabrication of the components (Piroozfaz and Farr, 2013).

Numerous benefits of prefabrication which promote its implementation have been documented in several academic and industrial research papers (Chauhan et al. 2018; (Lavikka, et al. 2018; Eastmann & Sacks, 2008). The following benefits have been emphasized:

- To convert the traditional site base industry to the modern industrialized industry
- To improve the resource-efficiency and productivity
- To secure the completion of the project on time, on budget and with the targeted quality
- To improve the quality and environmental performance of construction
- To minimize material waste
- To improve safety and ergonomics

More specifically, research by Jaillon et al. (2009) indicates that 52% of material waste was reduced after the adoption of prefabrication. Similarly, Khanzode et al. (2008) illustrate that a 30 % decrease in labour was gained through the implementation of Mechanical, Electrical and Plumbing (MEP) prefabrication. Thus, the implementation of prefabrication has increased by 86% within the last two decades (Paudel et al., 2016).

PREFABRICATION IMPACT MEASUREMENT

Literature shows that several methods have been applied to facilitate decision making on prefabrication in projects. For instance, Lu et al. (2018) have developed a framework for deciding on the optimal level of prefabrication. The framework involves thirteen PEST (political, economic, social and technological) factors which together determine the optimal level of prefabrication. Li et al. (2014) have applied the system dynamics approach and scenario simulation as an instrument in evaluating the impact of prefabrication on material waste. Hong et al., (2016) propose the 'prefabrication rate' that calculates prefabrication volume to the total volume of the building materials. Similarly, Alinaitwe et al. (2006) propose a ratio of the value of work done onsite and offsite as an instrument to access the impact of prefabrication. However, those studies focus mostly on measuring single impacts factors, instead of multiple different factors which have to be considered in decision making.

In order to measure prefabrication impact with multiple dimensions, Pasquire et al. (2005) have presented the factors that are essential for the prefabrication impact measurement. The results of that study are part of the IMPREST toolkit. They presented the cost as the major factor followed by quality, time and safety. Furthermore, Cook (2013) (Cited in Antillon et al. 2014) has emphasised the cost as the major impact factor for the prefab impact measurement. Antillon *et al*. (2014) further presented several other value components for prefab impact measurement, such as prioritised time, waste, quality, safety, ergonomics. They conducted a value-based cost-benefit analysis approach to evaluate the impact of prefabrication on direct costs, safety and schedule in the hospital project. The authors were able to produce a cost-benefit-ratio for four prefabrication solution which would reveal which production method is more suitable.

Cost-benefit analysis is a promising method for evaluating multiple impacts of prefabrication in projects. However, as all impact factors are not easily converted to cost impacts (e.g. environmental effects, completion on time, quality), there is a need for an evaluation method which would combine monetary and non-monetary impacts. It can be even argued that some impact factors, such as time, should be in some cases to be considered both as monetary impact (reducing contractor's general costs) and non-monetary impact (shortening the schedule).

CHOOSING BY ADVANTAGES

Choosing by advantage (CBA) is a tool that could be adopted while deciding between alternatives. It is also known as a multidisciplinary decision-making method (MCDM) for selecting between alternatives based on the advantages between them. Major concepts in the CBA include *alternative, factor, criterion, attribute, advantages* and *importance of advantages* (Parrish and Tommelein, 2009). The glossary terms included in the CBA process has been defined by the Suhr (1999) as follows:

Alternatives: Different options between which has to be decided with the CBA process. A minimum of two options is required.

Factors: Common factors for all the alternatives, based on which best alternative could be decided.

Criteria: Criteria for judging based on factors, whether, e.g. higher value is better or less is better.

Attribute: Characteristics or values that resemble each alternative in each factor.

Advantage: Advantage of each alternative's attribute relative to that least-preferred one.

Arroyo (2014) has defined seven steps of the CBA method (Figure 1).

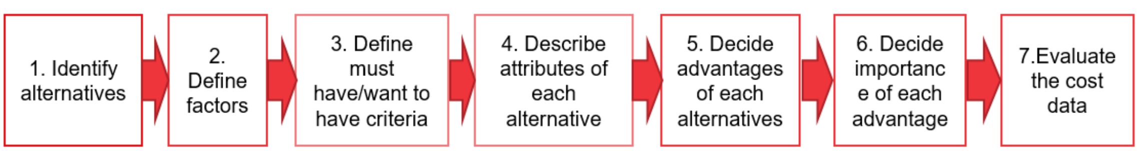

Figure 1. CBA steps (Arroyo, 2014)

CBA method has been already adopted to choose appropriate wastewater treatment technology (Arroyo and Senate, 2018), best construction flow option (Murguia & Brioso, 2017), and best HVAC system (Arroyo et al. 2016). However, CBA method has not yet been adopted when choosing a suitable construction method. We argue that the flexibility of the CBA method in the situation of multiple non-comparable factors makes it a promising method to apply when evaluating the impact of prefabrication compared to on-site construction in projects.

DEVELOPMENT OF AN EVALUATION PROCESS

Based on the literature, we were able to gather all the major impact factors of prefabrication into one table. After that, we organized two focus group discussions which both consisted of around 20 industry experts from construction companies, design offices and building product companies. In the first discussion, we validated the impact factors. New factors were not added, but some of them were revised based on the discussion. Majority of the participants involved in the discussion indicated that cost is a major motivating factor of the prefabrication implementation followed by project schedule, waste, quality and requirement from the site environment. For the second discussion, we prepared material about measurement method for each impact factor. Those methods were validated and modified based on the second focus group discussion.

The validated impact factors, their mechanism and measurement methods are presented in Table 1. Regarding the measurement method, we have also identified whether the factor can be measured as cost impact (€), other quantitative methods, or qualitative method. For example, project time can be measured as quantitative analysis or even as costs, but required design flexibility is a factor which can be measured only with qualitative methods, such as interviewing the customer or designers.

Table 1: The impact factors of prefabrication, mechanisms and possible measurement methods

Impact factor	**Prefabrication Expectation**	**Expected mechanism**	**Measurement method (€ / QUANTITATIVE / QUALITATIVE)**
Labour and material costs	Neutral or Lower	Decreases labor and material costs because trade bottlenecks are reduced, less material waste	Compare labour and material costs between trad & prefab projects (QUANT / €)
Waste and disposal	Reduced	Enables recycling and JIT material deliveries, components ordered to exact lengths	Compare the amount of waste between trad & prefab projects (QUANT / €)
Safety (worker and environment)	Improved	Reduces dangerous onsite working conditions (scaffolding, ladders), less traffic on site	Compare the number of work incidents between trad & prefab projects (QUANT)
Ergonomics	Better	Controlled work heights, tool weights, and environmental conditions	Worker surveys (QUAL)
Project schedule	Compressed	Speeds up the assembly time, reduces staging on site, better coordination between trades	Compare the completion times between trad & prefab projects (QUANT / €)
Quality	Equal or Better	Standardized working methods, clear quality control points in a	Achievements of quality standards, Quality checks throughout the

		stable environment, product certifications	process, Quality errors, Fixing costs (QUANT / €)
Surrounding environment	Favorable	Less (noise, logistics) disturbance to neighbors, more environmental friendly	Surveys, interviews (QUAL/QUANT)
Design costs	May increase or decrease	Requires more detailed designs but enables reuse of existing designs	Compare costs and resources between trad & prefab projects (€/QUANT)
Design flexibility	Decreased	Late customer changes are not possible	Interview (QUAL)
CM/GC coordination costs	Reduced	Decreases needed coordination between subs, fewer coordination costs	Compare the size and costs of management team (€/QUANT)
Site deliveries and supplies	Reduced	Materials are delivered in bigger units	Compare the number of deliveries between trad&prefab projects (QUANT)
Sub-trade activity on site	Reduced	Reduces assembly work and number of sub-contractors	Compare the number of sub-contractors and workers on site between trad&prefab projects (QUANT)
Weather conditions	Controlled	Assembly is independent of weather, which can increase work efficiency and avoid damaged building materials	Compare the interruptions and problems related to weather conditions between trad&prefab projects (QUANT/QUAL)
Procurement	Favorable	Better productization (material and installation) and easier to purchase	Compare the actual costs of procuring and installing materials between trad&prefab projects (QUANT)
Maintenance	Equal of Favorable	Makes maintenance easier if maintenance is considered during the design of the prefabricated products	Evaluate implications on maintenance work (QUAL/QUANT)

After defining the impact factors and their measurement methods, we adopted CBA steps proposed by Arroyo (2014) for prefabrication context. In our case, we have assumed that after defining the impact factors, it is important to categorise which factors should be measured as a monetary factor, non-monetary factor or both. For instance, construction time is a factor which has a cost impact, but it can be valuable also in itself for the project to be completed in a short time (not just cost-effect). The modified evaluation process is presented in Figure 2 and the description of each step is presented in Table 2.

In the suggested process, prefabrication solutions and its counterpart in on-site construction are first defined. It is important to define accurately which materials, tasks and activities are included in the analysis. In the second step, the impact factors in the specific project context are defined. The importance of some factors, such as the surrounding environment, might vary a lot between projects. For simplicity of the analysis, some factors could be excluded from the analysis. In the third step, a decision is made which factors are considered in cost analysis and which in non-monetary CBA analysis. After that, an analysis of non-monetary factors follows typical CBA process. Regarding monetary factors (including impacts which could be converted to costs), the process includes steps to calculate direct costs of alternatives as well as indirect costs regarding other benefits, such as shortened project time, decreased defects or decreased injuries. In the end, the importance points of alternatives are visualized with total costs. The final decision could be made by a single manager or in a group of experts including, e.g. clients, designers and different trade contractors.

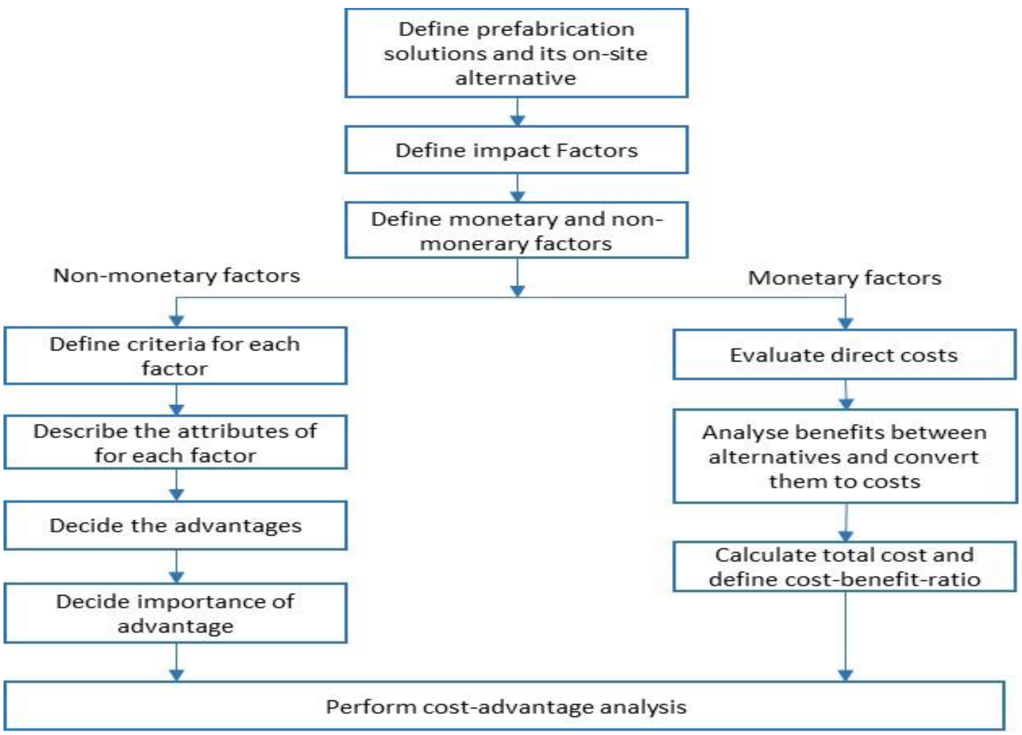

Figure 2. Combining CBA with a cost-benefit analysis for choosing between prefabrication and on-site construction

Table 2. Description of steps in the prefabrication evaluation process

Steps	Description
1. Define prefabrication solutions and its on-site alternative	Select potential prefabrication solution and its counterpart in on-site construction
2. Define impact factors	Define relevant impact factors for the selected prefabrication solution in the specific project context
3. Define monetary and non-monetary factors	Determine whether the impact factor should be measured as monetary impact, non-monetary impact or both
4. Define criteria for each factor	For non-monetary factors, decide the criteria for judging each factor; can include also must have/want to have criteria
5. Describe the attributes for each factor	For non-monetary factors, define the attributes of each alternative of each factor.
6. Decide the advantages	For non-monetary factors, define the least preferred attributes for each factor. Define the advantage for the other alternative compared to the least preferred attribute.
7. Decide the importance of each advantage	For non-monetary factors, first, based on subjective project criteria and each advantage, decide which single advantage is the most essential and give certain points for that. Then, based on subjective knowledge decide the (lower) points of the other advantages.
8. Evaluate direct costs	Direct costs include material, labour and transportation costs of prefabricated modules as well as responding costs in the conventional method.
9. Analyse benefits between alternatives and convert them to costs	This analysis takes into account indirect costs including other monetary factors cost implications, such as time-related costs, additional design costs, costs of injuries etc.
10. Calculate total cost and define cost-benefit-ratio	Sum up direct costs and indirect costs. Calculate cost-benefit-ratio by comparing total costs of prefabrication solution and on-site construction
11. Perform cost-advantage analysis	Finally, compare total costs with the CBA importance points of alternatives. Make the final decision.

CONCLUSION AND DISCUSSION

This paper developed a process to facilitate decision making between prefabrication and on-site construction in projects. The study identified the impact factors of prefabrication and proposes a way of applying Choosing by Advantage (CBA) combining with the cost-benefit analysis for selecting between prefabrication and on-site construction in different project circumstances. Based on the literature, we presented fifteen impact factors of prefabrication. Cost, project schedules, quality, design flexibility and the surrounding environment are the major factors. A focused group discussion (FGD) was used to validate the impact factors and discuss the process of applying CBA.

Based on our study, we argue that CBA combined with the cost-benefit analysis could be a suitable approach to decide on whether or not to apply prefabrication. It allows making transparent decisions based on several impact factors of which some can be converted to cost impacts, but others can be evaluated only as non-monetary impacts and their advantage comparison between the alternatives. The originality of this paper is that it presents a new process which supports decision making between production methods which have multiple different impacts in specific project contexts. The authors will conduct further research by testing the process in real-life projects which utilize different prefabrication products.

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