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To prefabricate or not? A method for evaluating the impact of prefabrication in building construction

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Abstract

Purpose – Prefabricated products are continually entering the building construction market; yet, the decision to use prefabricated products in a construction project is based mostly on personal preferences and the evaluation of direct costs. Researchers and practitioners have debated appropriate measurement systems for evaluating the impacts of prefabricated products and for comparing them with conventional on-site construction practices. The more advanced, cost–benefit approach to evaluating prefabricated products often inspires controversy because it may generate inaccurate results when converting non-monetary effects into costs. As prefabrication may affect multiple organisations and product subsystems, the method used to decide on production methods should consider multiple direct and indirect impacts, including nonmonetary ones. Thus, this study aims to develop a multi-criteria method to evaluate both the monetary and non-monetary impacts of prefabrication solutions to facilitate decision-making on whether to use prefabricated products.

Design/methodology/approach – Drawing upon a literature review, this research suggests a multi-criteria method that combines the choosing-by-advantage approach with a cost–benefit analysis. The method was presented for validation in focus group discussions and tested in a case involving a prefabricated bathroom.

Findings – The analysis indicates that the method helps a project's stakeholders communicate about the relative merits of prefabrication and conventional construction while facilitating the final decision of whether to use prefabrication.

Originality/value – This research contributes a method of evaluating the monetary and non-monetary impacts of prefabricated products. The research underlines the need to evaluate the

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diverse benefits and sacrifices that stakeholder face when considering production methods in construction.

Keywords Cost–benefit analysis, Prefabrication, On-site construction, Multi-criteria decision-making method (MCDM), Choosing-by-advantage (CBA)

Paper type Research paper

1. Introduction

Prefabrication increases productivity in the construction industry (Lavikka *et al.*, 2021; Peltokorpi *et al.*, 2017; Wuni and Shen, 2019) and may be fully or partly adopted depending on the project. For instance, Jonsson and Rudberg (2014) classify building construction in four categories based on the degree of prefabrication used:

(1) *modular building* involves a high level of prefabrication;

(2) *volumetric construction* consists of preassembled units (e.g. modular bathrooms);

(3) *non-volumetric construction* includes products that do not create usable space (e.g. structural frames and wall panels); and

(4) *component manufacturing and subassembly* have the lowest level of prefabrication, with construction using factory-made products, such as windows and bricks (Gosling *et al.*, 2015).

Several studies have noted that adopting a greater degree of prefabrication benefits construction projects (Gibb and Isack, 2003; Sandanayke *et al.*, 2019). The chief benefits include improving safety (Fard *et al.*, 2017), lowering greenhouse gas emissions (Sandanayke *et al.*, 2019) and reducing project time (Bernstein *et al.*, 2011), waste (Khanazode *et al.*, 2008), costs (Hong *et al.*, 2018) and defects (Johnsson and Meiling, 2009). Despite these benefits, some still hesitate to use prefabrication, mainly because of rigid labour union rules, the lack of short-term benefits, reluctance to change a process and controversial cost–benefit analyses (Lavikka *et al.*, 2021; Jiang *et al.*, 2018; Said, 2015).

The impact on cost is the most controversial topic in the prefabrication literature. Prefabrication has been shown to be more cost efficient than on-site construction due to reduced labour, material costs and construction waste (Tam *et al.*, 2015). For instance, Boyd *et al.* (2013) identified a 30% savings from off-site construction. However, prefabrication also increases capital costs (Zhai *et al.*, 2014) through investments in new machinery and factories (Hwang *et al.*, 2018; Pan *et al.*, 2008). Costs also rise due to additional transportation expenses (Tam *et al.*, 2015), complex techniques and the need for highly skilled workers (Molavi and Baral, 2016).

Due to the cost–benefit controversies, construction stakeholders are often confused about adopting prefabrication. Decisions on using prefabrication in a project are based mostly on personal preferences, anecdotal evidence or direct cost-based evaluation rather than on holistic, sustainable performance metrics (Newman, 2002; Bansal *et al.*, 2017). In fact, no formal strategies exist to decide between prefabrication and on-site construction (Pasquire and Gibb, 2002). Pasquire *et al.* (2005) further indicate that insufficient attention has been paid to the question of whether to prefabricate a whole building or only its parts.

Prefabricated products are entering the market at an increasing pace; however, including modular bathrooms, plant rooms and mechanical, electrical and plumbing (MEP) service racks. Choosing a prefabricated product for a project is typically exclusionary, and prefabricated product categories differ significantly in their scope, scale and other main characteristics. This has increased the workload and research demands of stakeholders who need information about the monetary and non-monetary impacts of these products. Thus, practitioners need better frameworks to assess various prefabricated products as well as comparative information on their overall impacts.

Evaluating prefabrication's impact on projects is difficult. Implementing prefabrication affects multiple factors, such as cost, quality, safety and sustainability. Some of these factors are easily convertible to costs, but this can be difficult for others. Thus, the evaluation method should be able to measure impacts from both the monetary and non-monetary perspectives. Blismas *et al.* (2006) recommend using multi-criteria decision-making (MCDM) and an integrative approach (e.g. including designers, builders and manufacturers) to measure the impact of prefabrication. The MCDM should incorporate both the cost perspective and the non-monetary value perspective. Some MCDM methods have already been developed by researchers who use a cost–benefit analysis approach to compare the cost of prefabrication with on-site construction, such as Hong *et al.* (2018), Choi *et al.* (2019) and Lopez and Froese (2016). In their analyses, the indirect benefits of prefabrication were evaluated and then converted into costs, after which the total costs were compared with conventional on-site construction. However, this method cannot be used to analyse several non-monetary value components that do not easily convert into costs and that have been neglected in previous research, including aspects of quality, safety and sustainability. Indeed, these factors are subjective and depend on the weight they are given by various stakeholders. Suhr (1999) developed the choosing-by-advantage (CBA) approach to tackle the problem of non-monetary components by facilitating effective decision-making when both cost and non-monetary value components are important. However, CBA was not developed to address the shortcomings of other prefabrication studies but for use as a generic decision-making tool, and its cost component lacks guidelines for cost analysis. Thus, we propose the CBA method in conjunction with cost–benefit analysis as a potential method of evaluating the impacts of prefabricated products. Both the CBA and cost–benefit analysis methods have been extensively examined in previous research, so our combination of the two methods may potentially confuse end users. For this reason, we tested these methods in the case of a modular bathroom and organised focus group discussions (FGDs) to validate the results and elicit diverse stakeholders' opinions of the proposed method.

This paper contends that choosing suitable production methods in construction can be challenging due to the systemic nature of prefabrication and its multifaceted impacts. Thus, better processes and methods to evaluate the effect of prefabrication must be developed. This research developed a novel evaluation method for prefabrication solutions, taking into account their multiple impacts on various stakeholders. Specifically, it addressed the following research question:

RQ1. How can the direct and indirect monetary and non-monetary impacts of prefabrication solutions be evaluated in construction projects?

By developing and demonstrating a multi-criteria evaluation method in prefabrication, this study contributes to existing knowledge on evaluating production methods in construction projects.

2. Method

The development and testing of the evaluation method were conducted in two steps (Figure 1). In the first step, we reviewed and analysed the major MCDM methods used in construction management and selected for detailed analysis eight methods that have recently been adopted in the field. After analysing the strengths and shortcomings of those methods, we devised a new method that integrates CBA and cost–benefit analysis.

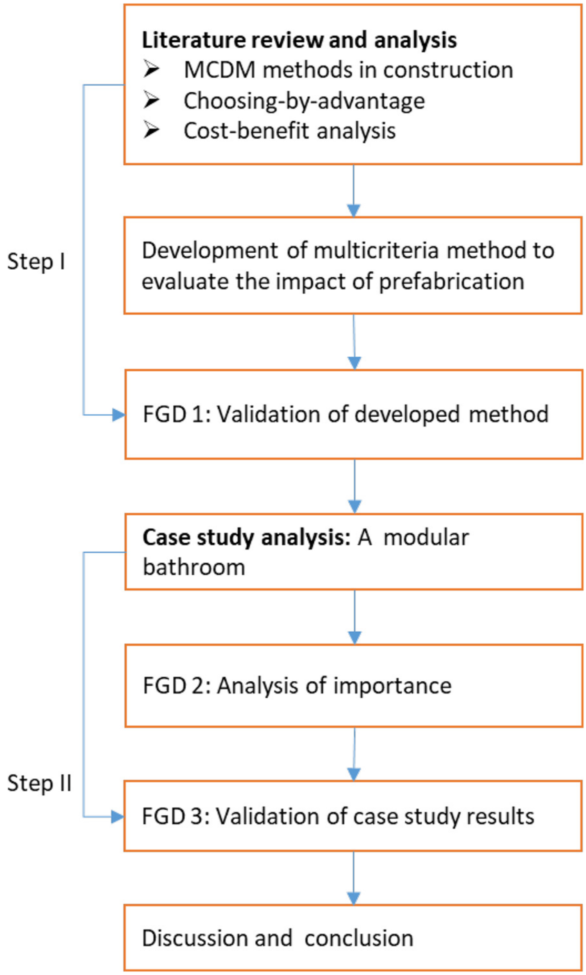

Figure 1.
Overall research process

The proposed method was then validated in the first FGD, which included 17 professionals from the Finnish construction industry. To ensure an integrative approach to prefabrication analysis, they represented several companies operating in the construction, design, building product and information technology (IT) domains.

The empirical component of the research aimed to test and validate the developed method in a practical context. A case study was determined to be the most appropriate research approach for the current work, as it allows for the in-depth study of a phenomenon or event (Yin, 2014). The proposed method was applied in the case of a modular bathroom installation in a residential building project. A modular bathroom is a suitable product for evaluation, as it involves the work of multiple designers and trade contractors and its impact on the schedule, for example, is not easily quantifiable.

The case's qualitative and quantitative data were both collected and analysed. The collected qualitative data included direct observation of the product (both in the factory and on the construction site), public documents on the module producer's website (such as marketing materials, the producer's initial calculations of the effects on on-site construction and testimonials from module customers), the financial status of the product manufacturer (which was analysed through the use of the governmental registration system) and interviews with three site managers, two project managers and a director of the module manufacturer. The quantitative data comprised the case documents, such as a summary of the cost of the product. The second FGD, which included 15 participants from various construction firms, was conducted to analyse the importance they assigned to the advantages of each impact factor as part of the CBA method. The third FGD, including representative of 21 construction companies, was organised to validate the case study results.

3. Theoretical background and method development

3.1 Multi-criteria decision-making methods in construction

Construction involves diverse tasks, stages and requirements, of which various aspects must be considered with great care. For instance, choosing the production method, materials and suppliers is a complex process in which multiple factors must be taken into account. For this reason, several MCDM methods are already used in construction. Table 1 briefly describes the main MCDM methods used in the construction management field.

Even though many MCDM methods could be used in the construction management field, no single method perfectly meets the needs of all stakeholders, because all have some limitations. Among the existing MCDM approaches, however, CBA overcomes some limitations because its decision-making process considers both cost and non-cost (value) aspects, which ultimately yields a sounder decision-making process. Consequently, if a factor has both a monetary and a non-monetary impact, CBA allows analysing both aspects. For instance, when choosing between prefabricated products and on-site construction, *quality* as a comparison factor would have to be evaluated from both aspects to make a more accurate decision. Both monetary and non-monetary impacts on cost have been widely discussed in the literature (Laukkanen, 2021; Love *et al.*, 2018).

Furthermore, several papers (Arroyo *et al.*, 2015) argue that CBA is more transparent than other MCDM methods and is the most appropriate one, mostly because it enables the consideration of multiple stakeholders' viewpoints when making decisions. Thus, we have adopted the CBA method in this study.

3.1.1 Choosing-by-advantage. The CBA approach developed by Suhr (1999) can be variously implemented depending on the complexity of the decision-making process. For instance, either simplified tabular method or the two-list method could be implemented for simple decisions. For a moderately complex decision, the tabular method is recommended. For complex and very complex decisions, CBA has a special method that differs from those already mentioned (Suhr, 1999).

CBA has already been adopted in several fields, e.g. for choosing the most appropriate wastewater treatment technology (Arroyo and Mollinos-Senante, 2018), the best construction flow option (Murguia and Brioso, 2017) and the best HVAC system (Arroyo *et al.*, 2016a, 2016b), but it has not yet been adopted in choosing the most suitable construction method. We argue that CBA's flexibility when there are multiple non-comparable factors makes it a promising approach for comparing the impacts of prefabrication to those of on-site construction. We considered the choice of a suitable construction method as a moderately complex challenge, because both monetary and non-monetary factors should be considered. Thus, the current paper adopts the CBA tabular method.

Method	Description	Limitation	References
Fuzzy decision approach	Uses fuzzy mathematics to alter and decipher ambiguous data; has a number of features related to object evaluation	Fuzzy decision approaches are generally not highly regarded due to inaccuracy in the results	Bansal *et al.* (2017), Zadeh (1971); Negoita (1988)
AHP	Uses pair-wise comparisons between criteria to select the optimal option	For judgements, AHP uses precise attributes (because, in practice, human emotions are confounding and the personnel may be unable to match the examination assessments to the meticulous numerical features). AHP is not relevant in this study	Saaty (2008); Thiranun and Xu (2015)
Analytic network process (ANP)	The ANP technique has been generalised to allow for the presence of interdependencies between criteria	Specific software is needed to calculate the results	Chen *et al.* (2019)
Data envelopment analysis (DEA)	A non-parametric approach for assessing the effectiveness of numerous decision-making units	Because the findings may be affected by the inputs and outputs chosen, it is necessary to assess their relative applicability before proceeding with the computation. However, there is no way to determine whether or not DEA is appropriate	Odeck (1996); Wang and Lan (2013)
Technique for order of preference by similarity to ideal solution (TOPSIS)	This technique posits that the best option in an MCDM case is the one that is closest to its ideal solution	This method relies on precise data, which are difficult to obtain in many real-world circumstances because decision-makers typically communicate their judgements using natural language, such as “poor” and “good”	Rahman *et al.* (2012), Simsek *et al.* (2013)
Interactive model for measuring preassembly and standardisation (IMMPREST)	This Web-based tool assists in quickly determining the optimal method for a specific project based on the available information	There is limited information accessible, and the algorithm is opaque	Pasquire *et al.* (2005)
CBA	Decisions are based on the benefits of one option over another	The cost component provides no clear guidelines	Arroyo *et al.* (2018), Murguia and Brioso (2017); Suhr (1999)
Cost–benefit analysis	Benefit–cost analysis is another name for the same approach, which evaluates a product’s or project’s total expenses against its benefits using a common metric (most commonly, monetary units)	Intangible costs and benefits have a higher level of subjectivity	Boardman *et al.* (2018), Florio (2019); Mao *et al.* (2016)

Table 1.
The most frequently used MCDMs in construction management

Even though CBA facilitates decisions from a cost and value perspective, the approach is more concerned with value than cost. In fact, CBA offers no clear guidance on how indirect costs could be evaluated. The method has been applied without the cost component, e.g. Arroyo *et al.* (2018) used it to choose a design alternative without evaluating costs. Other studies using CBA have evaluated only the cost from direct sources, including, e.g. operation and maintenance costs, material costs and transportation costs (Arroyo and Mollinos-Senante, 2018; Arroyo *et al.*, 2016a, 2016b). We argue that using prefabrication could have a greater impact on indirect cost factors than on direct ones, so, when selecting a suitable construction method, it would be beneficial to consider the cost component of the CBA approach, as doing so allows for a more comprehensive cost–benefit evaluation.

3.1.2 Cost–benefit analysis. Cost–benefit analysis is another popular, widely used MCDM tool in decision-making and cost estimations of direct and indirect factors, but the benefit valuations and effects assessments of the method involve a degree of uncertainty (Asplund and Eliasson, 2016) that has led many researchers to question the applicability of cost–benefit analysis in certain cases (Mouter *et al.*, 2013).

According to the European Commission (2014), a cost–benefit analysis has seven steps: description of the context, definition of the objectives, project identification, determination of technical feasibility and environmental sustainability, financial analysis, economic analysis and risk assessment. Following this guideline, we emphasise the financial and economic analysis by converting into costs all the factors possibly impacting prefabrication.

When deciding between prefabricated products and on-site construction, many factors are subjective, and various stakeholders will value them differently, e.g. maintenance could be important to the customer but less so to the main contractor. Neither CBA nor a cost–benefit analysis alone allows for measuring multiple monetary and non-monetary factors, so we developed a method that takes into account multiple factors.

Prefabrication can provide monetary and non-monetary benefits to a construction project, so a method for evaluating whether to prefabricate or not should consider both monetary and non-monetary benefits. An evaluation of several MCDM methods indicates that CBA, which allows more obvious and transparent decision-making than other MCDM methods, offers the most appropriate method. Its cost component is analysed by cost–benefit analysis.

3.2 A new method to evaluate multiple monetary and non-monetary factors

This research proposes a new method that evaluates impacts from both monetary and nonmonetary perspectives. The former is analysed through cost–benefit analysis, and the latter through CBA, so the method can be understood as a CBA tool in which the cost component is considered through cost–benefit analysis. Figure 2 presents the suggested method for evaluating the impact of prefabrication.

The proposed method's steps are outlined below:

(1) Define the prefabrication solutions and their on-site alternatives.

(2) Identify the most important factors that prefabrication will probably impact (or which factors may be considered to be inevitable consequences of the new production method).

(3) Classify all the factors defined in the second step that will be measured as having a monetary impact, a non-monetary impact or both.

(4) Analyse the factors that have been categorised as monetary through cost-benefit analysis using the following steps:

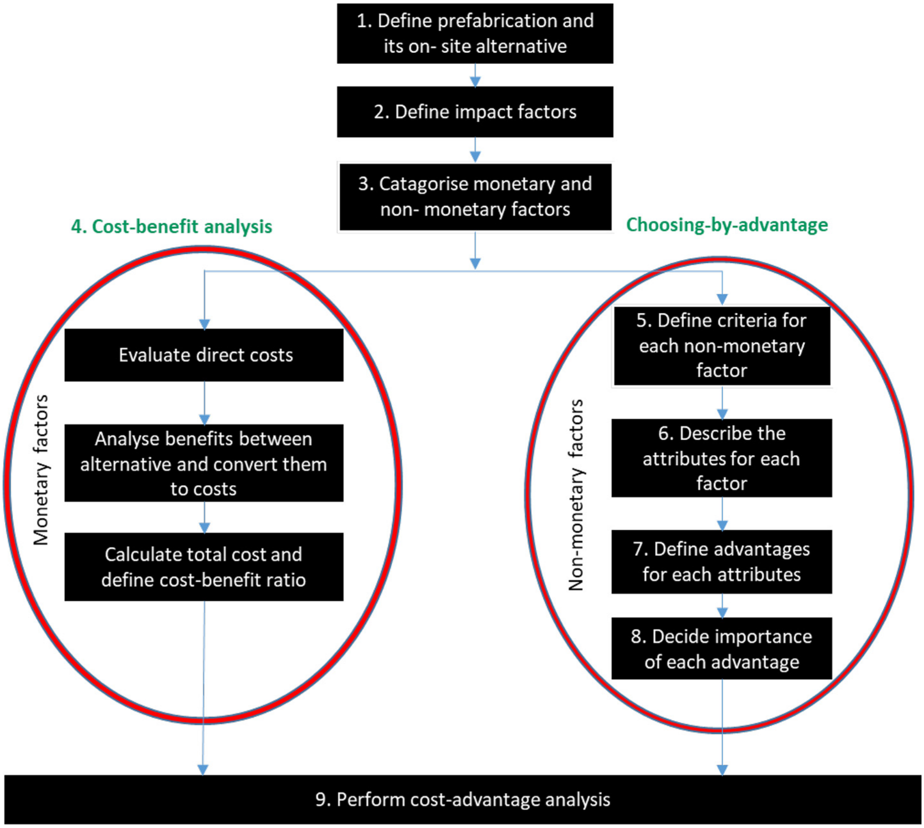

Figure 2.
Method to evaluate the impact of prefabrication

- Evaluate and define the direct costs of the prefabricated modules, including the material, labour (factory and installation) and transportation costs.
- Analyse the other benefits among the alternatives and convert them into costs. This analysis takes into account the indirect costs, including other monetary factors (such as time-related costs, additional design costs and costs of injuries).

(5) Define the judging criteria for the non-monetary factors. For instance, a criterion could be that less material risk is better.

(6) Describe the attributes of each factor. For example, an attribute could be "15 days shorter than the projected schedule".

(7) Define the advantages of each attribute, then mark the least-preferred attributes.

(8) Determine the importance of the advantage (IoA), assigning points on a scale to all the advantages. (Normally, a scale of 0–100 is preferred.) Because of subjectivity of importance, this is the most challenging part of the process, so Suhr (1999) recommends adhering to three principles when determining importance:

- Nothing has zero advantages, so unimportant factors are not ranked as having zero advantages.

- The scale of importance for all the alternatives should be the same.
- Decision-making is not a branch of mathematics or a calculation; thus, decisions must be made using one's own assumptions. However, those assumptions should be based on the purpose and circumstances of the decision, the needs and preferences of the customers and other stakeholders, the magnitude of the advantage and the magnitude of each associated attribute.

(9) Lastly, among the alternatives, compare the total costs or benefit-to-cost ratio with the CBA IoA points. If alternative has a clear advantage, choose that alternative. If the costs and the IoA points conflict among the alternatives, a subjective evaluation should be made in weighing the findings for a final decision.

4. Testing the developed method

The proposed method was applied in the case of a modular bathroom in residential construction. Aside from the physical product and standard bathroom equipment, the product included intelligent features that provide real-time information about energy consumption (including electricity, heat and hot water) as well as a water metering, ventilation and heating system. The product also featured several sensors, such as leak detection sensors to forestall leakage problems and structural measurement sensors that provide information about the building's life cycle operation.

The product had already been installed in several residential and commercial projects. The total budget of the analysed residential construction project of 100 flats was €10m, and the entire construction project would be completed in 330 days if the product was used, 30 days less than the time required to complete a similar project using traditional construction.

Our developed method to evaluate the multiple impacts of prefabrication was applied as follows:

Step 1: Identify alternatives	Bathroom product vs on-site construction of a bathroom.
Step 2: Define factors	Materials, labour, installation, quality, project schedule, waste, workflow, customer value, ergonomics and design flexibility.
Step 3: Define the monetary and non-monetary factors	*Monetary factors*: Materials, labour, installation, quality, project schedule and waste *Nonmonetary factors*: Project schedule, workflow, quality, customer value and design flexibility.

The project schedule was found to have both a monetary impact (reducing the contractors' general costs) and a non-monetary one (shortening the schedule). Thus, it was analysed from both monetary and non-monetary perspectives.

Step 4: Perform a cost–benefit analysis (i.e. monetary factor analysis).

The direct costs, including raw materials, labour and module installation, were found to be 4.41% higher for the prefabricated product than for conventional construction of a bathroom. During the factory visit, the manufacturer claimed that a modular bathroom significantly lowered the cost of materials and labour, but the product was quite complex to design, and this – together with the transportation and installation equipment – eventually resulted in a higher direct cost.

At the same time, the project gained benefits from indirect factors. In the manufacturing plant, quality assurance checks were conducted at several stages, which was expected to result in about 50% fewer quality defects than with the traditional method. The cost savings associated with not having to mend those defects or coordinate the repair work amounted to 3.53% when compared with conventional construction.

Second, the project would be completed a month earlier than with the conventional method, resulting in savings in general costs per day, reduced interest charges on the loan and the assurance of an earlier return from rental revenues. Specifically, the project would save 0.02% per bathroom through site costs compared with total conventional bathroom construction. Based on the cost data, the capital cost was lowered by 2.29% through the use of modular bathrooms.

Third, 0.70% of the savings were procured through the waste-handling costs. During the on-site visit, it was mentioned that the design and manufacturing processes optimised the use of materials by eliminating unnecessary material waste.

After analysing the direct and indirect costs of the product, the cost–benefit ratio was calculated (Table 2). Even though the direct cost of the prefabricated bathroom module was found to be slightly higher, the savings from the indirect costs resulted in the total cost being 4% less when compared with the conventional construction method. This impact alone amounted to a savings of €1,364 per bathroom, equivalent to a savings of 16.0% when compared with the direct costs of a conventional bathroom. (It should be noted that this calculation does not include the increased annual profit for the construction company due to the shortened schedule.)

Based on the benefit–cost ratio, it was economically beneficial to implement the modular bathroom in the project from the general contractor's point of view. However, that ratio excludes several important non-monetary factors, one of them being design flexibility, which is greater in conventional construction and represents a major barrier to using a prefabricated product.

Step 5: Define criteria for non-monetary factors.

Non-monetary factors were compared by the judging criteria. In our case, based on site visits, interviews and public reports, the researcher developed a rule upon which a judgement could be based for each factor. For instance, "Shorter is better" was a judging criterion for the project schedule. Table 3 shows the criteria adopted for each factor.

Step 6: Describe the attributes of each factor.

To summarise the attributes of each alternative, site visits, interviews and cost data were analysed. Those attributes were inherent to the alternatives, so this step allowed for

Total project cost = €10m
Total cost of a conventional bathroom = €8,500

Monetary factors	Cost of a modular bathroom compared with conventional construction
Direct cost (material, labour, transportation and installation)	+375
Indirect costs	
Defects	−300
Waste	−60
Project schedule (capital cost)	−195
Project schedule (site cost)	−150
Total cost	8,170
Product-level benefit-cost ratio = 1.04:1.00	
Project-level benefit–cost ratio in total project cost = 10,000k/9,830k = 1.02:1.00	

Table 2.
Cost–benefit analysis of a modular bathroom (in €)

Factors (Criteria)	Alternative 1: Modular bathroom		Alternative 2: Conventional bathroom	
Customer value	Att.: Has intelligent features		Att.: Impossible to monitor energy consumption	
(Higher is better)	Adv.: Customer value is greater due to the remarkable features added to the product	Imp: 80	Adv.:	Imp:
Project schedule	Att.: Quick to construct		Att.: On-site construction is slower	
(Shorter is better)	Adv.: Faster than conventional construction	Imp.: 75	Adv.:	Imp.:
Work coordination	Att.: Fewer workers in a small space		Att.: More people working in the same place	
(Smooth flow is better)	Adv.: Remarkably easier to coordinate on site	Imp.: 65	Adv.:	Imp.:
Design flexibility	Att.: Lack of design flexibility		Att.: Possible to change the design	
(More is better)	Adv.:	Imp.:	Adv.: Design can be altered later	Imp.: 60
Risk of additional work and delays	Att.: The entire bathroom is installed at one time		Att.: Installed by assembling several parts of the bathroom	
(Lower is better)	Adv.: Somewhat lowers the risk of additional delays	Imp.: 35	Adv:	Imp.:
Transportation	Att.: Bigger units need to be transported		Att.: Smaller units need to be transported	
(Lower is better)	Adv.:	Imp.:	Adv.: Easier to transport	Imp.: 15
Total IoA		255		75

Notes: Key: att. = attribute; adv. = advantage; imp. = importance; IoA = importance of the advantage.

Table 3. CBA analysis for a modular bathroom

decisions to be based on accurate information. (The least-preferred attribute of each factor is underscored in Table 3.)

Step 7: Define the advantage of each attribute.

The advantage of each attribute was defined by comparing each attribute to the least-preferred attribute. In our case, most attributes were subjective, so subjective judgement was adopted to define the advantage.

Step 8: Determine the importance of each advantage.

The IoA was determined in the third FGD. Based on site visits, interviews and public reports, the researcher presented the non-monetary factors, criteria and attributes. The stakeholders involved in the FGD discussed the non-monetary factors and ranked each factor on a scale of 0–100 based on their preference. After the discussion, common points for each factor were identified.

The manufacturer of the bathrooms assumed that the value of the flats would significantly increase due to the intelligent features of the bathroom, as the product's technical system can help to evaluate the life cycle of the building. Thus, during the FGD, all the stakeholders agreed to give the intelligent features 80 points.

As mentioned, the use of modular bathrooms shortened the entire project schedule by a month. This reduced the possibility of accidents at the site, which could improve the reputation of the main contractor. This benefited all the stakeholders, such as clients, project owners and investors. Therefore, 75 points were allocated to this advantage.

Conventional bathroom construction involves several sequential activities that must be completed by different subcontractors, including electrical, plumbing and finishing work, and ranging in complexity from painting to mirror hanging. In addition, all the trades must work in a tight area. Because of the size of a bathroom, it is difficult to increase the number of crew members to complete the task earlier, which extends the project schedule. Using the modular bathroom would eliminate these problems, streamlining the workflow of the whole project. Therefore, 65 points were agreed on for this advantage.

The product manufacturer assumed that the risk related to materials would be significantly reduced. In conventional construction, small parts need to be brought to each flat, raising the risk of their being damaged during transportation. Also, traditional bathroom installation requires more tools and equipment, which must be moved frequently to each bathroom section, increasing the risk of injuries for workers on the site. In addition, the risks of equipment being stolen from the site are higher in conventional construction. Thus, 35 points were assigned to this factor.

Despite the benefits of modular bathrooms, they have several limitations. For example, sometimes a customer wants to change the bathroom design during the last phase of the project. This possibility is limited with a prefabricated product. Also, transportation from the manufacturing plant to the installation site may bring additional complications compared to conventional construction. For these reasons, 60 and 15 points were assigned to these factors, respectively.

The overall CBA steps for the analysed modular bathroom are presented in Table 3.

Step 9: Perform the cost–advantage analysis.

Based on Figure 3, it is clear that the modular bathroom was more attractive than conventional construction from the cost and value perspective. The total cost was assumed to be slightly lower for the modular bathroom than for conventional construction. This is mainly because of the earlier completion of the project, reduction of waste, better safety and higher quality. Also, all the project stakeholders involved in the FGD agreed that a modular bathroom would be more useful in terms of risk, customer value, work coordination and project schedule, providing additional benefits to the project stakeholder. Thus, the importance of these advantages was higher for prefabrication than for conventional construction.

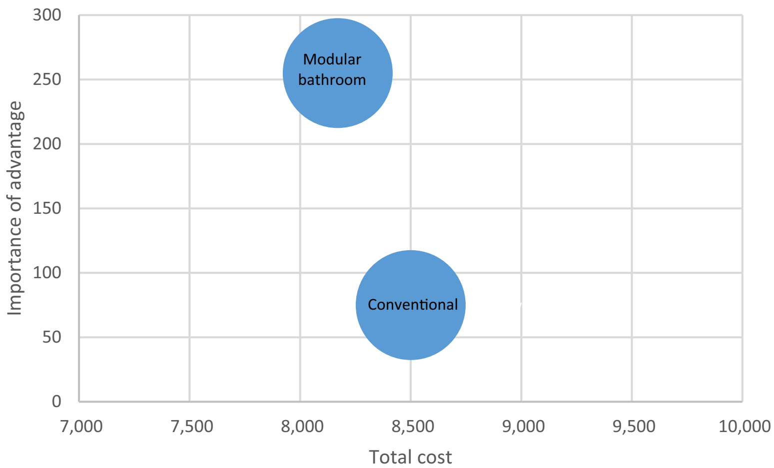

Figure 3.
Cost–advantage analysis

In short, when making a decision on whether to adopt a modular bathroom in a construction project, Figure 3 clearly suggests that using the prefabricated bathroom brings much greater benefits than conventional construction from both the monetary and nonmonetary perspectives.

5. Discussion

Several MCDM methods have been adopted in the construction management field, including weighting, rating and calculating (WRC), analytic hierarchy process (AHP) and CBA. However, none of them can be considered the "best" and/or most appropriate for all situations, especially when deciding whether to adopt prefabricated products, which affect multiple factors, including both monetary and non-monetary ones. Thus, with prefabricated products, it is more challenging to find a suitable method. Consequently, new methods and improvements to existing ones are being suggested.

Some previous studies have reviewed and compared the existing decision-making methods used in the construction field (Espino *et al.*, 2014; Arroyo *et al.*, 2015). In their analyses, CBA is considered the most suitable MCDM method, as it helps the decision-maker reach a decision based on both the monetary and non-monetary perspectives (Arroyo, 2015). However, the cost component of CBA does not provide clear guidance on indirect cost analysis. For instance, when implementing prefabricated solutions, several indirect costs need to be considered, such as those related to project schedules, workers' ergonomic concerns and safety. For this reason, this study suggests a cost–benefit analysis method to improve the cost component of CBA.

The cost–benefit analysis alone has been applied, for instance, by Hong *et al.* (2018) to evaluate barriers to prefabrication. Still, that assessment lacked several value impacts of prefabrication, such as safety, quality and environmental factors. Asplund and Eliasson (2016) note that the uncertainty of several factors in the early phase of a project, such as demand forecast, cost estimation and benefit valuation, can make the use of a cost–benefit analysis pointless. Thus, our proposed approach converts only those factors that are directly convertible costs, while those factors that have high levels of uncertainty – such as design flexibility, ergonomics and environmental factors – can be analysed through CBA.

We used the proposed method to evaluate the impacts of a modular bathroom. Following the method's guidelines, we first analysed the non-monetary factors, including project schedule, workflow, quality, customer value and design flexibility. Each factor's advantage over its traditional bathroom counterpart was graded on a scale of 1–100. The marked point was discussed in an FGD in which diverse stakeholders' viewpoints on each factor were considered. For instance, the owner involved in the FGD would have liked to assign a higher mark to the project schedule and quality factors, while the main contractor equally emphasised design flexibility, worker safety and ergonomics. The FGD participants reported that the method was valuable to them.

By developing a multi-criteria evaluation method and implementation process for choosing between prefabrication and conventional construction, this study contributes to existing knowledge on evaluating production methods in construction projects. The proposed method offers a formal process for combining multiple factors and viewpoints when evaluating the impacts of prefabricated products. For example, clients often prioritise impacts on use and maintenance, whereas general contractors focus on impacts related to execution in the project phase, such as scheduling and material logistics. Direct and indirect costs, however, are highly prioritised by both these key stakeholders.

We used cost–benefit analysis to evaluate the cost. Specifically, we evaluated the benefit-to-cost ratio ($\Delta B/\Delta C$). A ratio greater than 1 is economically beneficial (Antillon *et al.*, 2014).

In our case, the results yielded a ratio above 1, so using the modular bathroom was financially beneficial to the construction project. In analysing the total cost, accurately evaluating the indirect cost factors presented a challenge. To mitigate this, we first evaluated the indirect cost factors on the basis of the literature. At that time, the approximate cost was assumed, e.g. to reduce the cost due to reducing the number of meetings. Some studies have indicated that implementing prefabrication would be an additional financial burden on construction projects (Hwang *et al.*, 2018; Zhai *et al.*, 2014; Molavi and Baral, 2016). For instance, Taylor *et al.* (2009) evaluated the overall cost of modular bathrooms as higher than their traditional counterparts. However, their cost analysis was conducted without following proper guidelines and failed to evaluate the indirect cost savings (e.g. costs due to a reduction in project schedule). For this reason, we suggest cost evaluation through the cost–benefit analysis approach in our proposed method.

After the impacts of modular bathrooms were evaluated, a second FGD was organised to discuss and validate all the non-monetary and monetary impacts evaluated by our proposed method and to consider its applicability. The participants' major concern was how to evaluate the IoA points of non-monetary factors; the decision-making process includes human preferences, which are hard to evaluate with a numerical method. However, our proposed method makes it easier to value preferences and take more accurate decisions. Generally, the participants believed that our method contributed to their decision-making processes and, in the end, they all agreed that it may be the most suitable approach to evaluating the impacts of a prefabricated product, as it will ultimately improve or facilitate the decision-making process.

Although the method was considered the most useful for communicating and evaluating multiple factors, some challenges and weaknesses were also be identified. For example, gathering all the real data is difficult at the beginning of a project; in this case, the only option was to compare the proposed project to similar projects and rely on the experts' experience. Thus, decisions based on the assumed data may have a slightly different impact in a practical scenario.

6. Conclusion

This research proposes an MCDM method to evaluate the impact of prefabrication products and thereby facilitate decision-making on adopting prefabrication in a construction project. The method is aimed primarily at selecting prefabricated products but could also be used in other domains.

The proposed method includes the CBA approach, which is already one of the more popular methods. In addition, it analyses both non-monetary and monetary components. Suhr (1999) has explained in detail the process of evaluating non-monetary aspects, which has been followed in later research (Arroyo *et al.*, 2016a, 2016b). However, the monetary component of CBA lacks a detailed explanation of how to evaluate indirect monetary factors. While selecting alternatives, especially in cases involving the potential selection of prefabricated products, more indirect factors must be considered, so this research suggests a cost–benefit analysis to evaluate costs in the conventional CBA approach. In the case analysis, we evaluated all monetary and nonmonetary benefits and compared them with those of traditional construction. The FGD participants evinced significant interest in adopting this method in their decision-making processes when we shared the results of the analysis. Therefore, we argue that combining the CBA method with the cost–benefit method will help practitioners take more accurate and informed decisions.

The major limitation of the current research is that our method was tested in a case in which information was analysed based on the best available sources and not with precise project information, which is required for a detailed and accurate analysis. This is often the case in real-life projects, especially in the early phases, when decisions about the production method should be made. Once the real project is started, the results may be slightly different. Further research should conduct more case studies in different contexts to validate the tool and deepen our understanding of the multiple impacts of prefabricated products. Also, in the early phase of a project, it is difficult to obtain the data required to apply our proposed method, so further research is needed to develop a method that would help in gathering the relevant information in the early phase of a project. The method proposed in this research could also be converted into a more user-friendly electronic version, e.g. a platform or application, to make it more easily accessible to the construction stakeholder.

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