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# APPLICATION OF FUZZY LOGIC FOR SELECTION OF OFF-SITE CONSTRUCTION APPROACH

**Amirhossein Mehdipoor[1], Ivanka Iordanova[2], and Mohamed Al-Hussein[3]**


## ABSTRACT

Compared to other industries, the construction sector has poor productivity performance. Many megaprojects in this industry incur cost overruns, and this is largely due to inefficiencies. Although there are several reasons for these inefficiencies, the most significant factor is the lack of efficiency. One effective solution to improve productivity in construction projects is to adopt Off-site construction (OSC) methodology, which enhances efficiency. The construction method selection is an important exercise toward the productivity and success of a building project. This exercise is particularly critical during the early stages of a building project, as it is important for decision makers to consider all criteria and make a prompt decision.

The use of off-site construction (OSC) is gaining popularity in building projects. Therefore, assessing the most relevant and key success factors in this context is necessary. Multiple Criteria Decision Making (MCDM) techniques have been widely used in the construction management domain. These are being applied as a medium for decision-making purposes in the construction sector. One of the most frequent methods is Fuzzy Logic to select an option among different alternatives based on a ranking system. In this paper, Fuzzy logic was applied to evaluate and rank the performance of two alternatives i.e. conventional method of on-site construction cast in situ works and Off-site construction steel structure fully modular approach. This project forms part of a Ph.D. research program which aims to develop a Two-Stage BIM-Lean Decision Support System (DSS) for the selection of a suitable Industrial Building System (IBS).

The proposed DSS development consists of two main steps: 1) Identification and evaluation of Key Decision Support Factors (KDSF) for the selection of the OSC approach and 2) Choosing an appropriate IBS for a building project. This paper focuses on the second step where fuzzy logic is applied to rank and select the appropriate alternative. A decision maker was provided with a list of Key Decision Support Factors (KDSF), which had been validated by industry experts, to input data and measure the importance and performance of each alternative. Crisp scores calculated using a fuzzy model indicated the rank of each alternative**.** The highest score of alternatives indicates the best approach. The result shows that alternative B – Off-site construction Steel Structure Modular approach, is the better option.



## KEYWORDS

Off-site construction, Fuzzy Logic, Decision Making.



[1] Ph.D. Student, Department of Construction Engineering, École de Technologie Supérieure (ÉTS), Montreal, Canada, amirhossein.mehdipoor.1@ens.etsmtl.ca, https://orcid.org/0000-0002-9889-2478

[2] Professor, Department of Construction Engineering, École de Technologie Supérieure (ÉTS), Montreal, Canada, ivanka.iordanova@etsmtl.ca, https://orcid.org/0000-0002-4596-2604

[3] Professor, Department of Civil and Environmental Engineering, University of Alberta, Canada, malhussein@ualberta.ca, https://orcid.org/0000-0002-1774-9718

## INTRODUCTION

The construction industry is known for its subpar productivity when compared to other industries. It is common for large-scale construction projects to go over budget. The primary cause of these inefficiencies is a lack of productivity. While there are various reasons for this, adopting Off-site construction (OSC) methodology has proven to be an effective solution to improve efficiency in construction projects (Abdul Nabi & El-adaway, 2020). Using decision-making models in the Off-site construction (OSC) domain has improved project productivity and sustainability in building projects. Therefore, it is necessary to promote the OSC approach by proposing a comprehensive decision-making model from the perspective of the Canadian construction industry. While various forms of OSC systems are available in the market, there is a need for a comprehensive decision-making tool that can effectively aid decision-makers in swiftly and confidently selecting the appropriate method during the preliminary design phase (Daget & Zhang, 2019).

The process of selecting an appropriate construction method can be complex due to the many options available. Those responsible for making these decisions must take into account various factors and considerations to determine the most appropriate construction method. As a result, the process of selecting a suitable construction methodology is complex and involves multiple attributes and objectives (Attouri et al., 2022). Moreover, the selection of the construction approach method includes multiple factors and criteria which can turn it into a complex process. This paper is part of a more comprehensive project to develop a decision support system (DSS). The main focus of this project is to demonstrate and present the proposed methodology to assist a decision maker in the construction management domain. The authors employed a mixed method of qualitative and quantitative expert review in addition to a systematic literature review (SLR) to identify and validate the Key Decision Support Factors (KDSF) utilized for data collection and implementation.

## RESEARCH BACKGROUND

Considering Off-site construction approach at the early design stage of the project would assist all the team members to “think offsite” which is very important for the success of the project (Attouri et al., 2022). In the construction industry, decision-making is an important and relevant task which can be supported by the use of computer technology to improve quality and efficiency in building projects (Marcher et al., 2020). Due to the complexity of the construction process and the variety of different techniques and methods in planning, manufacturing and constructing a building project, the significance of decision-making becomes prominent.

Earlier scholars have examined decision-making elements associated with Off-site construction. Wuni (2019) discerned the primary five factors involved in the selection of modular integrated construction (MiC) including the availability of skilled labour and management, project timelines, transportation, limitations in size, and equipment availability. The process of decision-making in the construction management domain based on Multi-criteria decision-making (MCDM) techniques has been reviewed by pioneer researchers such as Aboelmagd (2018), Alhumaidi (2015), An et al. (2020), Daget & Zhang (2019), and Ordoobadi (2009). Aboelmadg (2018) used Analytical Hierarchy Process (AHP) as a tool in MCDM to select the best constriction bid price. In that research, the benefits of MCDM techniques were demonstrated. Specifically, in the OSC domain, Daget & Zhang (2019) developed a decision-making model for the assessment of Industrialised Building System (IBS) using MCDM techniques. However, that research is limited to housing projects in Ethiopia.

There are different techniques in the MCDM approach. Ordoobadi (2009) applied fuzzy logic for the selection of a proper supplier capable of meeting the client’s requirements and demands. Daget et al. (2019) preferred to use the analytical hierarchy process (AHP) to develop a decision-making model in the OSC domain. Wuni (2020) developed a decision-making framework by determining fuzzy modelling to evaluate the critical failure factors for OSC projects. Poor design and lack of proper supervision and management were considered the main key failure factors for modular projects (Wuni & Shen, 2020). Ishuzaka (2014), compared the most widely used techniques in MCDM i.e. fuzzy logic, AHP, Fuzzy AHP (FAHP) and hybrid fuzzy AHP. Integration of Fuzzy logic with AHP is a new trend to overcome the challenges of uncertainties in the MCDM approach (Ishizaka, 2014).

This research is focused on applying fuzzy logic in the MCDM approach to evaluate and rank alternatives in a case study based on relevant factors that influence the decision making process in OSC building projects. The alternatives taken into consideration are Alternative A- Conventional method of onsite construction using cast in situ concrete works and Alternative B- Off-site construction steel structure fully modular approach.

# RESEARCH METHODOLOGY

This section explains the methodology that will be applied in the case study, followed by an elaboration of the procedure for using Fuzzy Logic to rank each alternative. The data analysis calculation and results will be discussed in the next section. The selection of the proper construction method in this paper is part of a larger project that aims to develop a two-stage computerized decision support system (DSS) for selecting an appropriate Industrial Building System (IBS) in OSC projects.

The process of developing the proposed Decision Support System (DSS) consists of two main aspects: 1) identification and evaluation of Key Decision Support Factors (KDSF) for the selection of the OSC approach, and 2) choosing an appropriate approach based on a ranking system for a building project. This study mainly focuses on the second part, where fuzzy modeling is chosen to analyze and rank the alternatives. The list of KDSF validated in the first stage of the research project was used to collect data from a decision-maker to rank alternatives. The expert was asked to give a value to the importance and performance of each factor. A mixed method of quantitative and qualitative techniques was implemented to identify, validate, and assess Key Decision Support Factors (KDSF) for the selection of the OSC concept. The assessment of KDSF importance and relevancy resulted in generating a list of the system's suggestions of weighting based on the mean score ranking.

The list of the system's suggestions assists the decision-maker in proceeding with the application of the Multi-criteria decision-making (MCDM) model using Fuzzy logic. The expert can refer to the values suggested by the system and adjust them according to the nature of a specific project to determine the best judgment in this process. Fuzzy logic evaluation and modeling determine the ranking of the alternatives. Figure 1 shows the overall fuzzy modeling methodological framework applied in this project. However, this project is only focusing on Fuzzy logic analysis and system recommendations on the selection of the proper alternative.

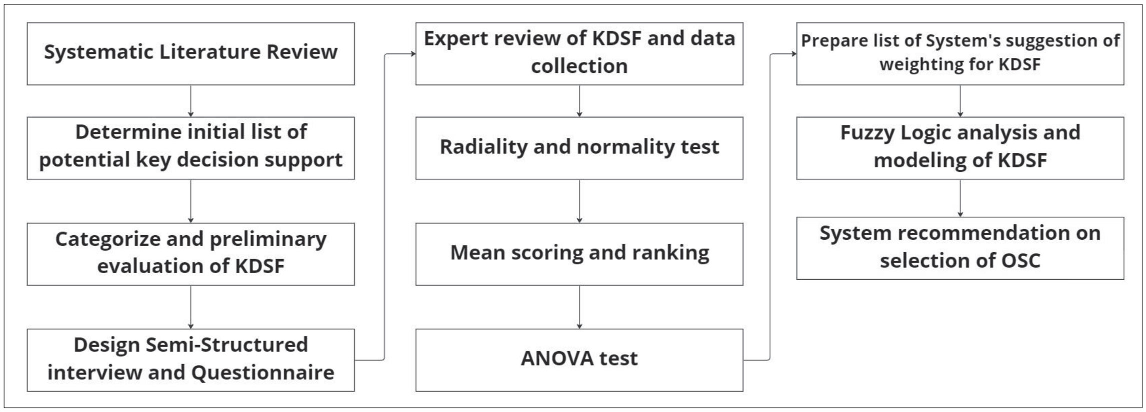


Figure 1: Fuzzy modelling methodological framework

The initial list of potential key decision support factors consisted of 32 factors that were categorized into seven dimensions. These were validated by 12 experts through semi-instructed interviews. A total number of 21 KDSFs were used to implement Fuzzy logic as per Table 1. A real case study was selected to assess the functionality of the proposed method. The selection process was based on the list of KDSF validated during the first stage and the expert's (decision maker's) weighting for each factor's importance and performance in stage two.

Table 1: Key Decision Support Factor (Main and sub-criteria)

| Main Criteria | Key Decision Support Factor (KDSF) | Weights |
|---|---|---|
| **Project characteristics (D1)** | Project Location (F1) | $w_1$ |
| | Project Design (Size, complexity and flexibility) (F2) | $w_2$ |
| **Supply chain (D2)** | Financing (F3) | $w_3$ |
| | Available Manufacturer (F4) | $w_4$ |
| | Available Infrastructure (Hardware & Software) (F5) | $w_5$ |
| | Available experts and skilled workers (F6) | $w_6$ |
| **Time (D3)** | Design period (F7) | $w_7$ |
| | Production time (F8) | $w_8$ |
| | Mobilization & transfer time (F9) | $w_9$ |
| | Assembly & construction period (F10) | $w_{10}$ |
| **Cost (D4)** | Design (F11) | $w_{11}$ |
| | Production & Manufacturing (F12) | $w_{12}$ |
| | Logistics (F13) | $w_{13}$ |
| | Assembly & Construction (F14) | $w_{14}$ |
| | Maintenance (F15) | $w_{15}$ |
| **Quality (D5)** | DfMA + Disassembly (F16) | $w_{16}$ |
| | Standards and protocols (F17) | $w_{17}$ |
| | Sustainability (Carbon emission, Energy consumption, waste) (F18) | $w_{18}$ |
| **Procurement (D6)** | Type of procurement & delivery method (F19) | $w_{19}$ |
| **Socio-Cultural (D7)** | Cultural resistance (F20) | $w_{20}$ |
| | Local authority regulation (Workers Union-Syndicate) (F21) | $w_{21}$ |

The alternative weight given to each factor is based on the importance and performance scale given verbally by the decision-maker. For this case study, the value is assigned by an expert user with more than 10 years in OSC. Fuzzy logic is used to convert the ‘linguistic’ assessment into a numeric scale (Zadeh, 1965). The perception of the expert (decision maker) is based on 2 aspects, i.e. 1) the importance of each dimension ($D_i$) and 2) performance rating of DKSF ($F_i$). Ordoobadi (2009) applied membership functions consisting of two axes. The vertical axis represents the degree of membership and the horizontal axis represents the importance and performance scale (Ordoobadi, 2009). Table 2 and Table 3 respectively show the importance and performance of linguistic scale to fuzzy importance/performance. The importance of each dimension for each alternative is assessed by assigning a linguistic importance set of “Low”, “Medium”, “High” and “Very High” which correspond to their relevant fuzzy value on a scale of 0-1 as per Table 2. The membership functions of the linguistic importance weight and performance rate are based on the linguistic importance and performance scale presented by Ordoobadi (2009). The performance of an alternative with respect to each factor is evaluated on the linguistic scale of “Poor”, “Good”, “Very Good” and “Excellent” which correspond to a fuzzy value of 0-10 as per Table 3.

Table 2

| Linguistic Importance | Fuzzy importance value |
|---|---|
| Low (L) | (0.0, 0.0, 0.2, 0.4) |
| Medium (M) | (0.2, 0.4, 0.4, 0.6) |
| High (H) | (0.4, 0.6, 0.6, 0.8) |
| Very High (VH) | (0.6, 0.8, 1.0, 1.0) |

Table 3

| Linguistic Performance | Fuzzy Performance value |
|---|---|
| Poor (P) | (0, 0, 2, 4) |
| Good (G) | (2, 4, 4, 6) |
| Very Good (VG) | (4, 6, 6, 8) |
| Excellent (EX) | (6, 8, 10, 10) |

Equation 1 shows the calculation of the Fuzzy weight of a KDSF, where $I_{Di}$ is an importance fuzzy value of a dimension and $I_{Fi}$ is an importance fuzzy value of a factor. For example, the Fuzzy weight $w_1$ is calculated by multiplying the importance of project characteristics $D_1$ by the importance of size $F_1$ as per Equation 1.

Equation 1: $w_i = I_{Di} \times I_{Fi}$

The next step is to construct the fuzzy performance rate for each KDSF and to calculate the fuzzy score for each alternative. The fuzzy score of an alternative is calculated by multiplying the fuzzy performances by the fuzzy importance weights in a weighted sum according to equation 2, where $fs_i$ is a fuzzy score, $fp_i$ is a fuzzy performance and $w_i$ is a fuzzy importance weight:

Equation 2: $fs_i = \sum_{i=1}^{n} fp_i \times w_i$ ; where *n = number of KSDF*

The final step is to rank the alternatives based on crisp scores. Fuzzy scores are defuzzified using the centroid method according to equation 3 where *(l, $m_l$, $m_u$, u)* construct fuzzy score. The alternative with the higher crisp score ranks first:

Equation 3: Crisp score $x = \frac{l+m_l+m_u+u}{4}$ ; where *l= first member,* $m_l$*= second member,* $m_u$*= third member, u= fourth member*

The following shows an example calculation of fuzzy weight $w_i$, fuzzy score $fs_i$ and fuzzy performance $fp_i$:

Importance input by the expert for D1 (Project characteristics): High (H)

Importance fuzzy value for D1: (0.4, 0.6, 0.6, 0.8) = $I_{D1}$

Importance input by the expert for F1 (Project Location): High (H)

Importance fuzzy value for F1: (0.4, 0.6, 0.6, 0.8) = $I_{F1}$

$w_1 = I_{D1} \times I_{F1}$= (0.16, 0.36, 0.36, 0.64)

Performance input by the expert for F1 in Alternative A: Poor (P)

Performance fuzzy value for F1 in Alternative A: (0, 0, 2, 4) = $fp_1$

Fuzzy score for F1 in Alternative A: $fs_1 = fp_1 \times w_1$ = (0, 0, 2, 4) × (0.16, 0.36, 0.36, 0.64) = (0, 0, 0.72, 2.56)

As discussed earlier, among various techniques in MCDM, Fuzzy logic was selected for this project since it was necessary to show the importance of decision making in the early design stage of a building project while the amount of information and data might be very limited. By using Fuzzy logic compare to other methods such as AHP or FAHP, the decision making process is faster (Ishizaka, 2014).

# RESULTS AND DISCUSSION

## CASE STUDY

A real case study is presented to evaluate the application of the proposed method. The case study is a building project located in Canada that had a unique characteristic in terms of location, accessibility, and delivery time. The weather condition of the case study is characterized by extremely cold winter and short summer duration. Accessibility is very difficult, and the client's priority is to have an efficient building that can overcome challenges in that area such as proper thermal insulation, fast delivery and minimum building energy consumption. The decision maker was asked to provide input based on the list of KDSF to be considered for the selection of an appropriate construction method. The decision maker in this case was an expert with more than 40 years of professional experience in the construction industry. The list of KDSF criteria as per Table 1, consisting of 7 Main criteria and 21 sub-criteria, was used to develop the fuzzy model. The first input set was the importance values for the main and sub-criteria. Table 4 shows the importance rating for Project characteristics (D1), Project Location (F1) and Project Design - size, complexity and flexibility (F2) as an example.

Table 4: Importance rating for Project Characteristics (D1)

| Main Criteria rate | Sub-Criteria rate | Weight |
|---|---|---|
| Project Characteristics (H) | Project Location (H) | $w_1$ = (0.16, 0.36, 0.36, 0.64) |
| | Project Design (VH) | $w_2$ = (0.24, 0.48, 0.60, 0.80) |

The other weights are calculated in the same manner:

$w_1$ = (0.16, 0.36, 0.36, 0.64), $w_2$ = (0.24, 0.48, 0.60, 0.80), $w_3$ = (0.24, 0.48, 0.60, 0.80),
$w_4$ = (0.16, 0.36, 0.36, 0.64), $w_5$ = (0.08, 0.24, 0.24, 0.48), $w_6$ = (0.24, 0.48, 0.60, 0.80),
$w_7$ = (0.36, 0.64, 1.00, 1.00), $w_8$ = (0.24, 0.48, 0.60, 0.80), $w_9$ = (0.36, 0.64, 1.00, 1.00),
$w_{10}$ = (0.36, 0.64, 1.00, 1.00), $w_{11}$ = (0.04, 0.16, 0.16, 0.36), $w_{12}$ = (0.04, 0.16, 0.16, 0.36),
$w_{13}$ = (0.08, 0.24, 0.24, 0.48), $w_{14}$ = (0.08, 0.24, 0.24, 0.48), $w_{15}$ = (0.04, 0.16, 0.16, 0.36),
$w_{16}$ = (0.36, 0.64, 1.00, 1.00), $w_{17}$ = (0.24, 0.48, 0.60, 0.80), $w_{18}$ = (0.36, 0.64, 1.00, 1.00),
$w_{19}$ = (0.16, 0.36, 0.36, 0.64), $w_{20}$ = (0.24, 0.48, 0.60, 0.80), $w_{21}$ = (0.16, 0.36, 0.36, 0.64).

Table 5 shows alternative A - Traditional method and alternative B – Off-site construction (Modular) performance rating in the case study.

Table 5: Performance rating with respect to KDSF

| Criteria | Rating of Alternative A | Rating of Alternative B |
|---|---|---|
| **Project characteristics(D1)** | | |
| Project Location (F1) | P | EX |
| Project Design (Size, Complexity and Flexibility) (F2) | VG | G |
| **Supply chain (D2)** | | |
| Financing (F3) | VG | VG |
| Available Manufacturer (F4) | P | VG |
| Available Infrastructure (Hardware & Software) (F5) | G | EX |
| Available experts and skilled workers (F6) | P | VG |
| **Time (D3)** | | |
| Design period (F7) | VG | VG |
| Production time (F8) | P | EX |
| Mobilization & transfer time (F9) | VG | G |
| Assembly & construction period (F10) | P | EX |
| **Cost (D4)** | | |
| Design (F11) | VG | VG |
| Production & Manufacturing (F12) | VG | VG |
| Logistic (F13) | VG | G |
| Assembly & construction (F14) | VG | EX |
| Maintenance (F15) | G | VG |
| **Quality (D5)** | | |
| DfMA + Disassembly (F16) | P | EX |
| Standards and protocols (F17) | VG | VG |
| Sustainability (Carbon emission, Energy, waste) (F18) | G | EX |
| **Procurement (D6)** | | |
| Type of procurement & delivery method (F19) | VG | VG |
| **Socio-Cultural (D7)** | | |
| Cultural resistance (F20) | VG | G |
| Local authority regulation (Workers Union-Syndicat) (F21) | G | EX |

Fuzzy score was constructed by using performance rating for each alternative with respect to the sub-criteria. Fuzzy scores of the alternatives were calculated by applying Equation 2 with respect to the expert's rating. The fuzzy scores were defuzzified by the centroid method determined in Equation 3. Finally, Alternatives were ranked according to their crisp score. The highest ranking was considered the most appropriate construction method for this project's specific case study. Table 6 summarizes the result. Alternative B- Off-site steel structure fully modular building, has a higher crisp score compared to alternative A- conventional method cast in situ concrete building. Therefore, the proposed fuzzy model ranked alternative A first. It is also supporting the critical success factors for this particular case study.

As mentioned earlier, due to the case study's location, weather conditions, accessibility, and specific client's quality requirement the factors of project location (F1), available infrastructure (F5), Production time (F8), assembly and production period (F10), assembly and construction cost (F14), DfMA + Disassembly (F16) and local authority regulation (F21) are major factors with higher performance value.

Table 6: Fuzzy score, crisp scores and ranking

| Alternatives | Fuzzy Score | Crisp scores | Rank |
|---|---|---|---|
| Alternative A | (9.60, 31.76, 48.24, 94.56) | 46.04 | 2 |
| Alternative B | (18.72, 55.84, 81.76,124.96) | 70.32 | 1 |

The finding of this research is also in line with discussions by previous scholars in this domain such as the study by Wuni (2019) on the five primary factors involved in the selection of modular methodology since skilled labour, project timeline, transportation, limitation in size and equipment availability have a similar perception to this study's factors with higher performance value. The significance of this study is the validation of the suggested alternative for the specific case study which is an ongoing project. The real scenario shows the reliability of the proposed system as well as its adaptability to other cases with different characteristics.

## CONCLUSION

The decision-making process for selecting a suitable construction method is complex and influenced by many factors. It is an important process since a rapid and proper decision needs to be made at the early stages of a project. The initial selection of the most suitable approach will assist all stakeholders, such as engineers and architects, to develop their detailed designs in compliance with the specificities of the selected method (in the case study, the Off-site concept).

This project studied the application of fuzzy logic in the MCDM concept to select an appropriate offsite construction approach. The decision maker was asked to rank their preferences in a linguistic manner using a given scale to address subjectivity during data collection. These data were used to measure the importance and performance of Key Decision Support Factors. For the specific case study used in this project, Alternative A is the conventional method of cast-in-situ concrete works on site, while Alternative B is the Off-site steel structure fully modular building. The results show that Alternative B, with a crisp score of 70.32, ranks first, while Alternative A scored 46.04 and ranked second. Since the case study of this project was an ongoing modular project, the decision maker could validate the suggestion of the proposed Decision Support System (DSS) and its functionality.

The outcome of this research provides a useful and applicable framework to support the management process to reduce failure risk and improve the decision-making process. The proposed framework can be relevant and applied to any similar context, such as the comparison between various types of Industrial Building Systems (IBS). The importance and performance of relevant KDSF may differ in other countries and different types of construction projects, such as infrastructure, which are excluded from this study. Therefore, a future comparative study is suggested to investigate these differences. This project is limited to the use of data input by one expert. Furthermore, future research aims to collect more data to cover a larger context.

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