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RESEARCH PAPER

Assessing the Effect of Building Information Modeling System (BIM) Capabilities on Lean Construction Performance in Construction Projects Using Hybrid Fuzzy Multi-criteria Decision-Making Methods

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Abstract
Despite possibly higher initial costs, owners and construction management organizations have demonstrated a growing interest in implementing practices that result in improved quality and fewer risks, disputes, and waste on their projects in recent years. Therefore, to solve this problem, a new method that has been considered for design and construction is lean analysis and construction. If this design is aligned with new technologies such as building information modeling (BIM), there will be a huge change in the success of projects. Integrated and synergistic integration of the two phenomena of lean construction (LC) and BIM can reduce errors and losses. The main purpose of the present study is to determine effective parameters of the synergy of LC technique and BIM system and identifying and evaluating the most important application and infrastructure required to apply an integrated model of application of these techniques in construction projects in the country. The data were examined utilizing the combined approach of FAHP and FTOPSIS after determining the relevant capabilities of BIM and LC functions. The results showed that among the identified BIM capabilities, the ability to integrate the database with a weight of 0.201 ranks first, and the standardization function in LC with a similarity index of 0.547 is also the optimal solution. Also, the results showed that based on the similarity index (CCi) illustration of the process of how to form a plan status plan at any time, "The closest solution to the function of teamwork culture, the ability to" assess compliance with the initial objectives of the plan "The closest solution to the function of continuous improvement/construction based on quality and capability" Fast construction and Time and cost optimization "The closest solution to the function of continuous improvement/construction based on quality and capability" Energy consumption "The closest solution to the function of waste and the ability to" Build and control computer scheduling and project budgeting "The closest solution to the function of waste be."

Keywords Capability · Functionality · Building information modeling system (BIM) · Lean construction · Construction projects · Fuzzy integrated multi-criteria decision-making methods

1 Introduction

In the last three decades, major progress has been achieved in the efficiency and effectiveness of the world manufacturing industry which has now minimized all work components (production space, manpower, production time, investment, and costs); in these industries, significant progress is seen in all productivity indicators compared and compared with classic models (Safa and Kachitvichyanukul 2019; Xu et al. 2022; Lu et al. 2022; Zhang et al. 2021). All these progress to increase productivity in production are not based on fundamental changes or the rapid growth of technology but are the result of the application of new production philosophies that lead to lean production and thinking. Based on this thinking, efforts are made to minimize (Muda) waste in the field of

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production and reduce the time of processing and operation of the product, thus increasing the added value of production and, at the same time, activities that have no added value. They are removed from the process (Alarcón 1997; Rouhanifar et al. 2021). The fundamental concept of lean thinking lies in eradicating the organization's loss and value creation (Safa et al. 2020; Rouhanifar and Afrazi 2019; Afrazi et al. 2018). Lean thinking is an attitude to increase continuous productivity and value creation and minimize costs and losses. In this way, the gateway to the land of values can be considered for the customer to eliminate obvious defects, losses, and errors through quick methods, such as concepts and techniques of lean thinking. It is very difficult for design and supervising engineers to balance optimal design and low cost and waste; therefore, to solve this problem, a new method considered for design and construction is the analysis and lean construction. This design has been considered by many researchers and industry owners in recent years (Nazari and Soleimani Ashtiani 2013; Hosseini 2017). If this design is aligned with new technologies such as BIM, there will be a huge change in the success of projects (Aksamija 2010; Luo et al. 2019). The building information modeling (BIM) system is highly efficient in solving problems such as many changes in different stages of construction and lack of integration in project parts, and time and cost management and rework. As a powerful tool, it can be attention that will lead to continuous improvement in the process of design and construction of construction projects. Building information modeling can be defined according to the BIM handbook as follows: "A concept for describing instrumentations, processes, and technologies facilitated by computer science to display a view of building information, performance, planning, construction and finally operation (Eastman et al. 2011; Afrazi et al. 2022; Afrazi and Yazdani 2021; Jahandari et al. 2022; Fan et al. 2020).

In terms of cost and schedule performance indicators, Nguyen and Akhavian (2019) analyzed the efficiency of and synergy between three such trending concepts in the construction sector, namely integrated project delivery (IPD), lean principles, and building information modeling (BIM) (Nguyen and Akhavian 2019). According to Zahraee's (2016) findings, major practices in lean manufacturing in Iranian manufacturing plants include processes and equipment, planning and control, supplier relationships, human resources, and customer interactions. Lean tools such as Kaizen, 5S, setup time reduction, cellular manufacturing, continuous flow, equipment layout, product design simplicity, and error proof equipment are also critical to lean manufacturing deployment, according to the findings of this survey. In another research, Heravi et al. (2020) studied installation of pre-fabricated steel frames (PSFs) of residential buildings. Their results showed that annual energy consumption and CO2 emissions were reduced by 9.2% and 4.4%, respectively. The impacts of adopting value stream mapping (VSM), just in time (JIT), continuous flow, and total productive maintenance (TPM) approaches throughout the manufacture and erection processes of pre-fabricated steel frames (PSFs) of construction projects were explored by Heravi et al. (2019). According to a study conducted by Amany et al. (2020), using the BIM approach in the planning phase reduces time conflicts between expert contractors on the critical path, and the overall delay of the scheduled time achieves zero. Furthermore, confrontations among contractors, whose suspension will provide no motivation and result in daily cost overruns, will be at an all-time low (Amany et al. 2020).

In order to evaluate and identify the most essential applications, capabilities, and infrastructure needed to use the integrated model, this paper attempts for the first time to verify the effective parameters of the synergy between lean construction technique (LC) and building information modeling system (BIM). It has also been thought of applying these techniques to various building projects around the country. By first defining the capabilities of the building information modeling system and the LC functions in infrastructure projects, a coherent framework for problem resolution was first proposed for this purpose. Then, the application of the suggested method to prioritize the capabilities of the building information modeling system was identified, and the impact of the most crucial BIM capabilities on LC functions was investigated, using integrated fuzzy multi-criteria decision-making methods by combining FAHP and FTopsis methods. It was closely looked at and scrutinized.

2 Theoretical Foundations

2.1 Lean Thinking

The fundamental concept of lean thinking lies in eradicating the organization's loss and creation of value. Lean thinking is an attitude to increase productivity and continuous value creation and minimize costs and losses in project-based projects and organizations (Baradaran et al. 2015). This thinking provides a way to achieve maximum efficiency with fewer resources, equipment, time, and space and to approach them according to the customer's needs and, at the same time, meet the needs of customers (Tavassoli and Mortahab 2008). The philosophy of this approach is production, generalization to a series of subsectors such as JIT-time production methods, total quality management (TQM), six standard deviations, and the like. In 2000, the US Department of Commerce's National Standards Institute defined lean manufacturing as follows: "Lean manufacturing is a systematic approach that seeks to identify and eliminate waste (non-value-added activities) through continuous improvement and streamlining." "Proper production is when the customer needs it." In other words, lean thinking is about focusing on waste disposal, increasing customer value, and streamlining processes (Olson 2003; Pour et al. 2022).

Lean thinking consists of five general guiding principles and how to apply them that lead any company or organization to create a stable and dynamic system that can be fully applied by understanding these principles and then trying to tie them together. Lean methods and techniques achieved a sustainable solution in the purification of the organization and its processes. By understanding these principles carefully and then trying to link them together, managers will be able to fully use lean methods and techniques to achieve a sustainable approach (Jørgensen and Emmitt 2009). These five principles are shown in Fig. 1 (Ohno 1988).

The starting point of lean thinking is the determination of value, which is defined by the end consumer in the context of a given product. Value flow refers to a set of steps of a process (with or without value-added) that starts from the neighborhood of receiving raw materials and continues until the product is completed and delivered to the customer in construction projects (employer) (Razavian et al. 2020; Armaghani et al. 2020). The third principle of lean thinking involves constantly moving for value-creating steps. The fourth principle enables the customer to extract the defined value from the manufacturer (Majedi et al. 2021, 2020). The fifth principle (pursuit of perfection) of lean thinking insists on continuous improvement and believes that to achieve the basic foundations of lean thinking must be the excellence and perfection of all four dimensions. The principle of this type of thinking is value, value flow, value flow movement, and considering increasing customer attraction and continuously changing and improving values by taking into account changes in the demands of consumers and users of value.

2.2 Lean Construction (LC)

The idea and philosophy of lean construction were first applied by Koskela in 1992, considering production methods in the construction industry (Koskela 2000). Lean construction is an attitude and style of construction that has brought many changes to the construction industry; in fact, using the concepts and principles of lean thinking to design the production system in the construction industry with the aim of increasing productivity, minimizing material waste, time and energy spent to produce the maximum possible value, reducing construction time and controlling project cost construction. This thinking is called lean because by identifying and eliminating waste. It can provide a way through which it is possible to perform the maximum operational volume of the project with the least resources (Salem et al. 2006; Afrazi et al. 2017; Safa et al. 2016; Toghroli et al. 2014; Gu et al. 2022). Designing such a production system achieves the goals. The mentioned is impossible except with the cooperation of all the people involved in the project (employer, contractor, managers, final beneficiaries) from the beginning of the project. This is more than just a contractual obligation. Refinement of construction complements traditional construction management by two basic criteria for the success of large projects: (1) the flow of materials, information, value generation in the production system, and (2) the use of different project management patterns and production, in planning, execution, and control. The basic features of lean construction include a clear set of objectives, maximizing project performance for the client at the project level and simultaneous construction design, and the use of optimal and optimal project control over the life of the project from design to delivery. Construction refinement complements traditional construction management by applying the key criteria necessary for the successful completion of large projects, considering and paying attention to the flow of materials and information and the production of value in the production system and various patterns of project and production management (in planning, execution, and control) is Arayici et al. (2011). Looking at the lean construction process, this attitude, the process of planning, engineering, design, construction, production, and delivery of materials (projects) in better compliance with the objectives of project management in transferring maximum value to project owners (Abdelhamid et al. 2008; Afshar et al. 2020; Naghipour et al. 2020). In 2008, the Lean Construction Institute listed the ten key elements shown in Fig. 2 for lean construction.

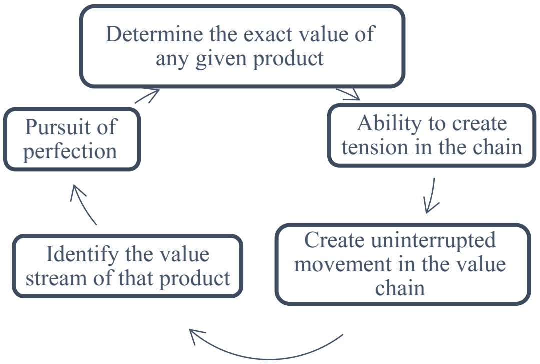

Fig. 1 Principles of lean thinking (Nguyen and Akhavian 2019)

2.3 Building Information Modeling System (BIM)

Building Information Modeling (BIM) describes tools, processes, and technologies that facilitate building, performance, planning, construction, and operations using digital facilities and readable documents (Eastman et al. 2011). The BIM system is an example of the latest 3D or multidimensional models to simulate the planning, design, construction, and operation of construction projects that help architects and engineers design and build what is to be designed and built. They must first build completely in a virtual environment and overcome those problems if they encounter possible problems at any stage of construction, such as design,

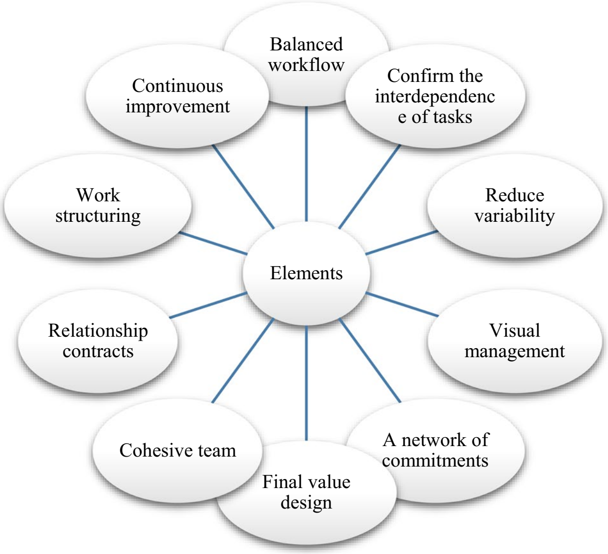

Fig. 2 Lean construction elements (Salazar et al. 2006)

implementation or operation (Sacks et al. 2009; Shariati et al. 2019; Davoodnabi et al. 2021).

The BIM system adds three- or two-dimensional modeling components with unique features to two-dimensional maps and related specifications. Its special feature is that each member designed in BIM, in addition to its multidimensional physical nature, has an array of information related to the various activities and tasks of designers and managers (Aksamija 2010; Shariati et al. 2020a). This information relates to the project's entire life cycle from its initial stages to its completion. It includes items such as the feasibility study stage to the conceptual design, the first- and second-stage studies, procurement, construction, installation and commissioning, operation period, and even the end. In short, BIM is the process of producing and managing building information throughout its life cycle (Kymmel 2008). In addition to creating intelligent connections between different design components, a BIM model allows the study of different design scenarios for all groups virtually (Aksamija et al. 2011). In addition, other design groups, including structural and facility design, are able to see the effects of these scenarios on project productivity by making changes to their model. Finally, contractors are able to design sequences such as execution sequences while designing and developing the building model—experience performance, construction, and installation virtually (Aksamija et al. 2011). The BIM system ensures continuous improvement in design and production and ensures integration in the construction industry by ensuring the transfer of communication from designers to builders (Eastman et al. 2011; Shariati et al. 2021; Tavakkoli et al. 2022).

Design in the construction industry based on the BIM system is one of the best types of building modeling to achieve the issues and topics in sustainable design, which is increasing every day around the world. This modeling is able to present new horizons such as increasing productivity, reducing operating time, and reducing the costs of the full life cycle of a building through optimization methods for the construction industry (Gu and London 2010).

3 BIM and Lean Interaction

Integrated and synergistic integration of two phenomena of lean construction (LC) and building information modeling (BIM) by reducing errors and losses can have a significant impact on increasing productivity in different phases of the project (Oskouie et al. 2012). Image analysis of LC and BIM systems reveals significant similarities between these two phenomena, which provide the interaction between these two loops, facilities management from the design phase to project delivery (Dave et al. 2011). So far, limited research has been conducted to investigate the extent of interaction between lean fabrication and the BIM system. A review of this research shows that there are positive interactions between LC and BIM techniques, and some of these interactions have been identified. This research can be done to analyze the interaction between LC and BIM at the conceptual level, and the study of the synergy of these two technologies by Sacks et al. (2009, 2010) pointed out. Based on their studies on the detailed analysis of the interactions between BIM and Lean, these researchers have concluded that there is a kind of alignment between the two techniques that, if properly understood, can improve construction processes. They showed that the use of the BIM system reduces changes in the construction industry (Kymmel 2008) in research such as Hamdi and Leite (2012), Lu et al. (2012), and Gerber et al. (2010). In addition to examining case studies of the simultaneous use of the concept of Lean and BIM in real construction projects, the existence of synergistic contexts and positive results of combining these two concepts has been pointed out (Nasrollahi 2018; Gerber et al. 2012; Liu et al. 2011; Hamdi and Leite 2012). In their research, Clemente and Cachadinha examined and evaluated the synergy of BIM and Lean techniques in public construction projects. The results of this study showed that in addition to significantly reducing the activities and duration of value-added activities, the implementation of this approach provides a correlation of the interests of all stakeholders in line with a common goal to meet the overall project plan (Clemente and Cachadinha 2013). Based on their studies, Nazari and Soleimani Ashtiani (2013) have proposed a model for the interaction between BIM and LC. The researchers examined the principles of lean thinking based on research by Koskela (2000), Sacks et al. (2009), Oskouie et al. (2012), as well as the capabilities of the BIM system based on research by

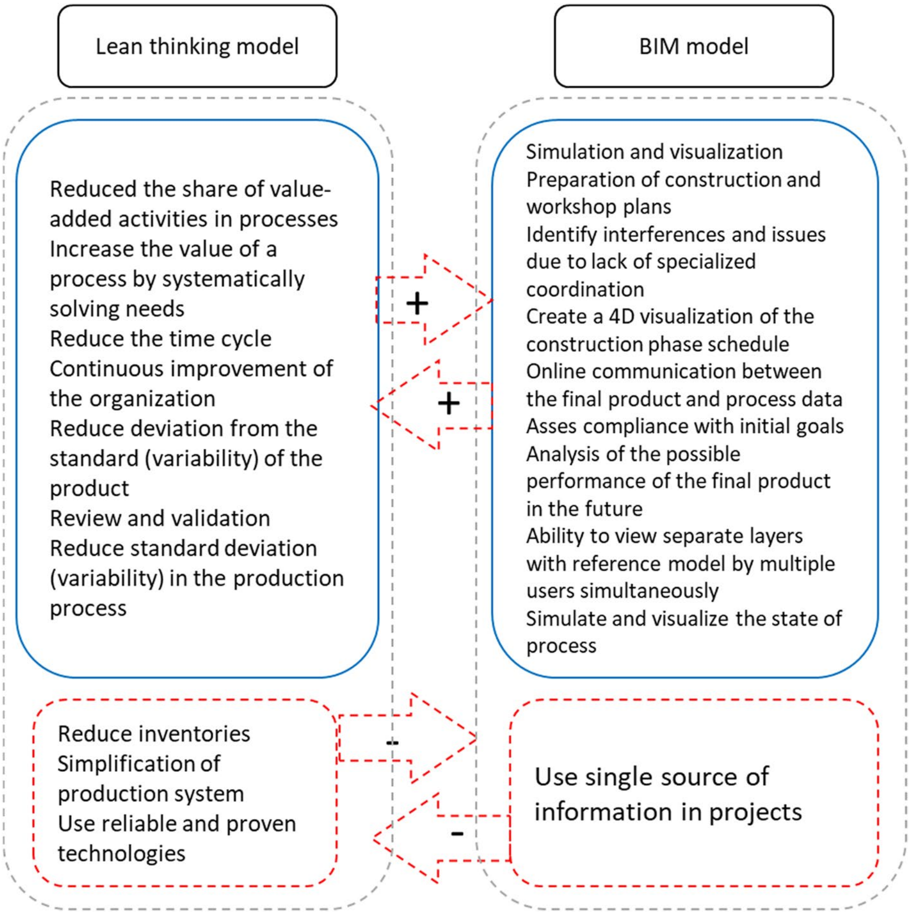

Fig. 3 BIM and LC interaction based on compatible and incompatible relationships (Carvajal-Arango et al. 2019)

Eastman et al. (2011) and Sacks et al. (2009). The structure of the interaction of these two concepts is presented according to Fig. 3. In their study, Yongge and Cheng analyzed the applications of the combined method of BIM technology and the concept of lean construction for cost management and value control throughout the life cycle of construction projects (Xu and Qian 2013). In a 2014 paper by Ahuja et al. (2014), how BIM is effective in creating lean construction is shown in Fig. 4. Based on their studies, Bortolotti et al. (2016) have proposed the reduction of repairability and waste to increase construction performance and reliability of the workforce as one of the principles of lean construction and analysis. In their research, the use of BIM and Lean for the requirements of modeling in the design of sanitary construction projects is examined. The purpose of this study is to understand how to model user needs to support decision-making in the design process (Junior et al. 2018). In their research, Carvajal-Arango et al. (2019) examined

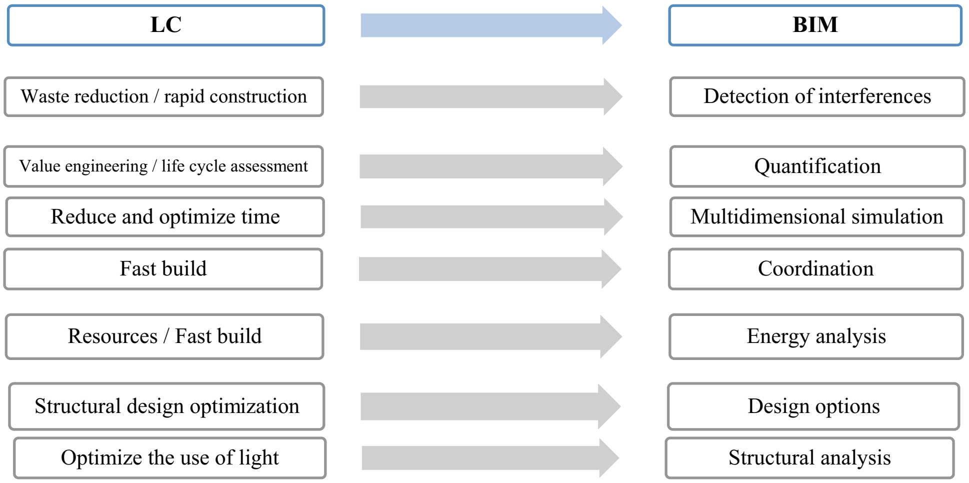

Fig. 4 Different BIM elements in LC guidance (Carvajal-Arango et al. 2019)

the relationship between lean construction and sustainable development and evaluated the positive effects of lean practices on sustainability in the construction phase. The results of this study showed that increasing productivity, reducing waste, and reducing cost and time will have the greatest impact on the purification of construction projects (Hamidian et al. 2011).

4 Research Method

The present study, while identifying and evaluating important capabilities in the field of using lean construction (LC) and building information modeling technology (BIM) in construction projects in Iran, provides a model to determine the effect of these two techniques (Shariati et al. 2020b; Zandi et al. 2018). To be, the research method is a quantitative survey that after identifying the capabilities of the BIM technique and LC functions based on a hierarchical combination of fuzzy multi-criteria decision-making method and TOPSIS data are analyzed. The questionnaires in this section are based on pairwise comparisons for analysis with fuzzy hierarchical multi-criteria decision-making methods. For this purpose, after determining the weight of the identified capabilities in relation to BIM by the FAHP method, they are prioritized, and the preferred capabilities in the main functions of LC are determined by the FTOPSIS method. For this purpose, five experts specializing in BIM and LC and working in Iranian construction companies were asked to investigate pairwise comparisons. After extracting pairwise comparisons, the analysis of fuzzy multi-criteria decision-making methods with coding in MATLAB software

Table 1 Principles and capabilities identified by BIM in the manufacturing industry

The main feature	Code	BIM detected capabilities	Codes
Design visualization and visualization	P1	Multidimensional visualization of construction planning	P1-1
		Evaluate the performance and beauty of the design	P1-2
		Visualization of the process of how the design status plan is formed at any given moment	P1-3
Scheduling and budgeting along with the sequence of construction operations	P2	Quickly create multiple alternative designs	P2-1
		Review construction steps and design assistance	P2-2
		Automation of various construction processes	P2-3
		Construction and computer control of project scheduling and budgeting	P2-4
Use data model to optimize design	P3	Performance forecast analysis	P3-1
		Estimate costs and process times automatically	P3-2
		Evaluate compliance with the customer value program	P3-3
		Automatic production of designs and documents	P3-4
		Documentation and facility management	P3-5
		Perform simulation of different design or construction scenarios and consequently analyze different options	P3-6
		Assess compliance with the initial objectives of the plan	P3-7
Collaboration and coordination between systems	P4	Coordination in design and construction	P4-1
		Multi-user editing of a single model	P4-2
		View multi-user integration of different model strings	P4-3
		Exchange design decisions with team members	P4-4
Database integration	P5	Data maintenance and integrated model design	P5-1
		Automatic checking of collisions	P5-2
		Integration with the project partner through the database (supply chain)	P5-3
		Provide a framework for determining the status of data on-site and off-site	P5-4
		Online / electrical communication based on objects and components	P5-5
Buildability and interference detection	P6	Fast build and time and cost optimization	P6-1
		Create and quickly evaluate alternative build programs	P6-2
		Prefabrication	P6-3
		Accurate simulation of processes in different phases of construction	P6-4
		Workshop site safety analysis	P6-5
Sustainable design and construction	P7	Energy consumption	P7-1
		Waste reduction and product life cycle assessment	P7-2

Table 2 Main functions of LC in construction projects

Main function	Code
Teamwork culture	S1
Continuous improvement / build based on quality	S2
Customer focus (employer)	S3
Eliminate waste	S4
Standardization	S5

was used to provide prioritization models based on FAHP and FTOPSIS methods. Tables 1 and 2 show the BIM capabilities and the main functions of LC (research variables), respectively. Codes have been assigned to them to facilitate future steps (Fig. 5).

4.1 Introduction of Fuzzy Hierarchical Analysis (FAHP)

The fuzzy AHP (FAHP) method takes into account the uncertainties and incorrect judgments of experts using linguistic variables or fuzzy numbers (Sedghi et al. 2018; Kordestani et al. 2021; Zhen et al 2022). The fuzzy numbers used in fuzzy decision research are mostly triangular or fuzzy trapezoids. In the first step of the FAHP method, the hierarchy structure of the decision problem is formed using the target levels, criteria, subcriteria, and options. Experts' views on the importance of the identified factors are then compared using linguistic variables in pairs. To express the importance of each factor, different language variables can be used in the very low to very high range (according to the 9-point range presented in Table 3). The fuzzy membership function for language variables is shown as fuzzy triangular numbers in Fig. 6. Then, the matrix of pairwise comparisons is formed according to Eq. 1 (Patil and Kant 2014).

$$\tilde{A} = \begin{bmatrix} (1,1,1) & \tilde{a}_{12} & \dots & \tilde{a}_{1n} \\ \tilde{a}_{21} & (1,1,1) & \dots & \tilde{a}_{2n} \\ \dots & \dots & \dots & \dots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \dots & (1,1,1) \end{bmatrix}, \tag{1}$$

where $\tilde{a}_{ij} = \left(M_1, M_2, \dots, M_9\right), \quad \tilde{a}_{ji} = 1/\tilde{a}_{ij}$

In the next step, using the geometric averaging method, the fuzzy mean weights of each criterion are determined.

The value of the fuzzy compound expansion for each target relative to the *i*th index is determined according to Eq. 2:

$$S_i = \sum_{j=1}^{m} M_{gi}^{j} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right]^{-1} \tag{2}$$

By performing a fuzzy addition operation on the expansion m:

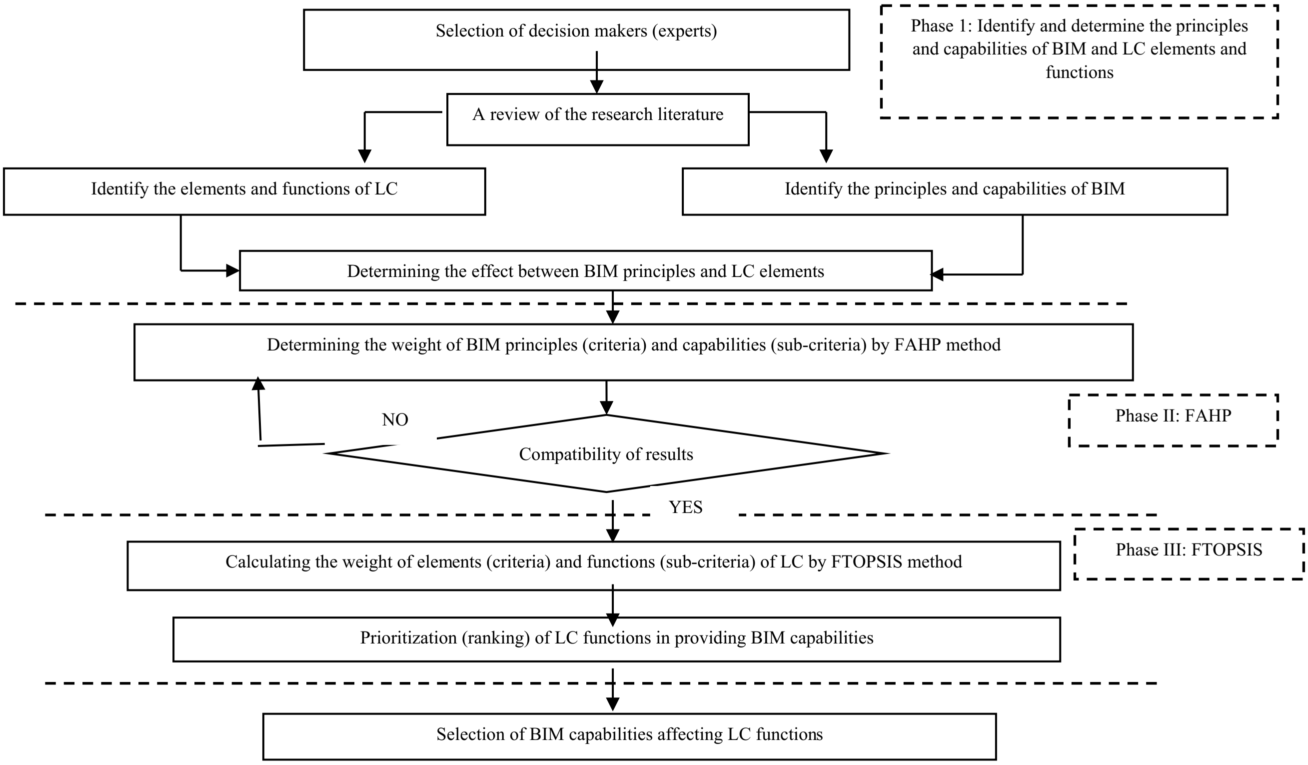

Fig. 5 Phased structure of research stages

Table 3 Scale 9 of relative importance options and linguistic variables corresponding to triangular fuzzy numbers and used to form a pairwise comparison matrix

Fuzzy linguistic importance	Number	TFN (l_i, m_i, u_i)	Reciprocal TFN ($1/l_i$, $1/m_i$, $1/u_i$)
Equally important	M_1	(1, 1, 1)	(1, 1, 1)
Equally moderate important	M_2	(1, 2, 3)	(0.333, 0.5, 1)
Weakly important	M_3	(2, 3, 4)	(0.25, 0.333, 0.5)
Moderate important	M_4	(3, 4, 5)	(0.2, 0.25, 0.333)
Moderately strong important	M_5	(4, 5, 6)	(0.167, 0.2, 0.25)
Strongly important	M_6	(5, 6, 7)	(0.143, 0.167, 0.2)
Very strongly important	M_7	(6, 7, 8)	(0.125, 0.143, 0.167)
Very strongly extreme important	M_8	(7, 8, 9)	(0.111, 0.125, 0.143)
Absolutely important	M_9	(8, 9, 10)	(0.1, 0.111, 0.125)

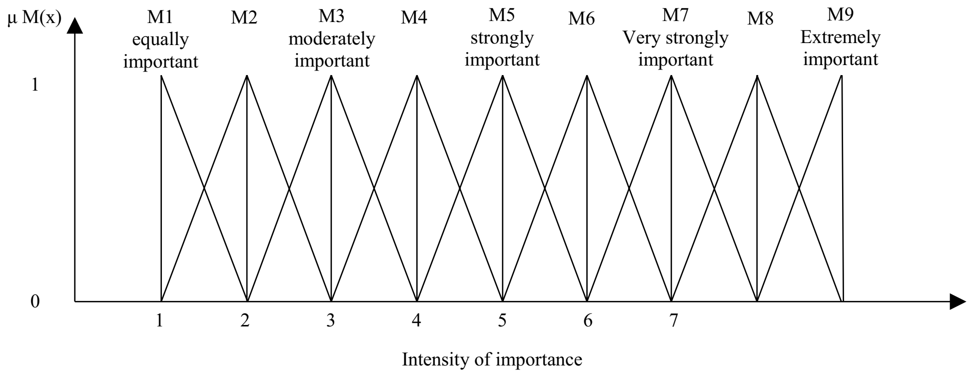

Fig. 6 Fuzzy membership functions for linguistic variables corresponding to triangular fuzzy numbers

$$\sum_{j=1}^{m} M_{gi}^{j} = \left(\sum_{j=1}^{m} a_j^{l}, \sum_{j=1}^{m} a_j^{m}, \sum_{j=1}^{m} a_j^{u}\right) \tag{3}$$

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m} u_i}, \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m} m_i}, \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m} l_i}\right) \tag{4}$$

$$V(S_i \geq S_k) = hgt(S_i \cap S_K) = \mu_{S_2}(d) = \begin{cases} 1 & \text{if } m_i \geq m_k \\ 0 & \text{if } l_k \geq u_i \\ \frac{l_k - u_i}{(m_i - u_i) - (m_k - l_k)} & \text{otherwise} \end{cases} \tag{6}$$

In Eq. 7, d is the coordinate of the highest point in the interface and collision of the two membership functions, $S1\mu$ and $S1\mu$. To compare S_1 and S_2, it is necessary to calculate both $V(S_2 \geq S_1)$ and $V(S_1 \geq S_2)$. The degree of the feasibility of a convex fuzzy number (S) is separated from k by another convex fuzzy number (S_i; $i = 1, 2, \ldots, k$) as follows:

$$\begin{aligned} V(S \geq S_1, S_2, \ldots, S_k) &= V\left[(S \geq S_1), (S \geq S_2), \ldots, (S \geq S_k)\right] \\ &= \min\left(V(S \geq S_1), (S \geq S_2), \ldots, (S \geq S_k)\right) = \min\left(V(S \geq S_i)\right) \quad i = 1, 2, \ldots, k \end{aligned} \tag{7}$$

Degree of preference (degree of feasibility) $S_2 = (l_2, m_2, u_2) \geq S_1 = (l_1, m_1, u_1)$ which S_1, S_2 are obtained according to Eq. 5 is calculated according to Equation

$$V(S_i \geq S_k) = \sup_{y \geq x}\left[\min\left\{\mu_{S_i}(y), \mu_{S_k}(x)\right\}\right] \tag{5}$$

The above equation can be expressed synonymously with Eq. 6:

Continued vector weights W' are obtained according to Eq. 8:

$$W' = \left(d'(A_1), d'(A_2), \ldots, d'(A_k)\right) \tag{8}$$

The vector elements are the calculated definite (non-fuzzy) weight.

Assuming

$$d'(A_i) = \min V(S_i \geq S_j) \text{ for } i = 1, 2, \ldots, k; j = 1, 2, \ldots, k; k \neq j \tag{9}$$

Finally, the normalized weight vector or the priority vector (W) is obtained according to Eq. 10

$$W = \left[\frac{d'(A_1)}{\sum_{i=1}^{n} d'(A_1)}, \frac{d'(A_2)}{\sum_{i=1}^{n} d'(A_2)}, \ldots, \frac{d'(A_k)}{\sum_{i=1}^{n} d'(A_k)}\right]^T \tag{10}$$

The weights of the vector W are the definite (non-fuzzy) relative weights calculated for the comparison matrix.

By repeating this process, the weights of all matrices are obtained. In the last step, by combining the weights of criteria and subcriteria according to Eq. 11, the final weights are obtained.

In this method, the consistency ratio (CR) is calculated, which is a tool that determines the consistency of the initial comparisons obtained from the opinions of experts and shows the extent to which the priorities obtained from the comparisons can be trusted (Deng 1999). Refer to Gogus and Boucher (1998) for details on the relationships and steps to calculate the adjustment rate.

The consistency index (CI) for each matrix is calculated using Eq. 12:

$$\mathrm{CI}^m = \frac{(\lambda_{\max}^m - n)}{(n-1)}; \quad \mathrm{CI}^g = \frac{(\lambda_{\max}^g - n)}{(n-1)} \tag{12}$$

Finally, the CR compatibility rate for each matrix is determined according to Eq. 13. The amount of incompatibility should not exceed 0.1.

$$\mathrm{CR}^m = \frac{\mathrm{CI}^m}{\mathrm{RI}^m}; \quad \mathrm{CR}^g = \frac{\mathrm{CI}^g}{\mathrm{RI}^g} \tag{13}$$

4.2 Fuzzy TOPSIS Technique (FTOPSIS)

The TOPSIS method is one of the classic multi-criteria decision-making methods developed by Huang and Yoon. According to this technique, the best option should have the closest distance from the positive ideal solution (PIS) and the farthest distance from the negative ideal solution (NIS) (Shariati et al. 2013). PIS is the answer that has the most profit and the least loss, and NIS is the answer that has the lowest profit and the most cost (Lima Silva and Almeida Filho 2020; Rezamand et al. 2021). In the first step of this method, language variables are used by decision-makers to determine the weight of criteria (n existing criteria $C = \{C_1, C_2, \ldots, C_n\}$) and ranking of options (m possible option $A = \{A_1, A_2, \ldots, A_m\}$) determined. For this purpose, the language variables presented in Table 4 and the fuzzy spectrum of 6 options are used. The weights of the criteria are denoted by w_j ($j = 1, 2, \ldots, n$) (Shariati et al. 2022). Then, the weight of the criteria and the ranking of the options are determined according to the opinions of the decision-maker according to Eqs. 14 and 15, respectively (Hwang and Yoon 1981):

$$\tilde{w}_j = \frac{1}{k}\left[\tilde{w}_j^1 + \tilde{w}_j^2 + \cdots + \tilde{w}_j^k\right] \tag{14}$$

$$\tilde{x}_{ij} = \frac{1}{k}\left[\tilde{x}_j^1 + \tilde{x}_j^r + \cdots + \tilde{x}_j^k\right] \tag{15}$$

Next, according to the number of criteria and options, the fuzzy decision matrix is formed according to Eqs. 16 and 17:

$$\tilde{D} = \begin{array}{c} \\ A_1 \\ A_i \\ A_n \end{array}\begin{array}{c} \begin{array}{cccc} C_1 & C_2 & C_j & C_m \end{array} \\ \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \tilde{x}_{1j} & \tilde{x}_{1m} \\ \ldots & \ldots & \ldots & \ldots \\ \tilde{x}_{n1} & \tilde{x}_{n2} & \tilde{x}_{nj} & \tilde{x}_{nm} \end{bmatrix} \end{array} \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots, n \tag{16}$$

$$\tilde{W} = \left[\tilde{w}_1 + \tilde{w}_2 + \cdots + \tilde{w}_m\right] \tag{17}$$

The fuzzy decision matrix ($\tilde{R}$) for the options is then normalized using linear scale transformation according to Eq. 18:

$$\tilde{R} = \left[\tilde{r}_{ij}\right]_{m \times n} \tag{18}$$

$$\tilde{r}_{ij} = \left(\frac{l_{ij}}{u_j^+}, \frac{m_{ij}}{u_j^+}, \frac{u_{ij}}{u_j^+}\right) \quad \text{and} \quad u_j^+ = \max_i u_{ij}(\text{Benefit criteria}) \tag{19}$$

$$\tilde{r}_{ij} = \left(\frac{l_j^-}{u_{ij}}, \frac{l_j^-}{m_{ij}}, \frac{l_j^-}{l_{ij}}\right) \quad \text{and} \quad l_j^- = \max_i l_{ij}(\text{Cost criteria}) \tag{20}$$

Then, the weighted normalized matrix decision matrix ($\tilde{V}$) by multiplying the coefficient of importance of the criteria ($\tilde{w}_j$) normalized fuzzy decision in matrix elements ($\tilde{r}_{ij}$) is calculated according to Eq. 21:

$$\tilde{V} = \left[\tilde{v}_{ij}\right]_{m \times n} \tag{21}$$

where $\tilde{v}_{ij}$ is obtained according to Eq. 22:

$$\tilde{v}_{ij} = \tilde{r}_{ij} \times \tilde{w}_j \tag{22}$$

For criteria with positive and negative aspects:

$$\begin{cases} \tilde{v}_{ij}^+ = \tilde{r}_{ij}.\tilde{w}_j = \left(\frac{a_{ij}}{c_j^+}.w_{j1}, \frac{b_{ij}}{c_j^+}.w_{j2}, \frac{c_{ij}}{c_j^+}.w_{j3}\right) \\ \tilde{v}_i^- = \tilde{r}_{ij}.\tilde{w}_j = \left(\frac{c_j^-}{c_{ij}}.w_{j1}, \frac{c_j^-}{b_{ij}}.w_{j2}, \frac{c_j^-}{a_{ij}}.w_{j3}\right) \end{cases} \tag{23}$$

In the next step, the ideal fuzzy positive solution(FPIS,A^+) and the ideal fuzzy negative solution (FNIS, A^-) are calculated according to Eq. 24:

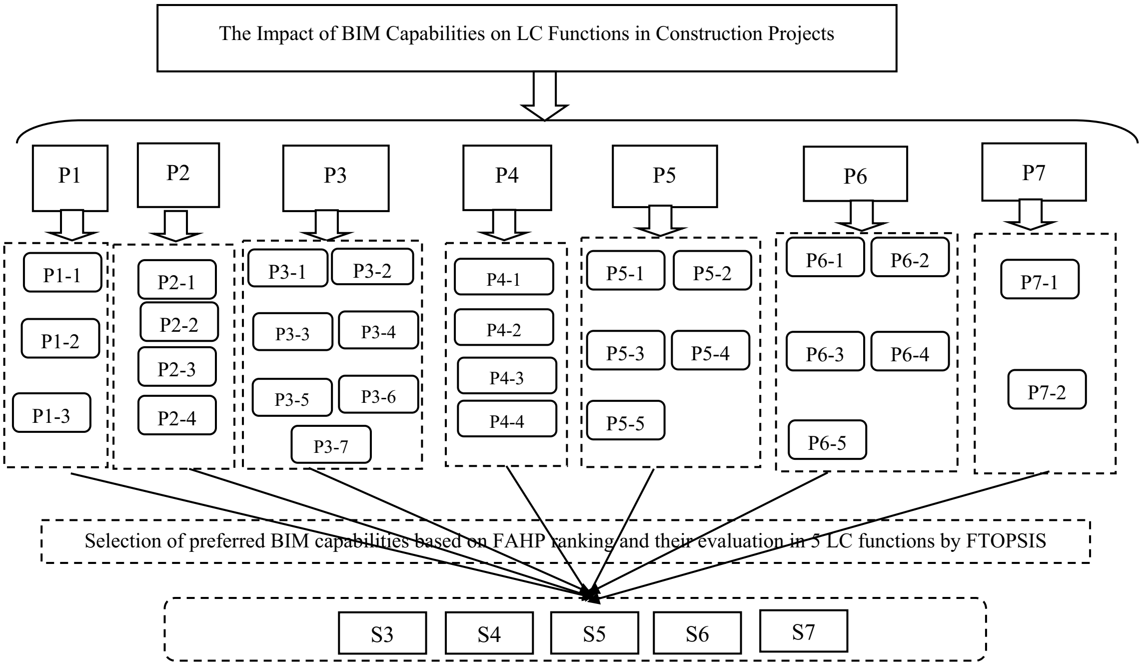

Fig. 7 Hierarchical structure of FAHP-FTOPSIS integrated decision-making based on research parameters

$$\begin{cases} \text{FPIS}, A^+ = \left\{\tilde{v}_1^+, \tilde{v}_j^+, \dots, \tilde{v}_m^+\right\} \\ \text{FNIS}, A^- = \left\{\tilde{v}_1^-, \tilde{v}_j^-, \dots, \tilde{v}_m^-\right\} \end{cases} \tag{24}$$

where $\tilde{v}_i^+, \tilde{v}_i^-$ respectively, are the best and worst value of criterion i among all the options and are determined according to Eqs. 25:

$$\begin{cases} \tilde{v}_i^+ = \max\limits_i \left\{\tilde{v}_{ij3}\right\} \\ \tilde{v}_i^- = \min\limits_i \left\{\tilde{v}_{ij1}\right\} \end{cases} \quad \forall i = 1, 2, \dots, m; \quad j = 1, 2, \dots, n \tag{25}$$

The options in A^+ and A^- indicate completely better and completely worse options, respectively. In other words, for positive (profit) indices, the positive ideal is considered to be the largest value of A^+, and the negative ideal is considered to be the smallest value of A^-. The sum of the distances of the alternatives from the positive and negative ideal fuzzy solutions (FPIS, $A^+$and FNIS, A^-) is calculated according to Eq. 26:

Table 4 Linguistic variables and corresponding fuzzy number to determine the importance of factors in FTOPSIS method

Linguistic phrase	Fuzzy numbers (l_i, m_i, u_i)
Very low (VL)	(0, 0, 0.2)
Low (L)	(0, 0.2, 0.4)
Medium (M)	(0.2, 0.4, 0.6)
High (H)	(0.4, 0.6, 0.8)
Very High (VH)	(0.6, 0.8, 1)
Excellent (E)	(0.8, 1, 1)

$$\begin{cases} S_i^+ = \sum\limits_{j=1}^{n} d_v\left(\tilde{v}_{ij}, \tilde{v}_j^+\right) \\ S_i^- = \sum\limits_{j=1}^{n} d_v\left(\tilde{v}_{ij}, \tilde{v}_j^-\right) \end{cases} \quad i = 1, 2, \dots, m; \quad j = 1, 2, \dots, n \tag{26}$$

In this equation, S_i^+ and S_i^- are the sum of the distances of the options from the positive ideal solution and $d_v\left(\tilde{v}_{ij}, \tilde{v}_j^+\right)$, $d_v\left(\tilde{v}_{ij}, \tilde{v}_j^-\right)$ the negative ideal solution, respectively. Also, $d_v(.,.)$ *is* the distance of each option from the ideal solutions are positive and negative, respectively. d_v (.,.) represents the distance between two fuzzy numbers. For two TFNs (M_1 (a_1, b_1, c_1) and M_2 (a_2, b_2, c_2)), the distance between the two numbers is equal to:

$$d_v\left(\tilde{M}_1, \tilde{M}_2\right) = \sqrt{\frac{1}{3}\left[\left(a_1 - a_2\right)^2 + \left(b_1 - b_2\right)^2 + \left(c_1 - c_2\right)^2\right]} \tag{27}$$

The relative similarity or relative proximity index for option i (CCi) is then calculated according to Eq. 28:

Table 5 Arithmetic mean of the pairwise comparison matrix of the main BIM capabilities

Main factors	P_1	P_2	P_3	P_4	P_5	P_6	P_7
P1	(1, 1, 1)	(0.2, 0.33333, 1)	(0.25, 0.5, 1)	(0.14286, 0.2, 0.33333)	(0.2, 0.33333, 1)	(0.2, 0.33333, 1)	(1, 2, 4)
P2	(1, 3, 5)	(1, 1, 1)	(1, 2, 4)	(0.2, 0.33333, 1)	(0.2, 0.33333, 1)	(0.2, 0.33333, 1)	(1, 3, 5)
P3	(1, 2, 4)	(0.25, 0.5, 1)	(1, 1, 1)	(0.25, 0.5, 1)	(1, 3, 5)	(1, 3, 5)	(2, 4, 6)
P4	(3, 5, 7)	(1, 3, 5)	(1, 2, 4)	(1, 1, 1)	(2, 4, 6)	(2, 4, 6)	(3, 5, 7)
P5	(1, 3, 5)	(1, 3, 5)	(0.2, 0.33333, 1)	(0.16667, 0.25, 0.5)	(1, 1, 1)	(1, 1, 1)	(1, 2, 4)
P6	(0.25, 0.5, 1)	(0.2, 0.33333, 1)	(0.16667, 0.25, 0.5)	(1, 2, 4)	(0.2, 0.333, 1)	(1, 1, 1)	(0.167, 0.25, 0.5)
P7	(0.25, 0.5, 1)	(0.2, 0.33333, 1)	(0.16667, 0.25, 0.5)	(0.14286, 0.2, 0.33333)	(0.167, 0.25, 0.5)	(0.25, 0.5, 1)	(1, 1, 1)

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad i = 1, 2, \ldots, m \tag{28}$$

Finally, according to the similarity index, the options are ranked in descending order. So that options with more similarity index are prioritized. In other words, the best (optimal) option is the one that has the shortest distance with FPIS and the farthest distance with FNIS.

5 Application of the Proposed Framework

The proposed framework is used to evaluate the effect of BIM capabilities on LC functions in construction projects (Arabnejad Khanouki et al. 2011; Afrazi and Dehghani 2014). The decision hierarchy was formed based on the parameters presented in Tables 1 and 2, along with the symbols assigned to each factor (for ease of data analysis), as shown in Fig. 7. There are four levels in the decision-making structure of the present study. The overall goal of the decision-making process, entitled "Investigating the Impact of BIM Capabilities on LC Main Functions in Construction Projects," is at the first level of the hierarchy. The main factors of BIM capabilities are in the second level, the secondary factors of BIM capabilities are in the third level, and the main functions of LC are in the fourth level of the hierarchy.

5.1 Data Analysis by FAHP Method and Determining the Weight of Main and Sub-Factors (Capabilities)

At this stage, the experts were asked to answer the questionnaire using the language expressions of the FAHP method, to compare a pair of seven main features of BIM and 30 sub-factors related to each of the main factors. After collecting the initial importance (weighting) determined by the experts, the arithmetic mean of these values was calculated to obtain a matrix of two-by-two comparison of the main factors and sub-factors. Arithmetic means matrices of pairwise comparisons are presented.

Table 6 Arithmetic mean of pairwise comparison matrix of sub-capabilities related to design visualization and visualization

P1	P1-1	P1-2	P1-3
P1-1	(1, 1, 1)	(1.3, 2.25, 4.14)	(0.2, 0.33333, 1)
P1-2	(0.24155, 0.44444, 0.76923)	(1, 1, 1)	(0.16667, 0.25, 0.5)
P1-3	(1, 2, 4)	(1, 3, 5)	(0.16667, 0.25, 0.5)

Table 7 Arithmetic mean of pairwise comparison matrix of sub-capabilities related to scheduling and budgeting program along with sequence of construction operations

P2	P2-1	P2-2	P2-3	P2-4
P2-1	(1, 1, 1)	(1, 3, 5)	(1, 2, 4)	(2, 4, 6)
P2-2	(0.2, 0.333, 1)	(1, 1, 1)	(0.25, 0.5, 1)	(0.2, 0.333, 1)
P2-3	(0.25, 0.5, 1)	(1, 2, 4)	(1, 1, 1)	(1, 2, 4)
P2-4	(0.167, 0.25, 0.5)	(1, 3, 5)	(0.25, 0.5, 1)	(1, 1, 1)

After obtaining the data in the form of average fuzzy pairwise comparison matrices, the values of the value of the fuzzy compound value (Si), the amount of normalized and normalized weight for each of the mentioned matrices were determined, the results of which are presented in Tables 5, 6, 7, 8, 9, 10, 11 and 12. The normalized weight is considered equal to the final weight and is considered the basis for ranking the capabilities in order to identify and prioritize the preferred items. The results for the final weight of each of the main and sub-capabilities of BIM are presented in descending order in Figs. 8 and 9, respectively (Tables 13, 14).

According to the weight of the main factors in Fig. 8, the ability to integrate the database with a weight of 0.201 is in the first rank. The ability to "use the data model to optimize

Table 8 Arithmetic mean of pairwise comparison matrix of sub-capabilities related to using data model for design optimization

P3	P3-1	P3-2	P3-3	P3-4	P3-5	P3-6	P3-7
P3-1	(1, 1, 1)	(0.25, 0.5, 1)	(1, 2, 4)	(1, 3, 5)	(1, 3, 5)	(0.2, 0.33333, 1)	(1, 2, 4)
P3-2	(1, 2, 4)	(1, 1, 1)	(1, 3, 5)	(2, 4, 6)	(1, 2, 4)	(1, 2, 4)	(2, 4, 6)
P3-3	(0.25, 0.5, 1)	(0.2, 0.33333, 1)	(1, 1, 1)	(0.25, 0.5, 1)	(0.2, 0.33333, 1)	(0.25, 0.5, 1)	(1, 2, 4)
P3-4	(0.2, 0.33333, 1)	(0.16667, 0.25, 0.5)	(1, 2, 4)	(1, 1, 1)	(0.25, 0.5, 1)	(0.2, 0.33333, 1)	(0.2, 0.33333, 1)
P3-5	(0.2, 0.33333, 1)	(0.25, 0.5, 1)	(1, 3, 5)	(1, 2, 4)	(1, 1, 1)	(1, 2, 4)	(2, 4, 6)
P3-6	(1, 3, 5)	(0.25, 0.5, 1)	(1, 2, 4)	(1, 3, 5)	(0.25, 0.5, 1)	(1, 1, 1)	(1, 3, 5)
P3-7	(0.25, 0.5, 1)	(0.16667, 0.25, 0.5)	(0.25, 0.5, 1)	(1, 3, 5)	(0.16667, 0.25, 0.5)	(0.2, 0.33333, 1)	(1, 1, 1)

Table 9 Arithmetic mean of pairwise comparison matrix of sub-factors related to joint cooperation and coordination between systems

P4	P4-1	P4-2	P4-3	P4-4
P4-1	(1, 1, 1)	(1.4, 2.2, 4.1)	(0.2, 0.33333, 1)	(0.2, 0.33333, 1)
P4-2	(0.2439, 0.45455, 0.71429)	(1, 1, 1)	(0.2, 0.33333, 1)	(0.16667, 0.25, 0.5)
P4-3	(1, 3, 5)	(1, 3, 5)	(1, 1, 1)	(0.2, 0.33333, 1)
P4-4	(1, 3, 5)	(2, 4, 6)	(1, 3, 5)	(1, 1, 1)

Table 12 Arithmetic mean of the pairwise comparison matrix of sub-capabilities related to sustainable design and construction

P7	P7-1	P7-2
P7-1	(1, 1, 1)	(1.3, 2.25, 4.14)
P7-2	(0.24155, 0.44444, 0.76923)	(1, 1, 1)

the design" with a weight of 0.185 has the second rank, and the ability "to schedule and budget along with the sequence of construction operations" with the weight of 0.174 are in the third rank.

The diagrams in Fig. 9 show the weight of the sub-factors of each of the main capabilities. Among the capabilities of design visualization and visualization (P1), according to weighted numerical results, the ability to "visualize the process of how to design a design status plan at any time" P1-3 with a weight of 0.143 first place and the ability to "multidimensional visualization of planning construction" with a weight of 0.124 are in second place. According to Fig. 9(P2), among the capabilities of the scheduling and budgeting program, along with the sequence of construction operations, the capability of "construction and computer control of project scheduling and budgeting" (P2-4) with a weight of 0.272, the ability to "review the construction process" and design assistance (P2-2) with a weight of 0.262 have won second place. According to the results presented in Fig. 9(P3), among the capabilities of using the data model to optimize the design, the ability to "estimate the cost and execution time of processes automatically" (P3-2) with a weight of 0.21, the first rank, capability "Assessment of compliance with the initial objectives of the project" (P3-7) with a weight of 0.195 are ranked

Table 10 Arithmetic mean of pairwise comparison matrix of sub-factors related to database integration

P5	P5-1	P5-2	P5-3	P5-4	P5-5
P5-1	(1, 1, 1)	(0.25, 0.5, 1)	(0.2, 0.33333, 1)	(0.125, 0.16667, 0.25)	(0.14286, 0.2, 0.33333)
P5-2	(1, 2, 4)	(1, 1, 1)	(0.25, 0.5, 1)	(0.1, 0.125, 0.16667)	(0.2, 0.33333, 1)
P5-3	(1, 3, 5)	(1, 2, 4)	(1, 1, 1)	(0.16667, 0.25, 0.5)	(0.14286, 0.2, 0.33333)
P5-4	(4, 6, 8)	(6, 8, 10)	(2, 4, 6)	(1, 1, 1)	(0.2, 0.33333, 1)
P5-5	(3, 5, 7)	(1, 3, 5)	(3, 5, 7)	(1, 3, 5)	(1, 1, 1)

Table 11 Arithmetic mean of pairwise comparison matrix of sub-capabilities related to constructability and interference detection

P6	P6-1	P6-2	P6-3	P6-4	P6-5
P6-1	(1, 1, 1)	(1, 3, 5)	(0.2, 0.33333, 1)	(1, 2, 4)	(1, 2, 4)
P6-2	(0.2, 0.33333, 1)	(1, 1, 1)	(0.16667, 0.25, 0.5)	(0.25, 0.5, 1)	(1, 2, 4)
P6-3	(1, 3, 5)	(2, 4, 6)	(1, 1, 1)	(2, 4, 6)	(1, 2, 4)
P6-4	(0.25, 0.5, 1)	(1, 2, 4)	(0.16667, 0.25, 0.5)	(1, 1, 1)	(1, 2, 4)
P6-5	(0.2, 0.33333, 1)	(1, 2, 4)	(0.16667, 0.25, 0.5)	(0.2, 0.33333, 1)	(0.25, 0.5, 1)

Table 13 Value of fuzzy combined value and normal weight of BIM main and secondary capabilities

Factors	S_i	Abnormal weight	Normalized weight
P1	(0.0295, 0.07607, 0.27714)	0.371434	0.101104
P2	(0.04648, 0.16841, 0.56537)	0.713882	0.174318
P3	(0.0581, 0.19164, 0.59862)	0.754709	0.185432
P4	(0.04613, 0.16696, 0.54874)	0.64367	0.1422
P5	(0.1162, 0.34843, 0.9977)	1	0.20175
P6	(0.02123, 0.04849, 0.16074)	0.129305	0.095197
P7	(0.068, 0.229, 0.744)	0.838996	0.151292
P1-1	(0.023, 0.054, 0.195)	0.243212	0.124149
P1-2	(0.031, 0.102, 0.319)	0.565822	0.09924
P1-3	(0.04, 0.116, 0.408)	1	0.143274
P2-1	(0.049, 0.146, 0.532)	0.675951	0.178287
P2-2	(0.099, 0.353, 1.028)	0.176134	0.263758
P2-3	(0.04133, 0.08324, 0.24172	0.534879	0.09575
P2-4	(0.07068, 0.16762, 0.52792)	1	0.272305
P3-1	(0.08139, 0.25656, 0.77635)	0.72496	0.16606
P3-2	(0.15421, 0.49259, 1.33088)	0.918272	0.210514
P3-3	(0.03559, 0.08884, 0.35532)	0.566095	0.129205
P3-4	(0.02257, 0.05427, 0.2036)	0.338418	0.07724
P3-5	(0.03997, 0.15437, 0.54665)	0.760434	0.153561
P3-6	(0.07666, 0.30243, 1.01521)	0.43276	0.14824
P3-7	(0.05749, 0.23627, 0.81997)	0.90542	0.19586
P4-1	(0.04819, 0.16382, 0.62474)	1	0.182168
P4-2	(0.02367, 0.04495, 0.12034)	0.4325	0.12314
P4-3	(0.03513, 0.08088, 0.24067)	0.157696	0.063108
P4-4	(0.0456, 0.13179, 0.36381)	0.408704	0.16356
P5-1	(0.18186, 0.39503, 0.87315)	1	0.260019
P5-2	(0.124, 0.34735, 0.83956)	0.932411	0.163142
P5-3	(0.05192, 0.17501, 0.55595)	0.898403	0.235741
P5-4	(0.03054, 0.10954, 0.38316)	0.878379	0.158144
P5-5	(0.01992, 0.05769, 0.21787)	0.431823	0.077746
P6-1	(0.01574, 0.04239, 0.16278)	0.763667	0.23633
P6-2	(0.03977, 0.13288, 0.42823)	0.297892	0.137491
P6-3	(0.03577, 0.13612, 0.43575)	0.772861	0.139146
P6-4	(0.0592, 0.15121, 0.4728)	1	0.21975
P6-5	(0.01912, 0.05406, 0.19283)	0.379419	0.168311
P7-1	(0.07846, 0.24112, 0.70621)	1	0.28004
P7-2	(0.0581, 0.2176, 0.7326)	0.831588	0.211504

second (Shariati et al. 2021a; Nowroozi et al. 2021). According to Fig. 9(P4), among the capabilities of joint cooperation and coordination between systems, the ability of "coordination in design and construction" (P4-1) with a weight of 0.182, the ability to "exchange design decisions with team members" (P4- 4) with a weight of 0.163 are in second place. According to the results presented in Fig. 9 (P5), among the database integration capabilities, the ability to "maintain information and integrated model design" (P5-1) with a weight of 0.26 ranks first, the ability to "integrate with the project partner through Database" (Supply Chain) (P5-3) with a weight of 0.163 are ranked second. According to the results of the diagram (9-P6), among the capabilities of buildability and detection of interferences, the ability of "rapid construction and optimization of time and cost" (P6-1) with a weight of 0.23, the ability to "accurately simulate processes in different phases Made" (P6-4) with a weight of 0.219 ranks. According to Fig. 9 (P7), among the capabilities of sustainable design and construction, the ability of "energy consumption" (P7-1) with a weight of 0.28 has gained the first rank.

Table 18 (in the "Appendix") presents the final results including the relative weights of the main factors and

Table 14 Final results of relative weight and final weight related to the importance of BIM main and secondary capabilities

Main capability	Weight	Compatibility	Sub-capability	Relative weight	Final weight
Design visualization and visualization (P1)	0.101	0.061	P1-1	0.124	0.0125
			P1-2	0.099	0.0100
			P1-3	0.143	0.0144
Scheduling and budgeting along with the sequence of construction operations (P2)	0.174	0.034	P2-1	0.178	0.0310
			P2-2	0.264	0.0459
			P2-3	0.096	0.0167
			P2-4	0.272	0.0473
Use data model to optimize design (P3)	0.185	0.028	P3-1	0.166	0.0307
			P3-2	0.211	0.0390
			P3-3	0.129	0.0239
			P3-4	0.077	0.0142
			P3-5	0.154	0.0285
			P3-6	0.148	0.0274
			P3-7	0.196	0.0363
Collaboration and coordination between systems (P4)	0.142	0.074	P4-1	0.182	0.0258
			P4-2	0.123	0.0175
			P4-3	0.063	0.0089
			P4-4	0.164	0.0233
Database integration (P5)	0.202	0.08	P5-1	0.26	0.0525
			P5-2	0.163	0.0329
			P5-3	0.235	0.0475
			P5-4	0.158	0.0319
			P5-5	0.078	0.0158
Buildability and interference detection (P6)	0.095	0.055	P6-1	0.236	0.0224
			P6-2	0.137	0.0130
			P6-3	0.139	0.0132
			P6-4	0.220	0.0209
			P6-5	0.168	0.0160
Sustainable design and construction (P7)	0.151	0.81	P7-1	0.280	0.0423
			P7-2	0.212	0.0320

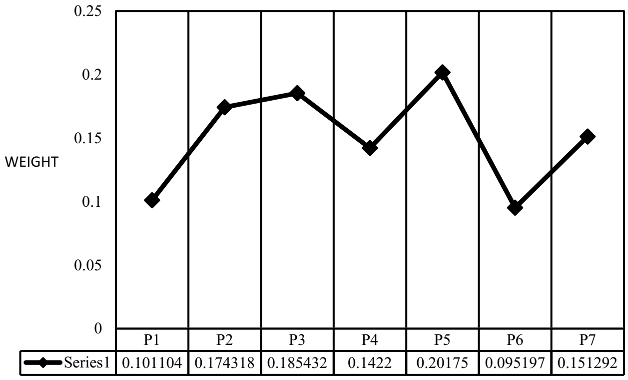

Fig. 8 Weight of BIM core capabilities

sub-factors of BIM capabilities and the results of the adjustment rate of the comparisons related to the factors as well as the final ranking obtained for the factors based on the final weight. According to the results, it can be seen that the compatibility value (CR) of all matrices is less than 0.1, so all matrices of pairwise comparisons were compatible.

After evaluating and prioritizing the BIM capabilities with the FAHP method, the preferred capabilities have been identified. For this purpose, following the Pareto principle, which states that typically 80% of problems are caused by 20% of causes (Kaplow 2005), action has been taken to determine the preferred capabilities. The purpose of this step was to find the most important BIM capabilities to examine their effect on the main functions of the LC and to facilitate the presentation of suggestions and solutions in a more desirable way. Using this mechanism and based on the comparison of the final weight results for BIM capabilities, a total of the following eight capabilities were selected:

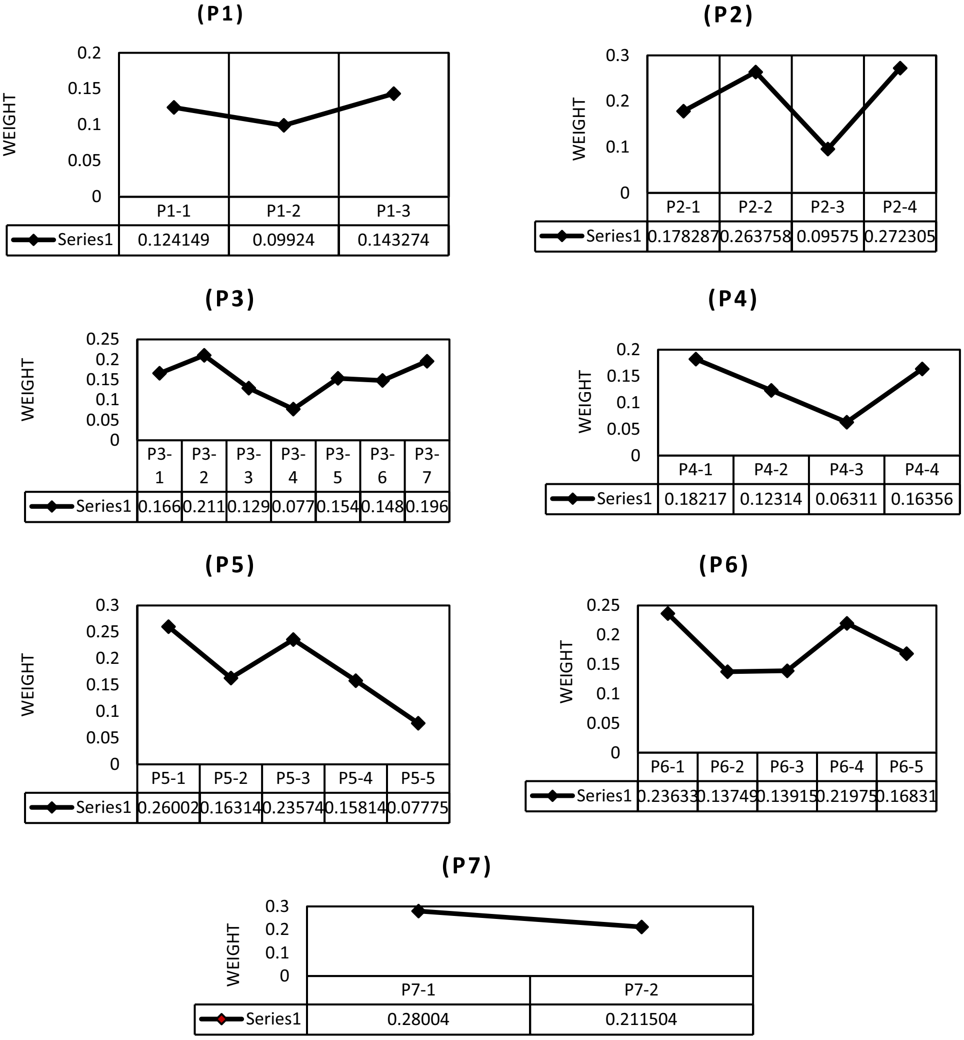

Fig. 9 Sub-factors weight of the main BIM capabilities in each main category: **P1** design visualization and visualization, **P2** scheduling and budgeting along with the sequence of construction operations, **P3** using data model to optimize the design, **P4** collaboration and coordination between systems, **P5** database integration, **P6** buildability and interference detection, **P7** sustainable design and construction

- Illustration of the process of how the design status plan is formed at any given time (P1-3),
- Construction and computer control of project scheduling and budgeting (P2-4),
- Estimation of costs and process execution time automatically (P3-2),
- Assessment of compliance with the initial objectives of the project (P3-7)
- Coordination in design and construction (P4-1),
- Information retention and integrated model design (P5-1),
- Fast construction and time and cost optimization (P6-1)
- Energy consumption (P7-1).

5.2 Analysis of the Effect of the Most Important BIM Capabilities on the Performance of LC Functions by FTopsis Method

After determining the ranking of BIM capabilities with a greater degree of importance in construction projects using the FAHP method in the previous section, this part of the data analysis to evaluate the rank of the main functions of LC (Table 2) to determine the effect of BIM capabilities on them and the most important function was discussed (Shariati et al. 2021b, c; Jahandari et al. 2021). For this purpose, the experts were asked to evaluate the importance and intensity of the effect of BIM capabilities of the main LC functions on BIM capabilities in comparison with each other, using the linguistic variables corresponding to the FTopsis method. Then, using the table, the verbal expressions were converted into corresponding fuzzy numbers, and the fuzzy decision evaluation matrices (Table 18) were collected to examine the intensity of the effect of BIM capabilities and LC functions. Next, normalized fuzzy decision matrices were compared to compare LC functions in terms of the ultimately preferred sub-capabilities extracted (not provided in the paper due to the limited number of pages). Weighted normalized fuzzy decision matrices were also obtained to compare LC functions in terms of final sub-capabilities extracted according to Table 19 (in the "Appendix"). Next, the distance from

Table 15 Distance from the ideal positive fuzzy solution (di+) for all BIM capabilities

Distance to the ideal solution	P1-3	P2-4	P3-2	P3-7	P4-1	P5-1	P6-1	P7-1
S1	0.0817	0.0695	0.0674	0.0312	0.0333	0.0382	0.0342	0.0289
S2	0.0859	0.0578	0.0476	0.0217	0.0247	0.0363	0.0197	0.0274
S3	0.0607	0.0728	0.0586	0.028	0.0362	0.0286	0.0169	0.0332
S4	0.0538	0.0366	0.0369	0.0248	0.0263	0.0199	0.0142	0.0223
S5	0.047	0.0505	0.0267	0.0248	0.0197	0.0144	0.03	0.0173

Table 16 Distance from the ideal negative fuzzy solution (di-) for all solutions BIM capabilities

The distance to the anti-ideal solution	P1-3	P2-4	P3-2	P3-7	P4-1	P5-1	P6-1	P7-1
S1	0.0381	0.0205	0.0177	0.0129	0.0139	0.0173	0.0118	0.0104
S2	0.0226	0.0134	0.0269	0.0317	0.0219	0.0095	0.0254	0.0125
S3	0.017	0.0202	0.0267	0.0157	0.0114	0.0171	0.0283	0.0063
S4	0.0138	0.0253	0.0276	0.0186	0.0197	0.0256	0.0113	0.0373
S5	0.0607	0.0505	0.0586	0.0186	0.0263	0.0315	0.0146	0.0223

Table 17 Determination of similarity index (CCi) and final ranking for all BIM capabilities

Symbol	LC functions	(CC_i)	S^-	S^+	Final rank
S1	Teamwork culture	0.266	0.118	0.3256	5
S2	Continuous benefit and improvement/build based on quality	0.4348	0.1864	0.2423	2
S3	Customer focus (employer)	0.3269	0.1356	0.2792	4
S4	Eliminate waste	0.3312	0.1462	0.2952	3
S5	Standardization	0.547	0.2635	0.2182	1

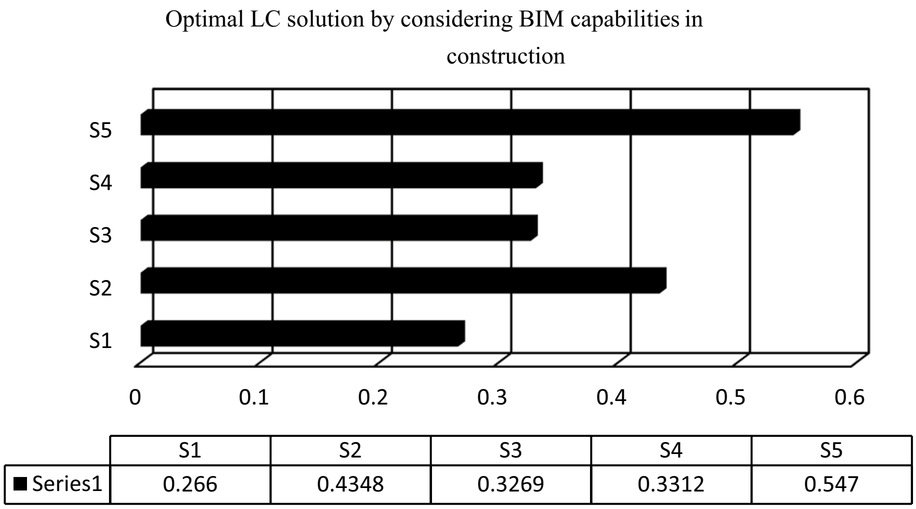

Fig. 10 Results of the final ranking of the optimal LC solution taking into account the BIM capabilities in construction based on the similarity index (CC_i)

the positive, positive fuzzy solution (di+) was calculated for all BIM capabilities. Given that in the present study, all the identified claims are considered as criteria of capability and capability; therefore, the ideal fuzzy positive solution (FPIS, A *) and the fuzzy negative ideal solution (FPIS, A-) for all the preferred cases identified as v * = (0,0,0) and v- = (1,1,1). Then, the distance (.,.) Dv of each criterion from FPIS, A * and FPIS, A- is calculated, the results of which are presented in Table 20 (in the "Appendix"). Accordingly, the relevant calculations were performed to determine the distance parameters of each of the BIM capabilities from the ideal (di+) and anti-fuzzy (di−) solution extracted from the previous step, and the final results were determined according to Tables 15 and 16, respectively. Based on the values of the similarity index (CCi) obtained in Table 17, the ranking of the options is determined in descending order, to understand better, the results are shown in Fig. 10.

According to Table 16, the ability to "visualize the process of how the design status plan is formed at any given time" (P1-3) is the closest solution to the function of a teamwork culture (S1). With the initial objectives of the project "(P3-7), the closest solution to the function of continuous improvement/build based on quality (S2) and the ability of" rapid construction and optimization of time and cost "(P6-1) is the closest solution to the function of continuous improvement / Quality-based construction (S3) and "energy consumption" capability (P7-1) the closest solution to the operation of waste (S4) and the ability to "build and control computer scheduling and project budgeting" (P2-4) the closest solution to operation losses (S5).

According to the final results (Table 17) of the ranking of LC functions, if the BIM capabilities are used simultaneously in the construction project, the standardization function will perform better and will be ranked 1, similar to the solution.

6 Conclusion

This study evaluated the simultaneous role of building information modeling system (BIM) and lean construction capabilities in projects using multi-criteria fuzzy multi-criteria decision-making methods. The results showed that among the main capabilities of BIM, the ability to integrate the database with a weight of 0.201 first place, the ability to use the data model to optimize the design with a weight of 0.185-s place, the ability to schedule and budget along with the sequence of construction operations with weight 0.174 ranks third. Among the capabilities of design visualization and visualization, the ability to "visualize the process of how to form the design status plan in any moment" with a weight of 0.143 ranked first and among the capabilities of the schedule and budgeting along with the sequence of construction operations, the ability to "build And computer control of project scheduling and budgeting" with a weight of 0.272 ranked first, and among the capabilities of using the data model to optimize the design, the capability of "estimating costs and time to run processes automatically" with a weight of 0.21 ranked first, capability "Assessment of compliance with the initial objectives of the project" with a weight of 0.195, second among the capabilities of joint cooperation and coordination between systems, the ability of "coordination in design and construction" with a weight of 0.182, and among the capabilities of database integration, ability to "maintain information and integrated design of the model" with a weight of 0.26 first place, and among the capabilities of buildability and detection of interference, the ability of "rapid construction and optimization of time and cost" with a weight of 0.23 first place, and among design capabilities and sustainable construction has gained the ability of "energy consumption" (P7-1) with a weight of 0.28 first place. After evaluating and prioritizing the BIM capabilities with the FAHP method, the preferred capabilities have been identified. The results of the study of the effect of BIM capabilities on LC operation and their user synchronization with the FTOPSIS method in the studied infrastructure projects and according to the ranking based on the similarity index (CCi), it was determined that the Status of the project at any time "The closest solution to the function of teamwork culture, the ability to" assess compliance with the initial objectives of the plan "The closest solution to the function of continuous improvement/construction based on quality and the ability to" Build fast and optimize time and cost "The solution to the function of continuous improvement/construction based on the quality and capability of "energy consumption" is the closest solution to the function of waste and the capability of "computer construction and control of project scheduling and budgeting" is the closest solution to the function of waste. With simultaneous application of BIM capabilities and lean construction in the construction project, the standardization function is better and ranked 1, similar to the solution. Further research needs to examine more closely the links between building information modeling system (BIM) and lean construction performance in construction projects.

Appendix

See Tables 18, 19 and 20.

Table 18 Fuzzy decision matrix collected to compare LC functions in terms of the most important BIM capabilities

Subcriteria	P1-3			P2-4			P3-2			P3-7			P4-1			P5-1			P6-1			P7-1		
Boundary limit	l_i	m_i	u_i	l_i	m_i	u_i	l_i	m_i	u_i	l_i	m_i	u_i	l_i	m_i	u_i	l_i	m_i	u_i	l_i	m_i	u_i	l_i	m_i	u_i
S1	0.07	0.27	0.47	0.13	0.27	0.47	0.00	0.13	0.33	0.13	0.33	0.53	0.07	0.27	0.47	0.00	0.07	0.27	0.00	0.20	0.40	0.07	0.20	0.40
S2	0.07	0.20	0.40	0.20	0.40	0.60	0.20	0.40	0.60	0.33	0.53	0.73	0.27	0.47	0.67	0.00	0.13	0.33	0.33	0.53	0.73	0.07	0.27	0.47
S3	0.27	0.47	0.67	0.07	0.27	0.47	0.07	0.27	0.47	0.20	0.40	0.60	0.00	0.20	0.40	0.13	0.33	0.53	0.40	0.60	0.80	0.00	0.07	0.27
S4	0.33	0.53	0.73	0.40	0.60	0.80	0.33	0.53	0.73	0.27	0.47	0.67	0.27	0.40	0.60	0.33	0.53	0.73	0.47	0.67	0.87	0.20	0.40	0.60
S5	0.40	0.60	0.80	0.27	0.47	0.67	0.47	0.67	0.87	0.27	0.47	0.67	0.40	0.60	0.73	0.47	0.67	0.87	0.13	0.27	0.47	0.33	0.53	0.73

Table 19 Weighted normalized fuzzy decision matrix for comparing comparison of LC functions from the perspective of the most important BIM capabilities

Subcriteria	P1-3			P2-4			P3-2			P3-7			P4-1			P5-1			P6-1			P7-1		
Boundary limit	l_i	m_i	u_i	l_i	m_i	u_i	l_i	m_i	u_i	l_i	m_i	u_i	l_i	m_i	u_i	l_i	m_i	u_i	l_i	m_i	u_i	l_i	m_i	u_i
S1	0.007	0.029	0.051	0.016	0.031	0.055	0.000	0.011	0.029	0.007	0.017	0.027	0.003	0.012	0.021	0.000	0.003	0.012	0.000	0.009	0.018	0.003	0.008	0.016
S2	0.007	0.022	0.044	0.023	0.047	0.070	0.017	0.034	0.051	0.017	0.027	0.037	0.012	0.021	0.030	0.000	0.006	0.015	0.015	0.024	0.033	0.003	0.011	0.019
S3	0.029	0.051	0.073	0.008	0.031	0.055	0.006	0.023	0.040	0.010	0.020	0.030	0.000	0.009	0.018	0.006	0.015	0.025	0.018	0.027	0.036	0.000	0.003	0.011
S4	0.036	0.058	0.080	0.047	0.070	0.094	0.029	0.046	0.063	0.013	0.023	0.033	0.012	0.018	0.027	0.015	0.025	0.034	0.021	0.030	0.040	0.008	0.016	0.024
S5	0.044	0.065	0.087	0.031	0.055	0.078	0.040	0.057	0.074	0.013	0.023	0.033	0.018	0.027	0.033	0.021	0.031	0.040	0.006	0.012	0.021	0.013	0.021	0.029

Table 20 Weighted normalized fuzzy decision matrix for comparison of LC functions in terms of the most important BIM capabilities

Subcriteria	P1-3			P2-4			P3-2			P3-7			P4-1			P5-1			P6-1			P7-1		
Boundary limit	l_i	m_i	u_i	l_i	m_i	u_i	l_i	m_i	u_i	l_i	m_i	u_i	l_i	m_i	u_i	l_i	m_i	u_i	l_i	m_i	u_i	l_i	m_i	u_i
FPIS, A^*	0.1088	0.1088	0.1088	0.1014	0.1014	0.1014	0.0797	0.0797	0.0797	0.0468	0.0468	0.0468	0.0443	0.0443	0.0443	0.0429	0.0429	0.0429	0.0425	0.0425	0.0425	0.0373	0.0373	0.0373
FPIS, A^-	0.0073	0.0073	0.0073	0.0078	0.0078	0.0078	0	0	0	0.0067	0.0067	0.0067	0	0	0	0	0	0	0	0	0	0	0	0

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