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A Constructability Assessment Model Based on BIM in Urban Renewal Projects in Limited Lands

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Abstract: One of the most significant concerns in urban development today is the organization of areas of cities that have become run-down over time. In order to complete previous constructability studies in other fields of construction, the current study evaluates constructability based on BIM, specifically in the context of the Tehran limited land renewal project. The motivation for this study is the current difficulties facing renewal designs for limited lands, and the lack of a quantitative constructability model for urban renewal projects in Iran. This paper aims (1) to discuss the design elements that should be considered in the design phase of urban renewal projects; (2) to identify the factors that may affect constructability; and (3) to propose a framework for assessing urban renewal designs by considering constructability factors using building information modeling (BIM). To meet these needs, this paper investigates constructability factors and their relative importance, considering the design elements that should be acknowledged in limited land renewal, using a multicriteria techniques. Some 28 constructability factors are identified through a literature review, and based on 52 responses received from a questionnaire survey, the factors are ranked using pairwise comparisons of the analytic hierarchy process (AHP). The final constructability factors that are identified through the technique for order preference using the similarity to ideal solution (TOPSIS) method are standard dimensions, safety, simplification of structure, resource intelligence and alignment, and skilled labor availability. The contribution of this research to the body of knowledge is, firstly, the development of constructability factors for measuring the constructability of urban renewal designs, and secondly, the introduction of BIM as a most beneficial tool for assessing the constructability of the proposed designs. In using the constructability assessment framework and identifying the trade-offs between the constructability of renewal projects in the limited areas of urban spaces, design alternatives become more feasible.

Keywords: constructability; building information modelling; urban renewal projects; limited lands; construction; MCDM techniques

Citation: Faraji, A.; Homayoon Arya, S.; Ghasemi, E.; Soleimani, H.; Rahnamayiezekavat, P. A Constructability Assessment Model Based on BIM in Urban Renewal Projects in Limited Lands. *Buildings* **2023**, *13*, 2599. https://doi.org/10.3390/buildings13102599

Academic Editors: Haifeng Liao and Maxwell Fordjour Antwi-Afari

Received: 1 August 2023
Revised: 23 August 2023
Accepted: 13 October 2023
Published: 15 October 2023

1. Introduction

Construction is a complex process that inquires a strong connection between the two main parts of it, which are design and construction. However, it is not that common for designers and contractors to communicate before the initiation of the construction phase. As a consequence, some changes might occur in construction activities, which may lead to time and costs overrunning [1]. To tackle this issue and increase designers' knowledge of construction, the concept of constructability was introduced and defined as "the optimum use of construction knowledge and experience in planning, design, procurement, and field operation to achieve overall project objectives" [2]. By applying constructability concepts in the early stages of construction projects, the cost of design and construction will be reduced, which will improve project planning and design coordination [3]. In order to build upon previous constructability studies in other fields, such as construction waste, safety performance, and building penalization design, the current study presents an investigation of constructability based on BIM, specifically in the field of urban studies in the renewal projects of limited lands within the selected geographical area of Tehran (the capital city of Iran), and based on specific features of the mentioned area (which despite its importance, has not been analyzed appropriately before). Among the current problems in limited lands, lack of the access inside these areas [4], narrow passages, lack of suitable infrastructure facilities, environmental problems, high volumes of pollution, and vulnerability to earthquakes can be considered threats to these areas [5,6]. Urban renewal projects involve a wide range of economic, environmental, cultural, political, and social effects [7]. Consequently, for reaching the objectives of each phase of the project, various stakeholders should be included [8]. For this reason, urban renewal designs need a constructability assessment model that facilitates easy, efficient, economical, and safe construction.

Building information modeling (BIM) has recently appeared as a comprehensive concept that encompasses the process and tools that integrate all projects requiring data and information. Due to automatic processes and minimized human involvement, it is argued that managing construction projects' life cycles will be enhanced through using BIM [9]. In BIM, construction actions are simulated as a 3D model, providing relevant digital information [10]. BIM presents the option of creating a 4D model by adding a time schedule to a 3D model, and it visually shows what the construction of a building would be like in reality. As a result of this, with the BIM model, not only does the constructability assessment of designs become more practical, it also becomes easier [11]. The main objectives of this paper are (1) to discuss the design elements that should be considered in the design phase of urban renewal projects; (2) to identify the factors that may affect the constructability; and (3) to propose a framework for assessing urban renewal designs by considering constructability factors with BIM models. Accordingly, the main questions of this study can be stated as follows:

1. What are the most significant constructability factors and their measurements regarding effective design elements in renewal projects in urban limited lands?
2. What are the main features of the BIM-based model that support the process of assessing the constructability of renewal projects in urban limited lands?

In the rest of the text, firstly, a list of constructability factors from a literature review are investigated. Then, the factors with the highest capacity to be assessed via BIM are introduced, using experts' judgments obtained through a questionnaire. Moreover, the findings of the questionnaire will be analyzed through MCDM techniques. Finally, a procedure for assessment of designs considering constructability factors using BIM will be presented.

2. Literature Review

2.1. Constructability Analysis

The Construction Industries Research and Information Association (CIRIA) describes the constructability of designs as "the degree to which the design of a building encourages ease of construction, subject to overall prerequisites for the completed building". It is accepted that the constructability of designs guarantees the capacity to develop the project. In addition, it facilitates efficient, economical, and safe construction [11,12]. Various studies have been conducted on the benefits of applying constructability, showing that by applying an assessment of the constructability of designs, 10.2% of the time, and 7.2% of the cost of a project can be saved [13]. Russel et al. introduced a framework to measure the benefits of constructability [14]. It demonstrated that the advantages of constructability are both quantitative and qualitative. The quantitative benefits of constructability are that it reduces production and manufacturing costs, the duration of the project schedule, and construction costs (labor, material, equipment) [15]. However, its qualitative benefits are that it decreases the number of issues involved in the project, improves site approachability, lessens the impact on existing productions, improves safety, minimizes repeated work, increases concentration on a common goal, increases collective understanding of the purpose/effect of individuals' involvement, improves team members' engagement with a project, etc. Al Hamadani claimed that with a lower bidding price, the number of site laborers was reduced, cost-effectiveness increased, and resource utilization improved [16]. He conducted a survey in his research to identify the obstacles/challenges related to implementing constructability practices. The most challenging obstacles were a lack of resources, adequate construction experience, and proper communication between the designers and contractors. The other factors, i.e., contract type, high cost, project delivery methods, and difficulty in coordinating disciplines, lengthy projects, and constructability not currently being part of the process, had almost similar weights. In recent years, several tools have been proposed to facilitate the implementation of constructability in research. These tools can be classified into three groups: (1) knowledge-based systems [17], which are based on a database, used to develop a set of constructability rules for analyzing and automatic decision-making [1]; and (2) quantitative analysis systems [1], which are an effective approach for evaluating alternatives, solving problems, and making decisions. The constructability score of a certain project's design is generated using this method. Designers can decide which design is more constructible by comparing their scores. Knowledge-based systems and quantitative analysis systems mostly focus on just one aspect of structural design, they are not able to visualize, and they are mainly applied in the late development phase of the design [17]. Another constructability tool that has proved to be more effective is (3) BIM-based assessment systems [11]. According to the objectives of the study, for constructability evaluation, it is necessary to identify the factors affecting it. Therefore, articles published in recent years (2016–2023) were analyzed. Based on these studies, we found constructability factors to be different according to the project life cycle. As a result, 28 effective and frequent factors of constructability are mentioned separately for each phase in Table 1. Most of the identified factors are classified in the two phases of design and construction, and seven of the identified factors are related to the construction sites.

Table 1. Constructability factors identified in the literature review.

CF Category	CF Code	Constructability Factors	Reference
Design factors	CF01	Prefabrication	[11]
	CF02	Grid Design	
	CF03	Standard dimensions	
	CF04	Design flexibility	
	CF05	Simplification of structure	
	CF06	Resource availability	
	CF07	Skilled labor availability	
	CF08	Resource intelligence and alignment	[3]
Construction factors	CF09	Construction sequence	[11]
	CF10	Excavation works	
	CF11	Weather effect	
	CF12	Safety	
	CF13	Personnel access	
	CF14	Space for material	
	CF15	Space for equipment	

Table 1. *Cont.*

CF Category	CF Code	Constructability Factors	Reference
	CF16	Material accessibility	[16]
	CF17	Equipment accessibility	
	CF18	Formwork	
	CF19	Repetition	
	CF20	Temporary Access	[3]
	CF21	Activities Interdepend	[18]
Site factors	CF22	Site facility availability	[11]
	CF23	Road use ability	
	CF24	Site impact on structures	
	CF25	Site impact on infrastructure	
	CF26	Construction site preparation	[3]
	CF27	Storage Spaces	[18]
	CF28	Adjacent Sites	

2.2. BIM as a Tool for Constructability Assessments

Building information modelling (BIM) has been introduced as a structured data model that depicts a building's components and functions from the pre-construction phase through the post-construction phase in the architecture, engineering, and construction (AEC) industry [19]. Several researchers have attempted to link the BIM methodology's application with the encouragement of constructability in construction projects [20]. Sompolgrunk et al. (2023) described BIM in their research as "a set of association approaches, forms, and innovations producing a strategy to oversee the basic building design and project information in computerized organization all through the building's life cycle" [21]. BIM maturity models may be employed to assess a project's level of BIM adoption [22]. BIM allows designers to communicate and share information with constructors. In BIM, construction products are simulated as 3D models with their linked digital information. The current BIM systems that store BIM models and offer model management services include BIM Software, BIM Server, and BIM Cloud. Real-time collaboration on BIM models is made possible via BIM Server and BIM Cloud from any Internet-connected location [23]. BIM promises to be an impressive tool for figuring out project management problems. In using BIM, productivity, process efficiency, and the quality of built assets will be improved, and design clashes and the cost of reworking onsite will be reduced [24,25]. In addition, BIM strengthens coordination between stakeholders [26,27]. However, due to a lack of trust, project members continue to adopt traditional collaborative methods. Therefore, Farouk et al. suggested that knowledge, skills, awareness, behavior, policy, system, cost, and management are the elements influencing trust in BIM-based construction projects [28]. One of the most significant benefits of utilizing BIM in the design and construction phase of a project is definitely its ability to model and test the constructability of a design [29]. In the BIM process, the applied information to a project can be updated from any department at any stage of the project [30]. Recent developments in BIM have altered the manner in which structural assets are digitalized, and how their data are stored in the form of a digital twin [31].

Khanzadi discussed some aspects of BIM application in the construction stage, which are safety, prefabrication, project coordination, constructability, clash detection, project supply chain, site layout planning, project scheduling and construction sequencing, cost estimation, etc. In addition, it is argued that by editing objects and reloading modified links in BIM, the entire model of a project will be updated based on these changes [9]. Construction project designs are commonly reviewed on 2D CAD drawings, which are not accurate. This leads to low constructability in designs [32]. To overcome this issue, BIM technology has been introduced as an effective solution that links a time schedule to a 3D model and generates a 4D-BIM model. Accordingly, the construction process can be simulated within this model, which allows every design component to be evaluated, and the constructability of the design can be analyzed. Moreover, the model minimizes unexpected problems during the construction phase.

2.3. Renewal Projects in Limited Lands

Limited land refers to the areas of the legal boundaries of cities that are vulnerable due to physical damage and a lack of proper vehicle access, urban facilities, and infrastructure. As a consequence of the poverty of residents and owners, these structures have a minimal possibility of renewal, and investors do not have enough motivation to invest in them. The Supreme Council of Urban Development and Architecture of Iran has determined the following three characteristics as the basis for identifying blocks of limited land: "(1) Instability: An unstable block is a block in which at least 50% of buildings are non-resistant, due to the lack of a suitable structural system and non-compliance with technical standards. (2) Impenetrability: An impenetrable block is a block where at least 50% of passages are less than 6 m wide, which represents a lack of proper access. (3) Granularity: A fine-grained block is a block in which at least 50% of its parts have an area of less than 200 square meters, which represents the compactness of the texture and the abundance of small parts with small area" [33].

Urban renewal projects offer an opportunity to develop the environmental sustainability of urban areas. The renewal of limited lands is not limited to physical dimensions, and necessarily includes renovation in social, cultural, and economic dimensions as well. From this point of view, the renovation is comprehensive, inclusive, based on a permanent movement, and relies on coherent and intelligent management in order for the goals of the renewal project to be achieved. These goals include securing and reducing the level of vulnerability of limited lands against earthquakes; creating equal opportunities for growth and development; taking the city out of the bipolar space; reducing inequality by bringing limited lands into the economic and social life cycle; strengthening residents' sense of citizenship and belonging to a place; and taking advantage of facilities and opportunities to renew limited lands in order to improve the city's capacities [34]. In order to assess constructability and examine the identified constructability factors in the design phase of a project, it is necessary to identify effective design elements in the project's area. In this section, a literature review in the field of urban studies was carried out with the aim of finding design elements in the renewal of the defined limited lands. As mentioned before, to achieve the renewal of limited lands, renewal is considered in terms of different aspects including accessibility, natural resources and the environment, the built environment, social life, and density of usage. Table 2 demonstrates these design elements, categorized using the different parts of limited land renewal projects.

In recent years, numerous studies have discussed the constructability of designs, and its implementation. One of the most challenging parts of assessing constructability is identifying a proper tool for this task. Recently, BIM has been introduced as an impressive tool for evaluating the constructability of construction projects. It is believed that by applying constructability and BIM in the design phase of a project, the whole constriction process will become more accurate, feasible, and faster. Table 3 determines the gaps in and proper tools of constructability assessments. Based on a comparison between previous studies, BIM is the most relevant tool to be implemented in the constructability assessment process. As is shown in Table 3, previous studies have focused on other fields and applications of constructability in the construction industry, such as commercial buildings, the general aspects of the design phase, safety, etc. However, the current study investigates constructability's role in urban studies and the renewal projects of limited lands, which have not been discussed appropriately.

Table 2. Design elements considered in urban renewal designs.

Design Category	Design Code	Design Elements	Reference
Accessibility	De01	Suitable design for disabled people, the elderly, and children	[35]
	De02	Facilities for disabled people, the elderly, and children	
	De03	Public facilities and easy access to limited areas	
	De04	Easy access to workplaces	
	De05	Mixed-use development model	
	De06	Efficient and safe design for pedestrian and public transportation	
	De07	Providing local employment	
	De08	Establishment of various commercial activity areas	
	De09	Efficient and safe design for drivers	
	De10	Flexible design of structures	
Natural resources and environment	De11	Water conservation	[36]
	De12	Energy conservation	
	De13	Waste management and pollution control	
	De14	Use of the land in order to protect the environment	
	De15	Material conservation	
	De16	Efficient use of land	
	De17	Environment and human health protection during construction	
	De18	Repairable structures reuse	
Built environment	De19	Environment compatibility	[37]
	De20	Appropriate forms of building	
	De21	Landscape	
	De22	Buildings and streets layout	
	De23	Open spaces' physical and aesthetic design	
	De24	Historical buildings protection	
	De25	Local properties protection	
	De26	Building design considering human comfort	
Social life	De27	Promoting communication	[38]
	De28	Involve community in public decisions	
	De29	Security measures	
High-density usage	De30	High-density use	[36]

Table 3. Comparative analysis of selected BIM-based studies of constructability assessment and the current study.

Ref.	Main Approach	Objectives	Methodology	Result
[39]	Finding an advanced tool to assess constructability	To propose a quantitative assessment of building constructability	Questionnaire	The proposed method provides the designer an accurate and faster mode for evaluating project constructability
[40]	Using integrated project delivery (IPD) to facilitate easier constructability implementation in the construction industry	To present a practical framework to reduce changes and duplications and facilitate constructability through focusing on the IPD approach	Case study	Having coordination between construction and pre-construction stages is very significant in reducing duplications and improving real implementation of designs
[9]	Identification of BIM in key performance indicators of construction projects	Identification of BIM applications compared to KPIs	Delphi method	Project coordination, collision detection, 4D, and 5D BIM are the most beneficial effects of BIM on the KPIs
[41]	The ability of BIM to simulate the field data to analyze the effects of construction changes	Dynamic modeling based on BIM to estimate garbage generation from change orders	A BIM-integrated SDM model	Decreasing waste in the pre-project planning stage, using BIM, could reduce construction waste by up to 25%
[42]	An exploration of BIM in managing safety issues	To promote the implementation of BIM in safety management	Questionnaire	BIM can help to improve safety in the planning phase, visualization, testing, and simulation of design solution
[43]	BIM as a digital resource	To assess the feasibility and challenges of adopting BIM technology	4D analysis of development evaluation; case study	Adopting BIM technology to promote better communication
[44]	A generative framework based on BIM	To propose a BIM framework for improving production efficiency	Rule-based design algorithm for panelization	A panel design construction computational framework to optimize panel design
[45]	Lack of 4D BIM for demolition and construction phases of renovation projects.	To produce guidelines for applying 4D BIM to complex cases of renovation projects	Case study	The proposed guideline helps in construction management of scheduling, disagreements, and errors
[46]	Integrating the knowledge and experience into the early design phase and presenting to the contractor will minimize delay and budget overruns	To develop a constructability index to make construction activities easier	Pre-designed surveys	Prefabrication of building components was found to have the highest effect on constructability
[47]	By considering sustainability and constructability in the initial phases of design, more efficient projects can be developed	To propose a BIM-based workflow that involves the different agents in construction	Plugin developed in Autodesk Revit	The framework promotes greater participation of builders and environmental engineers in the initial stages, and, thus, can promote more sustainable designs with better constructability
Current Study	Discussing the positive effect of constructability assessment in limited lands renewal projects	To propose a framework for assessing the constructability of urban renewal designs by considering constructability factors using BIM	Questionnaire; Delphi method	Through the proposed framework, BIM confirms the constructability of a design, which makes urban renewal projects more feasible

3. Materials and Methods

In continuation of the previous sections, in this part, we identify constructability factors with respect to the design elements that should be considered in the renewal process, and reveal their corresponding weights and importance. Figure 1. illustrates different phases of the research methodology. Based on a literature review, 28 constructability factors and 30 design elements were identified. Each factor has a different level of impact on constructability. Therefore, there was a need to specify the identified factors for the selected geographic area of the current study (Tehran). The importance of these factors can be specified based on several features including the geographic area, construction methods, city and construction regulations, and their ability to be assessed in the BIM. Consequently, to determine the most important factors, there was a need for experts' opinions, based on their experience and profession in the selected area. In order to obtain the relative importance of each factor, a questionnaire was conducted to collect opinions of experts in the construction field. The response from this questionnaire was used to calculate a relative importance value for each of the factors, to be used for the purpose of this research. The questionnaire was designed in two parts, to collect information about the opinions of different construction experts on the significance of the effect of the chosen factors on the constructability of a project. In the first section of the questionnaire, experts had to score the ability of each constructability factor to assess via BIM, and the second step involved scoring the design elements depending on their importance. In the final step, the results of the questionnaire were analyzed using MCDM techniques.

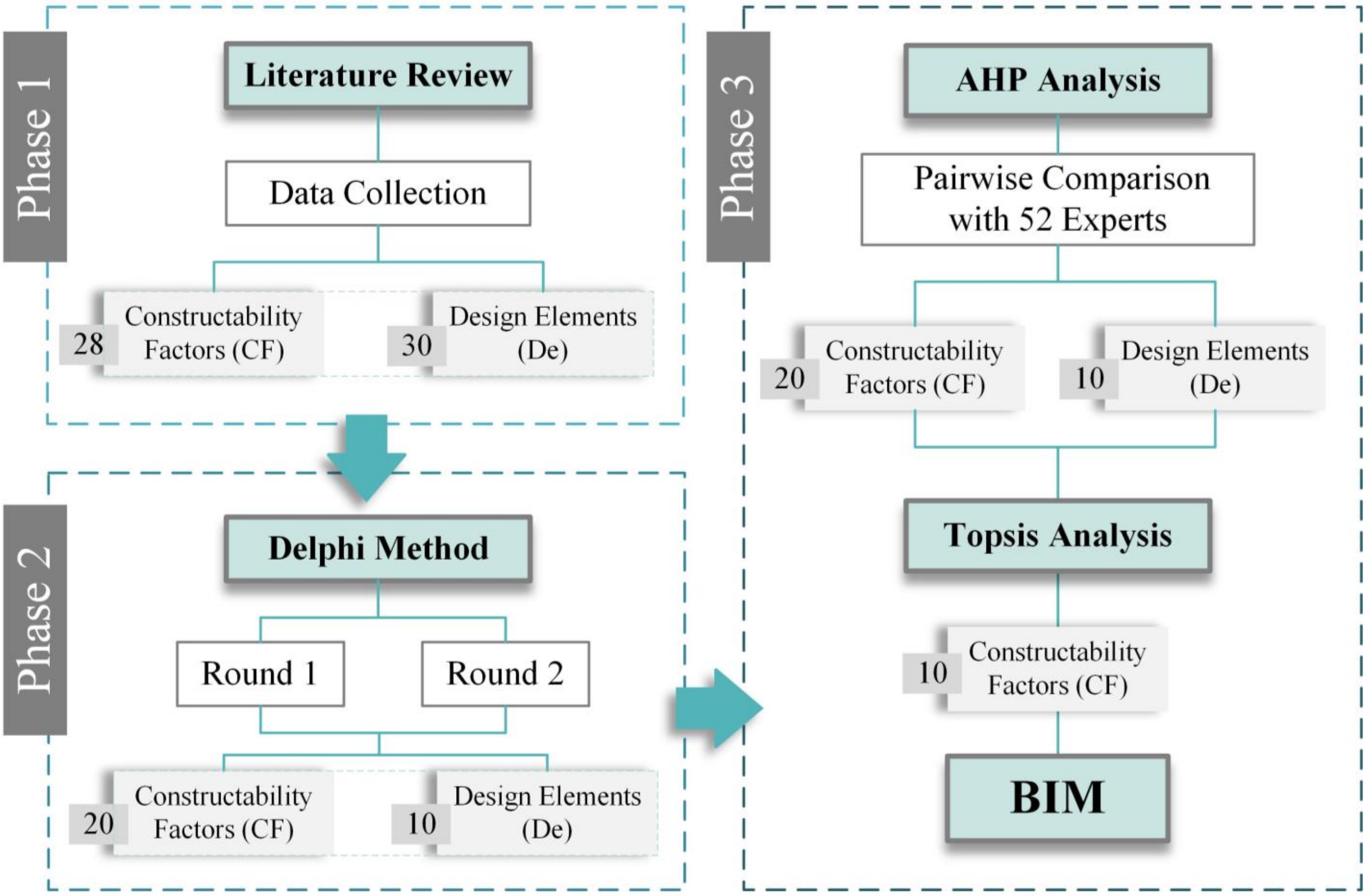

Figure 1. Schematic view of the sequential steps of the research methodology.

Delphi Method

The Delphi method was chosen for this research, since it is an organized procedure used to reach an agreement among an expert panel through repeated discussions in the form of a questionnaire [48]. Another reason for applying this method was its credibility in conducting an accurate investigation. In this research, the Delphi method was carried out in two rounds. After the first round, the answers were analyzed, and based on the evaluations, the questionaries were developed and sent to the experts for the second round. The first round was about developing the initial set of factors, and the second round was used to validate them and identify their levels of importance and expanding agreement [49]. The summary of the two-round Delphi method is shown in Figure 2. The iterative attributes of the Delphi method allow experts to receive feedback and new data from different perspectives, examining views from previous rounds and reconsidering them based on new announcement [9]. In practical Delphi studies, the agreement of the Delphi participants can be determined by measuring the variance in the responses. A lower variance leads to a higher agreement rate [50]. The selection of experts is critical in the Delphi method [51]. The questionnaire was distributed among three groups, including designers, contractors, and employers. All the invited expert panel members had to meet the following two requirements: 1. Graduates from a relevant construction fields of study, including BIM experts, project managers, heritage consultants, urban planning engineers, architects, civil engineers, restorers, geotechnical engineers, MEP engineers, and social studies consultants; 2. At least 5 years of professional experience in the construction industry. Due to the fact that this research was conducted in Tehran (the capital city of Iran), those participating in the study came from the urban renewal companies of said city; based on their experience in the specific field and more related expertise, 52 people from these companies responded to the questionnaire.

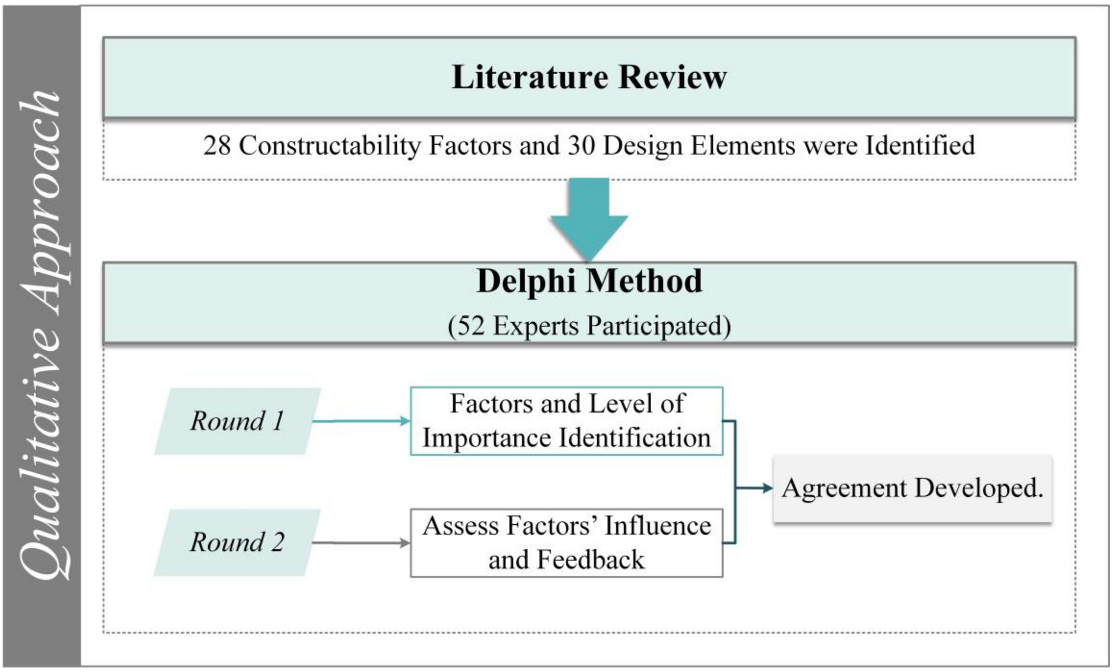

Figure 2. Research design using the Delphi method.

Table 4 lists the respondents' demographic data. Some 52 respondents completed all the stages of the Delphi process. The table categorized the information in five groups: Gender, age, educational level, profession, expertise, and years of experience.

Table 4. Respondents' demographic information.

		Frequency	Percentage
Gender	Male	38	73%
	Female	14	27%
Age	28–32	7	13.46%
	33–37	10	19.23%
	38–42	17	32.69%
	43–47	11	21.15%
	48–52	7	13.46%

Table 4. *Cont.*

		Frequency	Percentage
Educational level	Bachelor	27	51.92%
	Master	20	30.76%
	PhD	5	17.30%
Profession	Client	12	23%
	Designer	19	36.53%
	Contractor	21	40.38%
Expertise	BIM experts	6	11.53%
	Project manager	9	17.30%
	Heritage consultant	3	5.76%
	Urban planning engineer	6	11.53%
	Architect	8	15.38%
	Civil engineer	5	9.61%
	Restorer	7	13.46%
	Geotechnical engineer	4	7.69%
	MEP engineer	2	3.84%
	Social studies consultant	2	3.84%
Years of experience	6–10	19	36.53%
	11–15	22	42.30%
	16–20	11	21.15%

4. Analytical Techniques

A combination of multi-criteria decision-making (MCDM) techniques were used in this paper [51,52]. First, using the AHP technique, the constructability factors and design elements that had been scored the highest from experts' point of view were measured for their relative importance and then ranked. Second, with regard to the TOPSIS technique, 10 final constructability factors that should be considered using BIM in the constructability assessment were chosen.

4.1. Analytic Hierarchy Process (AHP)

In this research, the findings of the questionnaire were classified in two categories. First, the constructability factors that have the highest score due to their importance in analyzing within BIM were identified. Some 20 constructability factors from the whole list, identified through a literature review, were chosen to be ranked using the AHP method. These factors were selected by the experts and have the highest average scores among the other factors. Second, 10 design elements with the highest average score from the experts' point of view (regarding the features of Tehran limited lands) were identified, and ranked using the AHP. The analytic hierarchy process, one of the most widely used MCDM techniques, has been recognized as a key technique to address MCDM issues [53]. The AHP method is a systematic analysis method that breaks down the decision problem into multiple layers. Then, a hierarchical structure is formed, with one-way hierarchical relations between the layers. The advantage of AHP is its ability to combine qualitative and quantitative analysis. The AHP method was used twice for ranking the (1) constructability factors and (2) the design elements, separately [54]. Figure 3 shows the steps and equations used in the AHP technique.

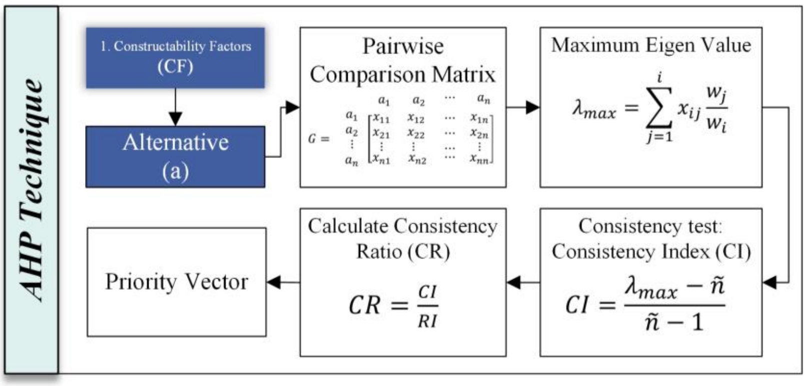

Figure 3. AHP technique representation of constructability factors.

For constructability factors, the weight of the attribute is calculated via pair-wise comparison of the relative importance. The deliberated priority is suitable if the comparison matrix passes the consistency test [55]. The AHP adopts the pair-wise comparison method to allocate the index weight at each level, and uses a 1–9 scale to measure relative importance (1: equal importance, 9: absolute importance) [56]. The AHP results of ranking constructability factors are shown in Table 5. As was mentioned above, for ranking the identified constructability factors in this study, the AHP technique was used. After a pair-wise comparison between the factors, Figure 4 shows the percentage of their importance, and their ranking.

Table 5. Constructability factors' ranking.

CF Code	Constructability Factor	Rank	Priority
CF03	Standard dimensions	1	11.20%
CF12	Safety	2	9.60%
CF10	Excavation works	3	9.50%
CF26	Construction site preparation	4	8.30%
CF04	Design flexibility	5	7.90%
CF06	Resource availability	6	7.30%
CF01	Prefabrication	7	6.90%
CF07	Skilled labor availability	8	4.50%
CF02	Grid design	9	4.30%
CF09	Construction sequence	10	3.80%
CF23	Road usability	11	3.30%
CF05	Simplification of structure	12	3.30%
CF08	Resource intelligence and alignment	13	3.10%
CF17	Equipment accessibility	14	2.90%
CF25	Site impact on infrastructure	15	2.80%
CF21	Activities' interdependence	16	2.60%
CF24	Site impact on structures	17	2.60%
CF16	Material accessibility	18	2.50%
CF28	Adjacent sites	19	1.80%
CF11	Weather effect	20	1.80%

The consistency ratio of each comparison matrix in the experts' responses was at a satisfactory level of less than 10%. In this study, standard dimensions have the highest priority for being assessed in BIM, as a constructability factor for urban renewal designs. Meanwhile, weather effect and adjacent sites have the lowest priority. Standard dimensions include the components' dimensions, which will decrease the amount of material waste. The size of the material and minimizing labor demand should be considered as two important factors in the dimensions of components.

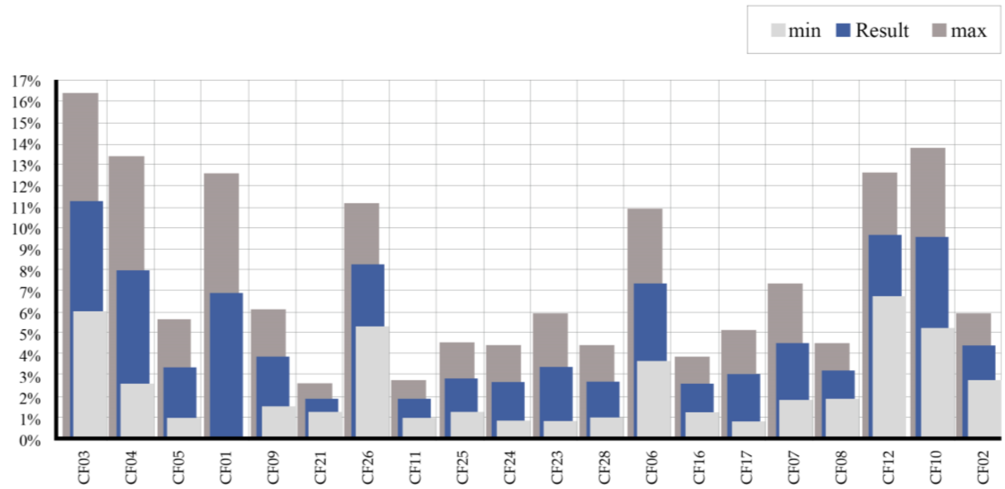

Figure 4. Constructability factors' ranking using the AHP.

For prioritizing the design elements using the AHP, the same process that was carried out in the previous section for ranking the constructability factors was carried out in this part. Some 30 design elements were identified through a literature review. For analyzing the most important elements, a questionnaire was conducted, and experts rated the importance of the identified design elements of the limited lands of Tehran. Then, 10 design elements with the highest average scores based on experts' opinions were selected to be ranked via the AHP.

In the next section, the TOPSIS method is used, in which the constructability factors are defined as the alternatives, and the design elements are defined as the criteria. As a result, the exact same process was carried out for ranking the design elements, using the AHP technique. However, instead of ranking the alternatives, this time, the criteria, which are the design elements, were ranked.

As shown in Figure 5, after a hierarchical structure is produced, the first step is establishing a judgment matrix. The AHP adopts the pair-wise comparison method to allocate the index weight at each level and measure its relative importance. Then, the comparison matrix is followed by the consistency test, which ensures that the calculated priority is accurate. The final step is ranking the design elements in descending order. The result of prioritizing the design elements and their importance is shown in Figure 6.

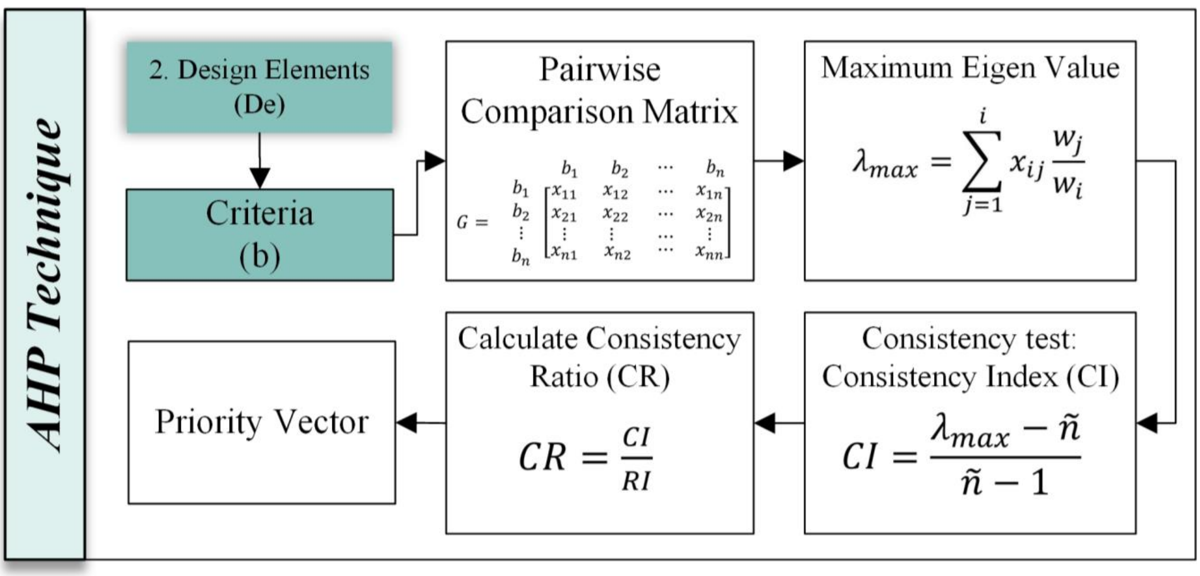

Figure 5. Representation of using the AHP technique for the design elements.

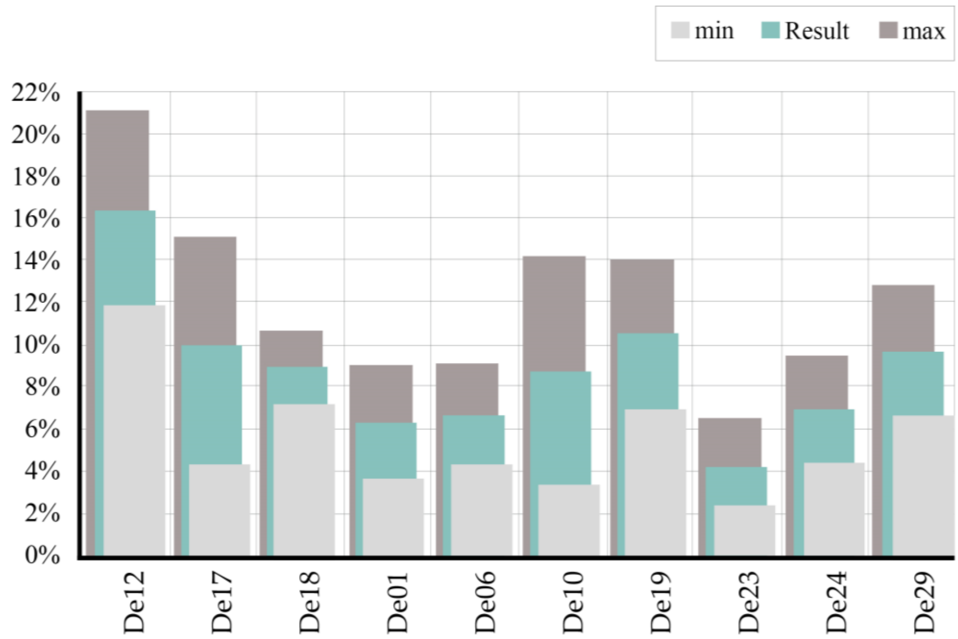

Figure 6. Design elements ranked using the AHP.

Similarly, the consistency ratio was at a satisfactory level of less than 10%. Based on these findings, energy conservation has the highest priority for design elements that should be considered in urban renewal designs. However, the physical and aesthetic design of open spaces have the lowest priority. As limited lands produce tons of poisonous waste, this element is vital in terms of environmental sustainability. Energy conservation, compatibility with the environment, and taking security measures should be considered the three most significant design elements in urban renewal projects. The AHP results of ranking the design elements are shown in Table 6.

Table 6. Design elements' ranking.

De Code	Design Element	Rank	Priority
De12	Energy conservation	1	16.40%
De19	Environment compatibility	2	10.40%
De29	Security measures	3	9.60%
De17	Environment and human health protection during construction	4	9.60%
De18	Repairable structures' reuse	5	8.90%
De10	Flexible design of structures	6	8.60%
De24	Historical building protection	7	6.90%
De06	Efficient and safe design for pedestrians and public transportation	8	6.60%
De01	Suitable design for disabled people, the elderly, and children	9	6.20%
De23	Open spaces' physical and aesthetic design	10	4.30%

4.2. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

The TOPSIS method is one of the most common MCDM techniques. The TOPSIS process is about finding the best alternative that is the nearest to the best ideal solution and the farthest from the worst ideal solution. The best ideal solution is a hypothetical alternative that maximizes the beneficial criteria and at the same time minimizes the cost criteria. The worst ideal solution minimizes the beneficial criteria and maximizes the cost criteria. As shown in Figure 7, the first step is creating the decision matrix, in which the alternatives are the constructability factors (CF), and the design elements (De) are the criteria. After that, the decision matrix must be normalized. The second step is calculating the weighted normalized matrix, then obtaining the best and worst ideal solutions. The third step is calculating the distance of each constructability factor from the best and worst ideal solutions. The final step is sorting the constructability factors in descending order, using the CC_i obtained. The highest CC_i value indicates the best performance in relation to the evaluation criteria [57].

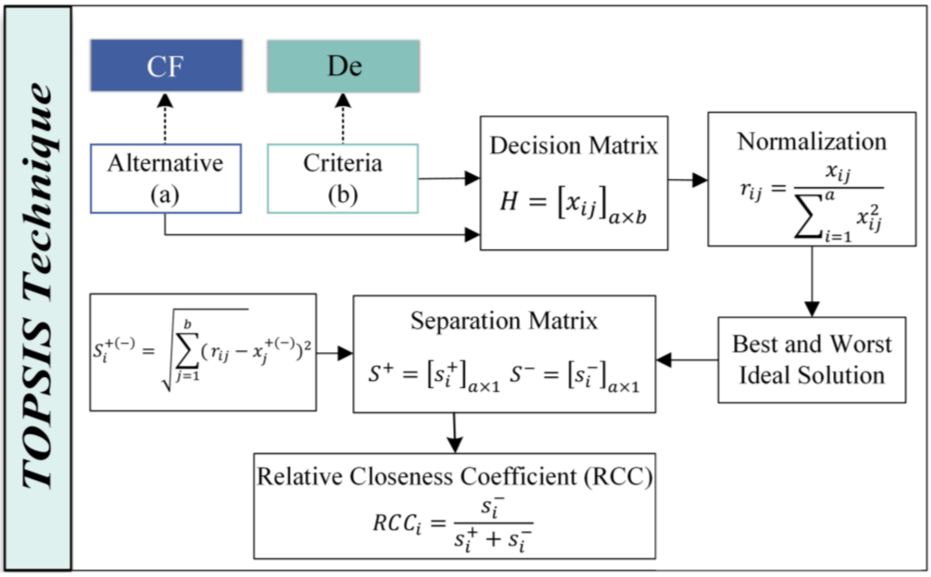

Figure 7. TOPSIS technique representation.

According to the TOPSIS steps shown in Figure 7, respectively, after creating a decision matrix and normalizing it, the best and worst ideal solution can be found. Then, the distance between each factor and the best and worst ideal solution is calculated. The final step is calculating the CC_i and sorting the factors based on their CC_i, from the highest CC_i to the lowest. The results of the TOPSIS method are presented in Figure 8.

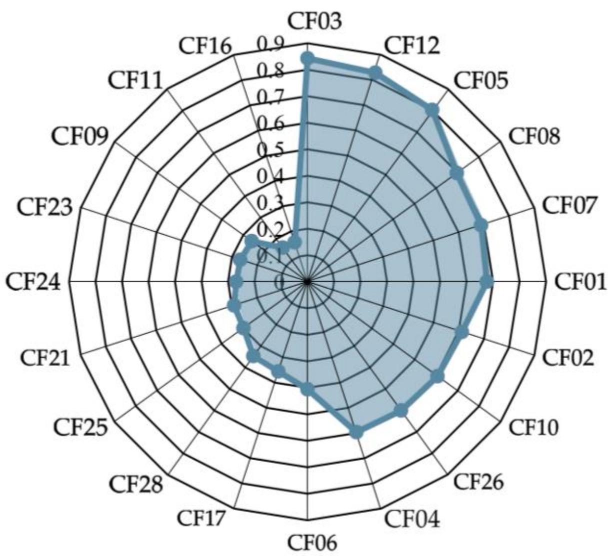

Figure 8. TOPSIS results.

As discussed above, first, a decision matrix is generated. Then, the best and worst ideal solutions will be calculated, after a normalization step, using the equations in Figure 5. As is shown in Table 7, the best and worst ideal solution is calculated separately for each criterion.

Table 7. Obtaining the best and worst ideal solutions.

	De12	De19	De29	De17	De18	De10	De24	De06	De01	De23
Ideal solution	Energy conservation	Environmental compatibility	Security measures	Environment and human health protection during construction	Repairable Structures' reuse	Flexible design of structures	Historical buildings' protection	Efficient and safe design for pedestrians and public transportation	Suitable design for disabled people, the elderly, and children	Open spaces' physical and aesthetic design
+	0.0263	0.0258	0.0258	0.0268	0.0275	0.0275	0.0289	0.0272	0.0308	0.028
−	0.0172	0.0184	0.0184	0.0172	0.0177	0.0163	0.0172	0.0157	0.0159	0.0158

In the next step, first, the distances between the best ideal solution and each constructability factor were calculated. Then, the distance between the worst ideal solution for each constructability factor were calculated separately. The distances were calculated using the equations shown in Figure 6. In the next step, from these distances, the closeness coefficient (CC_i) was calculated for each constructability factor. In calculating the closeness coefficient of the alternatives, Table 8 presents the last step, in which the alternatives are sorted in descending order based on the highest CC_i value. Standard dimension has the highest CC_i, which means in terms of essential design elements in urban renewal designs, the size of the components and materials should be considered in the design phase; the dimensions will be evaluated via BIM in order to check if the dimensions are standard, as defined, or not. The lowest CC_i referred to material accessibility.

Table 8. Ranking of Constructability factors based on the statistical analysis.

CF Code	Constructability Factors	d_i^+	d_i^-	CC_i	Rank
CF03	Standard dimensions	0.006	0.030	0.843	1
CF12	Safety	0.006	0.03	0.829	2
CF05	Simplification of structure	0.007	0.028	0.801	3
CF08	Resource intelligence and alignment	0.010	0.024	0.697	4
CF07	Skilled labor availability	0.011	0.024	0.689	5
CF01	Prefabrication	0.012	0.025	0.677	6
CF02	Grid design	0.014	0.022	0.613	7
CF10	Excavation works	0.015	0.022	0.607	8
CF26	Construction site preparation	0.015	0.022	0.601	9
CF04	Design flexibility	0.014	0.021	0.597	10
CF06	Resource availability	0.021	0.014	0.406	11
CF17	Equipment accessibility	0.023	0.013	0.356	12
CF28	Adjacent sites	0.023	0.012	0.347	13
CF25	Site's impact on infrastructure	0.024	0.010	0.298	14
CF21	Activities' interdependence	0.026	0.011	0.291	15
CF24	Site's impact on structures	0.026	0.010	0.269	16
CF23	Road usability	0.027	0.010	0.267	17
CF09	Construction sequence	0.027	0.010	0.260	18
CF11	Weather effect	0.030	0.006	0.159	19
CF16	Material accessibility	0.030	0.066	0.156	20

Finally, the 10 constructability factors with a CC_i higher than 0.5 are chosen to be analyzed for the urban renewal designs in BIM. The first factor is standard dimensions, which refers to the dimensions of the building's components in terms of reducing labor demand and material size. The second factor is safety, which refers to the creation of a safe working environment. Safety concerns, such as the locations of gas containers and chemical materials, the space between high-voltage power lines and cranes, must be considered. The simplification of structure refers to the complexity degree of the construction design details. A simple structure design has a significant effect on constructability. Resource intelligence and alignment refers to the availability of materials, equipment, and machinery. When resources are not available and constant, time and cost overrun may occur. The construction of some building components might require workers with special skills. If the number of required skilled laborers is high, the constructability of designs will decrease. Prefabrication means that more fabricated components are involved in urban renewal designs, the greater the positive impact on the constructability. A grid design will facilitate faster construction and reduce material waste. Excavation works are often a complex process, which will affect the overall constructability assessment of designs. Construction site preparation includes the availability of government facilities on site, road usability, etc., and saves time and cost. Design flexibility refers to the ability to adapt to any design change. Flexible designs will improve constructability.

5. BIM Conceptual Framework

As was mentioned before, BIM technology can assess the constructability of urban renewal designs. This research proposes a framework using a BIM model for analyzing limited land renewal designs considering constructability factors, as shown in Figure 9. This procedure can be considered the basis for the progress of a BIM-based constructability assessment, to support designers in analyzing design proposals for the renewal of limited lands, at the design stage. At the beginning of any construction project, designers should identify the constructability factors that need to be considered. This consideration relies on unique project characteristics, and the client's requirements should be acknowledged. As a result of this research, 10 constructability factors are presented. Since this paper analyzes the constructability of urban renewal designs, the identification of these factors is based on the features of the selected limited land. along with 10 design elements that should be considered during a renewal process in this area.

In the current study, 30 design elements (De) that should be considered in the renewal of limited lands, and 28 constructability factors (CF) were identified through a literature review. Then, 20 CF, along with 10 De that had the highest scores, were selected using the Delphi method and experts' opinions. Experts rated the CF with the highest capacity to be evaluated via BIM for urban renewal designs. Moreover, the De were ranked based on their importance in creating a more sustainable area during renewal processes in the selected area. MCDM methods were used in two separate stages for analyzing the results of the questionnaire. First, for prioritizing the CF and De, the AHP method was used. Then, using the TOPSIS method, 20 CF were scored according to design elements. As a result, 10 prioritized constructability factors were selected, to be assessed for urban renewal designs in the BIM.

To develop a constructability model in BIM and assess the constructability of designs, it was necessary to define measurements for each of the constructability factors. As shown in Table 9, after specifying a measurement for each factor, an accepted range of 1 (desirable) to 0 (undesirable) was determined. To score the renewal designs, each design will receive a score of 1 or 0 according to each constructability factor. For instance, in the process of assessing CF03, if the columns of a design have more than 15% deviation compared to national standards, it will receive a score of 0. Meanwhile, for 0% deviations, the design would receive a score of 1. At the end of the assessment process, a total number between 0 to 10 will be assigned to the design alternative. In selecting the most constructable design and ranking the alternatives, experts agreed that designs with a score of 7 or more would be approved. On the other hand, design alternatives that achieved 4 or less would not be selected for the renewal project. Design alternatives with a score of 4 to 7 will be referred back to previous stages for changes in design (for example, editing the dimensions of columns, or replacing some materials). Furthermore, the design might be referred back to the construction schedule for changes in the order of activities, or changes in dependencies.

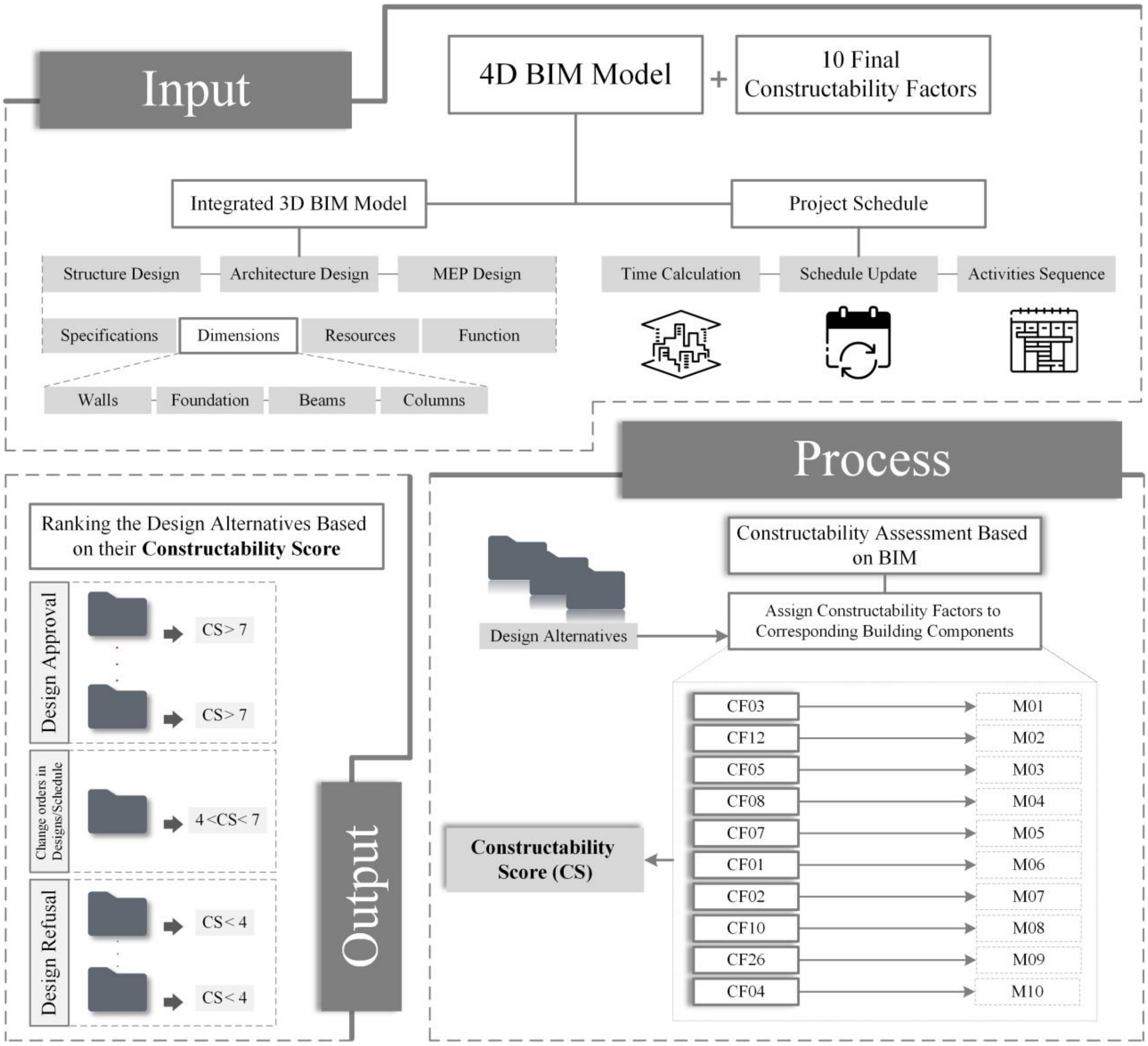

Figure 9. BIM conceptual framework for assessing urban renewal designs considering constructability factors.

Table 9. Assessment measurements for constructability factors.

CF Code	Constructability Factors	Measurement Code	Constructability Measurement	Accepted Range
CF03	Standard dimensions	M01	Comparison of the designed elements with national standards and codes: - Columns - Beams - Bars/joints	0 for more than 15% deviation in comparison with standard tolerances, and 1 for 0% deviation

Table 9. *Cont.*

CF Code	Constructability Factors	Measurement Code	Constructability Measurement	Accepted Range
CF12	Safety	M02	Risk assessment of construction phase based on the prevention-through-design (PtD) method.	0 for more than 15% deviation from targets and 1 for 0% accident probability
CF05	Simplification of structure	M03	The uniformity of the form of columns in all storeys.	0 for more than 3 types of forms/sizes and 1 for completely similar forms/sizes
			The uniformity of the form of bars in all storeys	
			The uniformity of the size of bars in all structures	
CF08	Resource intelligence and alignment	M04	The level of availability of appropriate cranes for lifting the elements (regarding narrowness of passages)	0 for unavailable resources to pass the conditions and 1 for completely conforming resources;
			The level of the moveability of materials and mechanical/ electrical systems to the site	
CF07	Skilled labor availability	M05	The level of required skilled or special laborers for work	0 for more than 3 required special skills at site, and 1 for one required skill
			The level of availability of skilled workers	
CF01	Prefabrication	M06	The level of prefabrication of elements off-site	0 for completely on-site works and 1 for completely prefabricated elements
CF02	Grid design	M07	The extent to which the design follows a modular grids in plan and façade.	0 for more than 3 grid shapes and 1 for completely similar shapes
CF10	Excavation works	M08	The volume of soil removal from the site	0 for designs based on full-site soil removal and 1 for zero volume of soil removal required (e.g., a top-down system)
CF26	Construction site preparation	M09	The level of simplicity and feasibility of preparing the site for construction work	0 for site preparation outside the land, and 1 for layout preparation on-site
CF04	Design flexibility	M10	The possibility of improving or changing the structural elements in the construction phase based on different situations	0 for completely permanent/non-changeable designs and 1 for flexible designs

In Figure 9, a conceptual framework for assessing the constructability of limited lands renewal designs is proposed. This framework ranks design alternatives and identifies the most feasible design for limited lands renewal projects. The input of this framework includes a 3D BIM model and construction time schedules of the design alternatives. Moreover, the identified constructability factors are defined as an input of this framework.

In the first stage, various types of designs will be integrated into one unified 3D model. Then, the construction time schedule will be added to the integrated 3D model.

All factors directly or indirectly have a time effect on the construction process, which subsequently affects the schedule; therefore, a 4D model will be generated, which includes all the essentials for the assessment. Most of the methods of constructing housing in limited lands are almost consistent, and are planned, designed, and carried out within pre-determined frameworks based on the regulations of the client. As a result, the schedule in the BIM system will be changed by the sequence of activities, and will not be impacted by other factors. For example, between two design alternatives based on prefabrication and traditional methods, the factor of construction site preparation affects the timing of the project.

The second stage of the process is based on the assessment of the 4D model based on BIM, and according to the 10 constructability factors: (1) standard dimensions, (2) safety, (3) simplification of structure, (4) resource intelligence and alignment, (5) skilled labor availability, (6) prefabrication, (7) grid design, (8) excavation works, (9) construction site preparation, and (10) design flexibility. As described above, each design alternative will be assessed using the measurements of Table 9 and will receive a score of 1 or 0.

Finally, the ranked design alternatives are the output of the assessment framework. If the model receives an acceptable total score of 7 or more after assigning the constructability factor measurements, the design is approved. If it does not receive an acceptable score, it will be ranked as the least constructable design, and will be rejected. This process assists the project team to select the most appropriate design for the renewal of limited lands, and saves time and costs for the whole construction project.

6. Conclusions

Constructability has been discussed by many researchers since it was introduced. Analyzing the constructability of renewal projects has positive effects on the design's quality, time, and cost. Moreover, it will facilitate the construction process. One of the issues concerning the city of Tehran is its large number of limited lands and lack of a proper assessment method for renewal designs' implementation. To overcome these issues, using constructability as a technique, which minimizes errors, clashes, etc., is proposed in this research. This study attempts to identify the specific constructability factors of the selected area, and proposes a framework for assessing the constructability of alternative designs, based on the measurement of constructability factors, and identifies the most feasible and constructable urban renewal designs. Between the many proposed constructability tools, BIM has proved to be an effective one for examining the ability to construct these designs. As a response to the questions of the study, this paper identified (1) constructability factors and (2) design elements through a literature review. Moreover, through a two-part questionnaire, 20 constructability factors with the highest capacity for assessment via BIM, and 10 design elements that should be considered in limited lands' renewal, were identified. Using the AHP technique, the identified constructability factors and design elements were ranked. Then, the TOPSIS method was used for classifying the best and worst solutions, for identifying the final 10 constructability factors to be inserted into the BIM, and for assessing the renewal designs. The final constructability factors are standard dimensions, safety, simplification of structure, resource intelligence and alignment, skilled labor availability, prefabrication, grid design, excavation works, construction site preparation, and design flexibility. Finally, a constructability assessment procedure using BIM and considering these factors is introduced in this paper. This procedure may be an effective approach to constructability assessment for urban renewal projects, particularly in countries where there is no available solution for these issues during the renewal process, and BIM is considered a new technology. Due to the fact that companies with professions related to renewal projects are fewer in Tehran, the number of eligible respondents was limited. As a result, the number of educated and experienced experts related to the field of urban renewal and BIM; the time and investment needed for adopting BIM during a project and educating BIM experts; and the lack of a BIM legal framework are the limitations of this study. For further research, since this study assesses constructability based on a 4D BIM model, cost estimations are not considered. Therefore, a 5D BIM model should be analyzed, using a constructability analysis. Limited-lands suffer from a lack of proper infrastructure and structural considerations, it is indicated that the proposed assessment process could be carried out for the mentioned considerations.

Author Contributions: Conceptualization, A.F. and E.G.; Methodology, S.H.A. and E.G.; Validation, S.H.A., E.G. and H.S.; Formal analysis, A.F., S.H.A. and P.R.; Investigation, E.G. and H.S.; Resources, E.G.; Data curation, S.H.A. and E.G.; Writing – original draft, S.H.A. and E.G.; Writing—review & editing, A.F., S.H.A. and E.G.; Visualization, S.H.A., E.G. and H.S.; Supervision, A.F. and P.R.; Project administration, A.F. and P.R.; Funding acquisition, E.G. and P.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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