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Author Information:

1) **Full Name:** Taylan TERZIOGLU

Academic position or professional affiliations: PhD Candidate

Last Degree earned: MSc

Name and complete address: Istanbul Technical University, Department of Civil Engineering, Istanbul, Turkey, Tel: (0090) 532 454 1180

E-mail: terzioglu17@itu.edu.tr

ORCID: <https://orcid.org/0000-0003-0950-0899>

2) **Full Name:** Harun TURKOGLU

Academic position or professional affiliations: PhD Candidate

Last Degree earned: MSc

Name and complete address: Istanbul Technical University, Department of Civil Engineering, Istanbul, Turkey, Tel: (0090) 212 285 3737

E-mail: hturkoglu@itu.edu.tr

ORCID: <https://orcid.org/0000-0002-2484-4553>

3) **Full Name:** Gul POLAT

Academic position or professional affiliations: Professor

Last Degree earned: PhD

Name and complete address: Istanbul Technical University, Department of Civil Engineering, Istanbul, Turkey, Tel: (0090) 212 285 3737

E-mail: polatgu@itu.edu.tr

ORCID: <https://orcid.org/0000-0003-2431-033X>

Designated corresponding author:

Full Name: Gul POLAT

Academic position or professional affiliations: Professor

Last Degree earned: PhD

Name and complete address: Istanbul Technical University, Department of Civil Engineering, Istanbul, Turkey, Tel: (0090) 212 285 3737

E-mail: polatgu@itu.edu.tr

ORCID: <https://orcid.org/0000-0003-2431-033X>

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Abstract

Formwork system (FWS) is one of the key components in reinforced concrete (RC) construction. Therefore, selection of the most appropriate FWS plays a critical role in the project success. Since the FWS selection is affected by several compromising and conflicting criteria, numerous studies have been carried out to identify the FWS selection criteria and/or have employed various multi-criteria decision-making (MCDM) methods since the early 1990s. However, there is no research that conducts a critical review of the previous studies addressing the FWS selection criteria in building construction projects. This study aims to fill this knowledge gap. For this purpose, a critical review of the relevant literature was carried out using an integrative approach and the findings were validated through face-to-face interviews with professionals specialized in formwork engineering. The findings of this study may provide practitioners with a useful guide that can assist them in selecting the most appropriate FWS.

Keywords: building construction project, formwork systems, selection criteria, critical review.

1. Introduction

RC is the most commonly used building material in the construction industry (Safa et al. 2016) as it offers greater durability, improved flexibility, longer service life, and cost-effective solutions when compared to other building materials (Hanna 1999; Hawkins et al. 2016). Formwork, rebar, and concrete are the main components of the RC construction (Nawy 2008). The basic activities in RC construction are the erection of formwork, the placement of rebar, the pouring of concrete, the curing of concrete, the stripping of formwork, and the movement of formwork from one location to another (Rogge and Tucker 1987; Nunnally 1993; Song and Liang 2011; Ko and Kuo 2015). Since these activities are repeatedly carried out throughout the construction process of RC structures, formwork affects the time and cost performances of such structures. Formwork may be the largest cost item in RC construction, which can constitute as high as 60% of the unit cost of the RC structure (Nunnally 1993; Hurd 2005; Krawczynska-Piechna 2017) and can account for up to 15% of the total construction cost (Ko et al. 2011). Formwork-related activities may also take 50-75% of the total time spent on the construction of RC structures (Jha 2012). Moreover, quality, safety, and productivity are the other important aspects directly affected by the type of FWS used in RC construction (Peurifoy and Oberlender 1996; Basu and Jha 2016). Consequently, the selection of FWS for a construction project plays a critical role in the overall project success.

FWSs used in building projects are generally classified into two types: horizontal and vertical FWSs (Elbeltagi et al. 2011). While horizontal FWSs are used for the concreting of slabs, vertical FWSs are used for the concreting of columns and walls (Hanna 1999). There are numerous alternatives for both horizontal and vertical FWSs, and each alternative affects the performance of RC construction in a different way. For example, the cost of RC construction can be reduced up to 25% by prioritizing the design of FWSs in building projects (Peurifoy and Oberlender 1996). However, selecting the most appropriate FWS for a construction project is a difficult task for project managers and site managers as it depends on several quantitative and qualitative criteria, some of which are compromising and conflicting. Therefore, researchers treat the FWS selection problem as a MCDM problem (Elazouni et al. 2005; Krawczynska-Piechna 2015; Hansen et al. 2020).

In the literature, the studies that aim to identify the criteria affecting the selection of the FWS to be used in a building construction project have been conducted since the early 1990s. However, some new selection criteria have been added to the relevant literature with the introduction of new technological developments in formwork engineering. Therefore, while some of the FWS criteria are widely accepted and frequently cited, the others are novel and relatively rarely cited in the literature. It should be highlighted that the most-cited criteria do not refer to the most important criteria and the least-cited criteria do not signify the least important criteria. The main objectives of this study include: (1) critically reviewing the studies that address the FWS selection criteria, especially in building construction projects and (2) identifying the most-cited and least-cited criteria, and discussing the main reasons behind these findings. For this purpose, first, a detailed literature review was conducted, and then face-to-face interviews with specialists, who have more than 20 years of experience in the field of formwork engineering, were carried out. Identifying all the potential criteria may assist construction professionals in selecting the most appropriate FWSs during the design phase, which will improve the overall project performance.

2. Literature Review

Several researchers have dealt with the selection process of FWSs in construction projects. The majority of these studies can be categorized into two main groups: (1) identification of the FWS selection criteria (e.g., Hanna et al. 1992; Krawczyńska-Piechna 2016) and (2) application of MCDM methods when solving the FWS selection problem (e.g., Elbeltagi et al. 2012). This study aims to conduct an integrative review of the literature on the identification of FWS selection criteria in building projects. Therefore, the purpose of this literature review is not to summarize all the studies that focused on formwork engineering but to analyze the studies that aim to identify

the FWS selection criteria in building projects and the studies in which MCDM methods are employed to solve the FWS selection problem. Some of these studies will be briefly explained below in chronological order.

First, Hanna (1989) identified 38 factors affecting the selection of horizontal FWSs for building projects in the United States and classified them into four main categories: building design, job specification, local conditions, and supporting organization. Hanna (1989) also developed a knowledge-based guide that explains the relationship between 18 factors affecting the selection of vertical FWSs and five vertical FWS alternatives. Hanna and Sanvido (1990) evaluated the selection process only for vertical FWSs using the factors and FWS alternatives described by Hanna (1989). Then, Hanna et al. (1992) developed a rule-based expert system that assists the formwork designers or decision-makers in selecting the most appropriate horizontal and vertical FWS for building projects based on the factors defined by Hanna (1989). Kamarthi et al. (1992) proposed a Neural Network (NN) model for the vertical FWS selection process using factors and alternatives identified by Hanna (1989). Hanna and Senouci (1995) developed another NN model that deals with the selection of horizontal FWSs using the information and rules presented by Hanna (1989). Hanna (1999) extended the knowledge-based guidelines and factors defined in previous studies to select horizontal and vertical FWSs, including new factors such as labor productivity. Proverbs et al. (1999) determined the importance levels of nine FWS selection factors for the contractors from France, Germany, and the United Kingdom, as well as the relationship between these factors. Proverbs et al.'s (1999) study revealed that while most of the selection factors have similar rankings, some factors' rankings differ from one country to another. Elazouni et al. (2005) estimated the compatibility of new horizontal FWSs using the Analytical Hierarchy Process (AHP) and NN based on the six selection factors that are considered to be the most important in Egypt among the factors identified by Hanna (1989). Tam et al. (2005) demonstrated that probabilistic neural networks (PNNs) combined with genetic algorithms outperform traditional NN models in the FWS selection problem. In these PNN models, four vertical FWSs commonly used in Hong Kong and six FWS selection factors identified by Kamarthi et al. (1992) were used. Shin et al. (2008) proposed AdaBoost and Artificial Neural Network (ANN) models for the selection of horizontal FWSs in high-rise building construction in Korea. In the proposed model, six selection factors and four FWS alternatives were used, and new selection factors such as floor area and number of floors were introduced. Shin (2011) developed Shin's (2008) study by taking into account seven selection factors and five FWS alternatives for solving the same problem. Elbeltagi et al. (2011) and Elbeltagi et al. (2012) developed fuzzy logic systems to select horizontal and vertical FWSs, respectively, using five selection factors determined to be the most important factors in Egypt and introducing new alternatives. Shin

et al. (2012) proposed a boosted decision tree (BDT) model to select horizontal FWSs in high-rise building projects in Korea based on seven selection factors identified in previous studies (i.e., Shin et al. 2008; Shin 2011).

Krawczyńska-Piechna (2015) used Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method for the FWS selection problem using nine criteria identified in the Polish construction industry.

Krawczyńska-Piechna (2015), Krawczyńska-Piechna (2016), and Krawczyńska-Piechna (2017) introduced the criteria, namely flexibility, durability, compatibility, safety, and weight of the FWS to the relevant literature.

Martinez (2016) discussed the applicability of previously used MCDM methods (e.g., AHP, NN, PNNs) for the FWS selection problem and applied the Choice by Advantage (CBA) method. In Martinez's (2016) model, 14 selection factors were used, and new selection factors such as complexity and size of FWS were proposed. Basu and Jha (2016) employed the AHP method to determine the most important selection factors in India. Loganathan and Viswanathan (2016) investigated the effects of using steel and aluminum FWSs in high-rise buildings in India

on the cost, duration, and quality performances of the project. Safa et al. (2016) considered the degree of formwork material recycling and the degree of building information modeling (BIM) applications for FWSs in the United States. Lohana (2018) examined the effects of productivity criteria, which can be evaluated as a function of cost, cycle time, and the degree of repetition of FWS, in the selection process of FWSs in high-rise buildings in India.

Rajeshkumar and Sreevidya (2019) and Rajeshkumar et al. (2021) studied the factors influencing the FWS selection in high-rise buildings in India and identified 40 selection factors grouped into five categories, namely general, structural, formwork, environmental, and cost. In these studies, transportation cost was introduced as a new factor for the selection of FWSs. Pawar et al. (2018) expanded Karke and Kumthekar's (2014) study and determined seven factors for the FWS selection considering three FWS alternatives in the Indian construction industry. Teja et al. (2018) developed a fuzzy logic model for selecting FWSs using 17 selection factors previously identified in India.

In summary, most of the FWS selection criteria that existed in the literature from 1989 to 2012 were based on the studies conducted by Hanna (1989). After 2015, some new criteria affecting the selection of FWSs were identified in the literature because of the widespread use of industrial FWSs in construction projects and technological innovations in formwork engineering. Previous studies mainly focus on identifying the country-specific widely accepted factors and introducing the new factors. However, no study in the literature critically reviews the previous studies and addresses all the FWS selection criteria in building construction projects in a single body of knowledge. This study aims to fill the important knowledge gap and provide a comprehensive guide for researchers and construction professionals involved in the FWS decision-making process.

3. Research Methodology

A literature review can be conducted in different ways, such as systematic, semi-systematic, and integrative. An integrative literature review analyzes, critiques, and synthesizes the literature on a specific research topic to develop new theoretical frameworks and perspectives (Snyder 2019). In order to achieve the objective of this study, an integrative literature review was adopted as a research method. The research methodology of this study consists of four main stages, which are: (1) retrieving and sorting the literature, (2) reporting the relevant studies, and identifying and interpreting the FWS selection criteria, (3) validating the FWS selection criteria, and (4) critically reviewing the relevant literature. The research methodology of this study is presented as a flowchart in Figure 1.

<< Insert Figure 1 >>

Stage 1. Retrieving and sorting literature

In this stage, firstly, the search engines Scopus (Elsevier), Web of Science (ISI), and Google Scholar, which are widely used to retrieve the studies, were selected. Then, keywords such as building construction, formwork criteria, formwork selection criteria, selection of formwork, and FWS selection were searched. The research was limited to fields of study such as FWS, building construction, engineering, management, and decision-making. While analyzing the abstracts of the retrieved studies, their relevance to the research topic was compared. The full texts of studies related to the research topic were reviewed in details, while studies that are not directly related to the research topic were excluded. The scope of this study also includes the most-cited studies on the research topic. A total of 26 studies, consisting of 19 articles, 1 book, 5 conference papers, and 1 Ph.D. dissertation, were selected for further review and analysis¹.

Stage 2. Reporting the relevant studies, and identifying and interpreting the FWS selection criteria

In this stage, the reviewed studies were reported in chronological order in order to identify changes over time and to categorize the FWS selection criteria. In the studies in which the difference between the factors and criteria that affect the selection of the FWS was not clearly stated, some of these factors were interpreted and evaluated as a criterion. At the end of this stage, the number of citations for each defined FWS selection criterion was calculated, thus determining the most-cited and the least-cited criteria.

Stage 3. Validating the FWS selection criteria

¹ Please refer to Table S1 for the list of reviewed sources within the scope of this study and their frequencies.

In this stage, face-to-face interviews accompanied by open-ended questions were conducted with five experts, who have more than 20 years of international experience in formwork engineering, in order to validate the FWS selection criteria determined within the scope of this study. All participants began their careers as formwork design engineers and have international experience in technical aspects. They also have experience in sales and administrative aspects of formwork engineering².

Open-ended question interviews are commonly used in the construction management domain (e.g., Soliman-Junior et al. 2019; Harris and Alves 2019) as it is an effective research method that allows participants to proceed with ideas in any direction they prefer (Seidman 2006). As there are numerous FWS selection criteria and alternatives, open-ended questions without any presumptive answers (Seidman 2006) provided some new insight into FWS selection criteria during the validation stage. The following objectives were pursued while creating the open-ended questions:

- To collect demographic information on the participants;
- To elicit suggestions or recommendations from the participants regarding the FWS selection criteria (e.g., additional criteria) retrieved from the literature;
- To gain more insight on conflicting and interdependent FWS selection criteria;
- To determine whether all of the identified FWS selection criteria are applicable to the FWS selection process.

All of the interviews were video recorded and then analyzed for interpretation. After that, the findings on the FWS selection criteria were presented to the participants, and their feedback was obtained to validate the findings. Finally, the findings were adjusted, if necessary, based on participant feedback.

Stage 4. Critically reviewing the relevant literature

In this stage, a critical review was conducted on the research topic based on the information gathered in the previous stages. A critical review of the relevant studies was carried out from the most-cited FWS selection criteria to the least-cited one. The main reasons why some of the criteria are frequently cited while others are rarely cited are also discussed.

4. Findings and Discussions

Hanna (1989) identified the majority of the criteria affecting FWS selection (i.e., horizontal and vertical FWSs) in the literature. Hanna's (1989) study served as the foundation for subsequent studies on this topic. In the following

² Please refer to Table S2 for the detailed background information about the participants and the description of the interviews conducted.

years, the widespread use of industrial FWSs in construction projects all over the world and new technological developments in formwork engineering have necessitated the inclusion of new criteria in the FWS selection process. In addition, the selection criteria for FWS and their importance levels may differ from one country to another (Proverbs et al. 1999).

One of the objectives of this study is to provide researchers and construction professionals with a comprehensive guide to the criteria that affect FWS selection in building construction projects. An integrative literature review and face-to-face interviews with five experts with more than 20 years of experience in formwork engineering were conducted to achieve this objective. Within the scope of this study, a total of 26 studies that focus on either identifying the criteria affecting the selection of FWSs in building construction projects or applying MCDM methods to solve this problem were thoroughly reviewed, and then 35 FWS selection criteria were determined. 35 criteria were classified under five main categories: structural design, project specifications, local conditions, supporting organization, and FWS characteristics. These criteria and the ID number assigned to each of them are presented in Table 1.

<< Insert Table 1 >>

Most of the studies in the literature (i.e., 22 of 26 studies) discussed the selection criteria either for FWSs in general (i.e., both horizontal and vertical FWSs) or only for horizontal FWSs. In these studies, 33 criteria are identified for both horizontal and vertical FWSs. On the other hand, there are only four studies in the literature (i.e., Hanna and Sanvido 1990; Kamarthi et al. 1992; Tam et al. 2005; Elbeltagi et al. 2012) that only consider the selection criteria for vertical FWSs. The main reason behind this finding is that horizontal FWSs are more important than vertical FWSs in building construction projects, particularly in high-rise ones (Kim et al. 2012). In general, vertical FWSs demand lower floor cycle time since they can be removed earlier than the horizontal FWSs (Love 1973). For instance, according to ACI (2004), walls and columns formwork (i.e., vertical FWS) can be removed after 12 hours, whereas slab formwork (i.e., horizontal FWS) should not be removed earlier than 3 to 21 days depending on the loading conditions and type of structural slab. Moreover, horizontal FWSs may require a greater initial investment and be more labor-intensive when compared to vertical FWS (Al-Tabtabai 2000). In the studies of Hanna and Sanvido (1990), Kamarthi et al. (1992), Tam et al. (2005), and Elbeltagi et al. (2012), two additional selection criteria were determined for only vertical FWSs: variation in column/wall dimensions and location and opening/inserts dimensions and location. Selection criteria for both horizontal and vertical FWSs are presented together in Table 2. Table 2, which is the main basis of this study, also presents the data on the researcher(s), the country examined, and the FWS selection criteria identified for the studies reviewed.

<< Insert Table 2>>

Based on the number of citations (i.e., frequency of citations) of each FWS selection criteria presented in Table 2, the mean value ($\mu = 9.17$) and the standard deviation ($\sigma = 5.60$) of the number of citations were determined. The most cited and the least cited FWS selection criteria were identified according to the upper and lower cut-off points, i.e., $\mu + \sigma$ and $\mu - \sigma$, respectively. The distribution graph of the FWS selection criteria based on number of citations, as well as the cut-off points are presented in Figure 2.

<< Insert Figure 2 >>

As illustrated in Figure 2, seven FWS selection criteria are above the upper cut-off point, while five FWS selection criteria are below the lower cut-off point. Thus, the following results can be interpreted:

- The seven most-cited FWS selection criteria in building construction projects around the world are “speed of construction”, “type of concrete finish”, “initial cost of FWS”, “type of structural slab”, “type of lateral loads supporting system”, “uniformity of building”, and “logistical support from formwork supplier”.
- The five least-cited FWS selection criteria in building construction projects around the world are “degree of BIM applications in formwork engineering”, “maximum size of formwork panels”, “complexity of FWS”, “transportation cost”, and “compatibility of FWS”.

The most-cited FWS selection criteria appeared in the literature from 1989 until 2021, while the least-cited FWS selection criteria appeared in the literature from 2015 until 2021³. The constructability of a RC construction project is mainly affected by the structural design of the building and the selected FWS (Fischer and Tatum 1997). Thus, the appearance of some of the structural design criteria (e.g., “type of structural slab” (ID 1), “type of structural lateral loads-supporting system” (ID 2), and “uniformity of building” (ID 10)) under the most-cited category is to be expected. The constructability can be improved by reevaluating the structural design of the building based on the available FWS sizes and dimensions, which may reduce the total unit cost of the RC structure (Peurifoy and Oberlender 1996). Moreover, “speed of construction” (ID 12) and “initial cost of FWS” (ID 18) are the criteria that may have a significant impact on the time and cost performance of the RC construction project (Safa et al. 2016; Rajeshkumar et al. 2021). Therefore, these criteria are widely accepted by researchers and practitioners and are used in MCDM problems for selecting the most appropriate FWS.

All of the least-cited FWS selection criteria have only recently been reported in the literature. Most of these criteria are under the FWS characteristics category (see Table 1). The extensive usage of different types of industrial FWSs

³ Please refer to Table S3 for the years of publication of the identified seven most-cited and five least-cited FWS selection criteria.

with varying FWS characteristics, as well as technological advancements and new trends towards prefabrication of formwork (Jha and Sinha 2014), have required the addition of certain new criteria to the FWS selection problem. For instance, as BIM becomes more widely used in the construction sector, its application and popularity are likely to increase in formwork engineering (Kannan and Santhi 2018). Hence, “degree of BIM applications in formwork engineering” should be considered an important criterion in the FWS selection problem. In general, the least-cited criteria should be regarded as recently introduced criteria rather than unimportant, and they are likely to be used more frequently in the FWS selection problem in the future.

Following the evaluation of the FWS selection criteria, the relevant literature was also critically reviewed, starting with the most-cited FWS selection criteria and progressing to the least-cited. The results of the integrative review of the relevant literature are presented below.

Speed of construction

Speed of construction is the most common criterion that is cited in 24 out of 26 reviewed studies. The speed of construction is dependent mainly on the floor cycle time (Hanna 1999), which can be determined by the erecting and stripping time of FWS, placing and curing time of concrete, and moving time of FWS to the next location. While the erecting, stripping, and moving times of the FWS depend on the characteristics of the selected FWS and available labor force (Kannan and Santhi 2018), the curing time of the concrete depends on the type of concrete mixture, required concrete strength, size and shape of the structural member, temperature, availability of chemical admixtures, weather conditions, and other concrete-related factors (ACI 2008). FWS should generally be selected according to the desired floor cycle time desired to match the project schedule. Therefore, this criterion can be observed in almost all studies in the relevant literature.

Type of concrete finish, and initial cost of FWS

Type of concrete finish and initial cost of FWS were cited in 18 out of 26 reviewed studies. Type of concrete finish, which reflects the desired concrete surface quality in the project, is an important part of the project specifications. For example, architectural concrete finish and exposed concrete finish require special considerations in the design of FWS and the selection of materials for the FWS (Peurifoy and Oberlender 1996; Hurd 2005). Therefore, this criterion should be taken into account when selecting the most appropriate FWS based on the project specifications.

Initial cost of the FWS refers only to the cost of purchasing or renting the FWS. Shin et al. (2008), Shin (2011), Shin et al. (2012) did not take into account the initial cost of the FWS, as they only used the criteria under the structural design category and speed of construction criterion in their research. Similarly, Martinez et al. (2016)

took into account criteria that are mostly dependent on the FWS characteristics, except for the cost of FWSs. Tam et al. (2005) also considered the FWS selection criteria identified by Hanna (1989), excluding the cost criteria. However, this criterion can be an important criterion in the selection process since FWS is a major cost item in RC construction (Ko et al. 2011; Krawczyńska-Piechna 2017).

Type of structural slab, type of lateral loads supporting system, uniformity of building, and logistical support from formwork supplier

Type of structural slab, type of lateral loads supporting system, uniformity of building, and logistical support from formwork supplier were identified in 15 out of 26 studies reviewed. Type of structural slab, type of lateral loads supporting systems, and uniformity of building are among the most important criteria for the selection of FWS under the structural design category. In general, from 1989 to 2021, at least one of the criteria under the structural design category was taken into account in the FWS selection problem in all countries, with the exception of Poland (i.e., Krawczyńska-Piechna 2015; Krawczyńska-Piechna 2016; Krawczyńska-Piechna 2017). The main reason behind this finding may be that the researchers addressed the flexibility criteria of FWS, which essentially determine how well the FWS can adapt to different sizes and shapes of the building's structural design. Nowadays, most industrial FWSs are manufactured as modular and standard elements that can be adapted to different building dimensions (Kannan and Santhi 2013).

Uniformity of building can be classified as building horizontal uniformity (e.g., same size and location of slabs, beams, and cantilevers), building vertical uniformity (e.g., same size and location of columns and walls), and building floor-to-floor height uniformity (e.g., same floor-to-floor heights). In other words, uniformity of building refers to the degree of repetition of the same layouts within the building. The uniformity of the building affects the selection of FWSs for building construction projects, as some FWSs are more difficult to adapt to major changes in the structural design of the building than others. Therefore, uniformity of building is an interdependent criterion with the degree of repetition and flexibility of the FWS. In addition, uniformity of building was mostly cited from 1989 to 2012, but rarely in later years. The main reason behind this finding may be that the widespread use of more flexible FWSs (i.e., industrial) worldwide with technological developments in formwork engineering.

Hanna (1999) stated that a local or regional yard facility influences the selection of FWS as some FWSs can be manufactured and assembled before being delivered to the construction site under effective supervision. In this case, the local logistical support from the formwork supplier can overcome this problem. In addition, local logistical support from the formwork supplier can reduce delivery lead time and save transportation cost (Terzioglu et al. 2019). This criterion is especially important in countries where FWSs need to be imported from abroad and

over long distances. However, this criterion was not taken into account in some studies (e.g., Elbeltagi et al. 2011; Elbeltagi et al. 2012) as it was considered less effective than others.

Total building height, and in-house capability

Total building height and in-house capability were cited in 14 out of 26 studies reviewed. Total building height can be classified into three groups as low-rise, mid-rise, and high-rise (Kamarthi et al. 1992). Some FWSs, such as crane-independent self-climbing formwork (i.e., hydraulic climbing systems), can provide better time and cost performance in high-rise buildings but may not be feasible for low-rise or mid-rise buildings (Abou Ibrahim and Hamzeh 2015). Therefore, the total building height is a criterion considered in the selection of FWSs in almost all countries except Ecuador and Poland. The main reason behind this finding may be that high-rise buildings are not common in these countries, or there is not much difference in average building heights.

In-house capability can be defined as the degree of experience with the selected FWS and the availability of in-house engineering control. This criterion may be important when there is a lack of technical support from the formwork supplier, or the selected FWS is unfamiliar to the laborers. In either case, this problem can be solved by supplying flexible, compatible, and simple FWSs that are easily learned and adapted by available laborers and engineers. In-house capability is identified in the same context as “home office support” by Hanna (1989) and has been considered in the selection of FWS in almost all countries except Korea and Hong Kong. As a result, this criterion is a decisive criterion in the selection of FWSs since it was taken into account in studies in all other countries from 1989 to 2018.

Degree of repetition of FWS, site access, and labor cost

Degree of repetition of FWS, site access, and labor cost were cited in 13 out of 26 reviewed studies. The degree of repetition of the FWS is determined partly by the structural design of the building. If the sizes and shapes of the structural elements of the building structure are irregular, a high degree of repetition of the FWS may be difficult. Additionally, if the FWS’s durability is insufficient to achieve the desired degree of repetition of the FWS, the FWS should be replaced. As a result, this criterion is regarded as an important one in the selection of FWS in the literature from 1989 to 2021 as it can affect both the cost and the duration of the project.

The availability of adequate site access is determined by site characteristics, which can be classified as restricted or unrestricted (Hanna 1999). Some FWSs may be large enough to be pre-assembled and transported to the construction site, while others may require a local assembly area. This criterion was considered in the selection of FWS in 7 out of 10 countries except for Korea, Poland, and Ecuador. Site access can also be considered an interdependent criterion with the size of the site as identified in the majority of studies in the literature.

Labor cost is related to the striking, stripping, and handling cost of the FWS. Traditional FWSs may have higher labor costs than industrial FWSs because their construction speed (e.g., erecting and stripping times) is slower. In addition, traditional FWSs may not be a cost-effective solution in terms of labor cost for large-scale construction projects since traditional FWSs require more labor force, which leads to an increase in total project cost. This criterion was taken into account in the FWS selection problem in only the USA, India, and Egypt from 1989 to 2021. The main reason behind this finding may be that only the initial cost of the FWS is addressed, while other cost criteria are neglected.

Labor quality, potential reuse of FWSs in other projects, weather conditions, floor-to-floor height, and hoisting equipment

Labor quality, potential reuse of FWSs in other projects, weather conditions, floor-to-floor height, and hoisting equipment were cited in 10-12 out of 26 studies reviewed. Labor quality can be classified as the availability of local skilled and unskilled laborers (Hanna and Senouci 1995). In countries with expensive but unskilled labor, the use of industrial FWSs can reduce overall labor costs without the need for skilled labor (Hanna 1999; Huang et al. 2004) as these FWSs are usually less complex and can be learned in less time than others. In some studies where this criterion was not cited (i.e., Krawczyńska-Piechna 2015; Krawczyńska-Piechna 2016; Krawczyńska-Piechna 2017), in-house capability (i.e., labor experience with the FWSs) was identified as a FWS selection criterion that could compensate for the lack of availability of local skilled labor.

Potential reuse of the FWS in other projects is an important criterion for FWS selection. If the selected FWS can be modified and reused in future projects, investment in FWSs can be reduced for a long time. Although this criterion was considered in the FWS selection from 1989 to 2018, it was disregarded in many countries. The main reason behind this finding may be that the existence of similar criteria to this criterion, such as flexibility and compatibility of FWSs.

Weather conditions include variables such as hot and cold outdoor temperatures and local wind speeds. These variables directly impact the FWS selection process since some FWS materials are less resistant to certain extreme cold or hot temperatures than others. In addition, the interviews conducted within the scope of this study revealed that special equipment easily installed on the FWS should be used to prevent the concrete from freezing in some regions where cold weather prevails. Wind speed should also be taken into account in the selection of FWS, especially in high-rise building projects, where it may be a critical factor (Gnida 2010).

Floor-to-floor height, which determines the height of the FWS, is a criterion defined under the structural design category. Most of the studies that did not cite this criterion took into account other criteria related to this criterion when selecting FWS, such as total building height, number of floors, degree of repetition of the FWS, and uniformity of building.

Hoisting equipment can be defined as the availability of sufficient crane capacity and crane time involvement if the FWS requires it. This criterion was mostly cited from 1989 to 2011 but occasionally in later years. The main reason behind this finding may be that new technological innovations in formwork engineering (e.g., the introduction of lightweight FWS, advancements in self-climbing FWS) often remove the need for hoisting equipment (Kanan and Santhi 2013; Martinez et al. 2016).

Labor productivity, floor area, and number of floors

Labor productivity, floor area, and number of floors were cited in 5-6 of the 26 studies reviewed. Labor productivity, first introduced by Hanna (1999), has a significant impact on the FWS selection problem since it may vary in different FWS alternatives (Smith and Hanna 1993). Traditional FWSs generally have lower labor productivity rates than industrial FWSs, as industrial FWSs are more flexible and easier to use. In addition, labor productivity can be measured as a function of cost, cycle time, and the degree of repetition of the FWS (Lohana 2018). Jarkas (2010) also stated that labor productivity could be affected by the uniformity of the building, floor area, and panel sizes of the FWS.

Number of floors is cited in the relevant literature between 2011 and 2021. Most previous studies used total building height and floor-to-floor height as the FWS selection criterion rather than the number of floors, as these criteria are interdependent in building construction projects with uniform building height. However, a building construction project can be designed without a relationship between the number of floors and the total building height and floor-to-floor height. Therefore, the number of floors should be considered an independent criterion when selecting FWS for building construction projects with a large variation in floor-to-floor height. Moreover, as there are different floor cycle times for different FWS alternatives, the number of floors may affect the total duration of the building construction project.

Technical support from the formwork supplier, maintenance cost, and transportation cost

Technical support from the formwork supplier, maintenance cost, and transportation cost are recently introduced criteria for the selection of FWS in the literature. Technical support usually refers to the engineering services (e.g., FWS calculations, FWS design drawings, FWS planning, training programs, engineering supervision, instructions for use, and handling documents for FWSs) provided by the formwork supplier. The increase in the number of

formwork suppliers, the widespread use of industrial FWSs, and the high level of competition among formwork suppliers contribute to a greater demand for these services among contractors.

Maintenance cost is associated with the cleaning, repairing, and storing of FWS. In some cases where the FWS components are handled poorly, the selected FWS is not durable, or large storage areas are required for the FWS, the maintenance cost of the FWS can be relatively higher. This criterion was only cited in studies carried out in India after 2016. The main reason behind this finding may be that the importance of maintenance cost is much lower than that of the other FWS selection criteria (Teja et al. 2018; Rajeshkumar et al. 2021).

Transportation cost of a FWS is an important criterion, particularly in developing countries where FWSs must be imported from other countries. In addition, the transportation cost of a FWS is directly related to both the size and weight of the FWS because the components of the FWS are packaged, then transported in trucks or containers. Local laws and regulations determine the maximum allowable weight and volume of a truck or container. Therefore, modular lightweight FWSs (e.g., FWSs with plastic or aluminum material components) may be more cost-effective in terms of transportation cost than traditional FWSs.

Sustainability, safety, durability, flexibility, compatibility, complexity, size, weight, and BIM

Sustainability, safety, durability, flexibility, compatibility, complexity, size, weight, and BIM have been identified as new criteria in the studies from 2015 to 2021 in the relevant literature. Some of these criteria (e.g., flexibility, compatibility) are linked to structural design criteria and determine the effectiveness of the performance of FWSs. In the light of the interviews conducted within the scope of this study, the criteria under the structural design category, in general, should not be discussed separately from the FWS characteristics as in some previous studies. Newly developed industrial FWSs have strengths for some criteria and weaknesses for others and should therefore be considered in future studies that will focus on the selection of FWS.

In recent years, sustainability has become an important criterion in building construction since material waste is common in RC construction (Rosenbaum et al. 2014; Vilventhan et al. 2019). In addition, since formwork is an essential component of RC construction supply chain, the sustainability of the FWS should be considered as an important criterion, especially in green building construction projects. The sustainability criterion in the selection of FWSs may depend on the type of material used in the FWS, the recyclable potential of the FWS, and the carbon footprint of the material used in the FWS. For example, traditional FWSs have lower sustainability performance than industrial FWSs (Al-ashwal et al. 2017) as they generate more waste (Karke and Kumathekar 2014).

The construction of the FWS has a high degree of construction accidents and poses a high risk for construction workers (Hallowell and Gambatese 2009). Therefore, safety is one of the most important criteria to be considered in the selection of FWS. In the context of this study, the safety criterion refers to built-in formwork safety systems without the need for additional manual safety precautions such as walking platforms for workers or ladders included in the FWS. These innovations are now required, rather than a criterion, for the selection of FWS due to strict safety regulations enacted in many countries.

BIM criterion is evaluated as the degree to which BIM applications can be applied in formwork engineering (Safa et al. 2016). This criterion was taken into account only once in the selection of the FWS. BIM applications can be used to evaluate the constructability of different FWS alternatives in order to improve the cost, time quality, safety, and sustainability performance of construction projects (Kannan and Santhi 2013). In addition, considering BIM applications and constructability knowledge in the selection of FWSs can improve project performance in RC construction projects (Jiang et al. 2014). As BIM becomes more common in the construction industry day by day, its use in formwork engineering is expected to become more popular in the future (Kannan and Santhi 2018).

5. Conclusions

In RC construction, formwork is one of the most critical components that may have a significant impact on the cost, time, quality, safety, and sustainability performance of a project. Since the early 1990s, there have been numerous studies in the literature that have determined the FWS selection criteria or used these criteria in decision-making methods to select the most appropriate FWS for a building construction project. In recent years, the widespread use of industrial FWSs, as well as technological innovations in formwork engineering, have necessitated the inclusion of some new criteria in the FWS selection problem (e.g., sustainability, safety, BIM). Although several studies have been conducted on this topic in the literature, FWS selection criteria have not been reviewed and analyzed in a systematic approach. This study aims to fill the knowledge gap by providing a comprehensive guide, which encompasses all the FWS selection criteria in building construction projects identified in previous studies. For this purpose, first, a detailed literature review was conducted, and then a critical review of the literature was carried out, supported by face-to-face interviews with specialists with more than 20 years of experience in the field of formwork engineering to verify the FWS selection criteria.

Within the scope of this study, a total of 26 studies were thoroughly reviewed, and then 35 FWS selection criteria were determined. These 35 criteria are classified into five main categories: structural design, project specifications, local conditions, supporting organization, and FWS characteristics. The findings of this study indicated that “speed of construction”, “type of concrete finish”, and “initial cost of FWS” were the most-cited FWS selection criteria

in building construction projects around the world. On the other hand, “degree of BIM applications in formwork engineering”, “maximum size of formwork panels”, and “complexity of FWS” were the least-cited FWS selection criteria in the literature. According to the interviews, the majority of the FWS selection criteria under the structural design and FWS characteristics categories are interdependent. Therefore, these criteria should not be considered separately in the FWS selection problem. Although new FWS selection criteria such as “safety”, “sustainability of FWS” and “degree of BIM applications in formwork engineering” are less-cited in the literature, these criteria should be considered in the FWS selection problem in order to improve the performance and constructability of construction projects.

Previous studies have concentrated on country-specific, widely known, and/or recently introduced FWS selection criteria. However, no study critically analyzes the studies through an integrative approach while addressing all of the FWS selection criteria as a single comprehensive guide. Therefore, the findings of this study provide a comprehensive guide on FWS selection criteria in building construction projects to help construction professionals and practitioners (e.g., formwork designers) in selecting the most appropriate FWS for their projects. Consideration of all potential FWS selection criteria determined in this study during the design phase of building construction projects (i.e., structural design and FWS design) can also improve constructability and overall project performance. Furthermore, these criteria can be used in MCDM methods to solve the FWS selection problem for building construction projects.

This study is limited only to the FWS selection criteria for building construction projects. In future studies, FWS selection criteria for different types of construction projects (e.g., infrastructure, industrial) can be identified, and validations and/or comparisons with the findings of this study can be made. In addition, interviews conducted in this study revealed that some of the structural design criteria are interdependent with the criteria under the FWS characteristics category. As a result, the quantitative relationships and interdependencies among these criteria can be determined in future studies.

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List of figure captions:

Figure 1. Flowchart of the research methodology.

Figure 2. Distribution graph of the FWS selection criteria and the cut-off points.

Tables:**Table 1.** FWS selection criteria in building construction projects and their ID numbers.

Category name	Main criteria	Sub-criteria	ID numbers
Structural design	Type of structural system	Type of structural slab	1
		Type of structural lateral loads-supporting system	2
	Building dimensions	Total building height	3
		Variation in column/wall dimensions and location	4
		Variation in openings/inserts dimensions and location	5
		Degree of repetition of FWS	6
		Number of floors	7
		Floor area	8
		Floor to floor height	9
	Uniformity of building	-	10
Project specification	Type of concrete finish	-	11
	Speed of construction	-	12
Local conditions	Area practice	Labor quality	13
		Labor productivity	14
	Weather conditions	-	15
	Site characteristics	Site access	16
		Size of site	17
Supporting organization	Cost	Initial cost of formwork	18
		Transportation cost	19
		Maintenance cost	20
		Potential reuse of FWS in other projects	21
		Labor cost	22
	Hoisting equipment	-	23
	In-house capability	-	24
	Formwork supplier support	Technical support	25
		Logistical support	26
FWS characteristics	Sustainability	-	27
	Safety	-	28
	Durability	-	29
	Flexibility	-	30
	Compatibility	-	31
	Complexity	-	32
	Size	-	33
	Weight	-	34
	BIM	-	35

Table 2. The data on the researcher(s), the country examined, and the FWS selection criteria identified for the studies reviewed.

Researcher(s)	Country	FSW selection criteria ID numbers																																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	
Hanna, 1989	USA	*	*	*	*	*	*			*	*	*	*	*		*	*	*	*			*	*	*	*		*										
Hanna and Sanvido, 1990	USA		*	*	*	*	*					*	*	*		*	*	*					*	*	*	*		*									
Hanna et al., 1992	USA	*	*	*	*	*	*			*	*	*	*	*		*	*	*	*			*	*	*	*	*		*									
Kamarthi et al., 1992	USA		*	*							*	*					*								*												
Hanna and Senouci, 1995	USA	*								*	*		*	*				*				*		*	*	*		*									
Hanna, 1999	USA	*	*	*	*	*				*	*	*	*	*	*	*	*	*	*			*	*	*	*	*		*									
Proverbs et al., 1999	France, Germany, UK	*	*	*			*			*	*	*	*	*			*		*						*		*										
Elazouni et al., 2005	Egypt	*	*	*						*	*	*	*	*		*	*	*	*			*	*	*	*	*		*									
Tam et al., 2005	Hong Kong		*	*							*	*					*							*													
Shin et al., 2008	Korea	*		*				*	*	*		*																									
Elbeltagi et al., 2011	Egypt	*										*	*						*			*	*	*													
Shin, 2011	Korea	*		*			*	*	*		*		*																								
Shin et al., 2012	Korea	*		*			*	*	*		*		*																								
Elbeltagi et al., 2012	Egypt		*							*	*		*					*																			
Krawczynska-Piechna, 2015	Poland											*	*					*						*		*		*	*	*	*			*		*	
Safa et al., 2016	USA						*					*	*		*			*			*	*	*	*	*		*	*		*						*	
Martinez et al., 2016	Ecuador						*					*	*											*	*				*	*		*	*	*		*	
Basu and Jha, 2016	India	*	*	*			*	*	*		*	*	*	*		*	*	*	*			*	*	*	*	*		*									
Krawczynska-Piechna, 2016	Poland											*	*					*					*		*		*		*	*	*			*		*	
Loganathan and Viswanathan, 2016	India	*	*									*	*	*	*	*	*	*	*		*	*	*	*		*	*	*		*		*					
Krawczynska-Piechna, 2017	Poland											*	*					*					*		*		*		*	*	*	*			*		
Lohana, 2018	India						*						*					*					*														
Pawar et al., 2018	India						*					*	*	*				*							*		*		*								
Teja et al., 2018	India	*	*							*	*	*	*	*	*	*	*	*	*		*	*	*	*	*	*		*									
Rajeshkumar and Sreevidya, 2019	India	*	*	*			*	*	*	*			*			*	*		*	*	*		*			*	*	*	*	*	*	*			*		
Rajeshkumar et al., 2021	India	*	*	*			*	*	*	*	*	*	*		*	*	*		*	*	*		*			*	*	*	*	*	*	*			*		
Total number of citations		15	15	14	4	4	13	5	6	11	15	18	24	12	5	10	13	7	18	2	4	10	13	11	14	4	15	4	8	6	8	3	2	1	6	1	