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Formwork System Selection Criteria for Building Construction Projects: A Structural Equation Modelling Approach

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Abstract: Selecting the appropriate formwork system (FWS) is a critical aspect in the successful completion of reinforced concrete (RC) building construction projects. The selected FWS has a significant impact on the cost, time, and quality performances of the project. As there are many FWSs and formwork fabricators (FWFs) available, the selection of the FWS depends on several compromising and conflicting criteria. This study aims to identify the FWS selection criteria groupings (e.g., latent factors) and investigate the quantitative interrelationships among them. For this purpose, 35 FWS selection criteria were identified through literature review, and a questionnaire was developed. The data from the questionnaire were statistically analyzed, and five latent factors were identified: FWS-FWF characteristics, structural design, local conditions, cost, and performance indicators. A conceptual framework was developed based on the latent factors, and a structural equation modelling (SEM) approach was utilized to identify the effects among the latent factors. The results of the SEM approach confirmed that FWS-FWF characteristics are affected by the structural design and local conditions and FWS-FWF characteristics have a substantial effect on cost and the performance indicators of the project. The findings of this study may assist construction professionals in selecting the FWS in building construction projects.

Keywords: building construction project; formwork systems; selection criteria; structural equation modelling

Citation: Terzioglu, T.; Polat, G.; Turkoglu, H. Formwork System Selection Criteria for Building Construction Projects: A Structural Equation Modelling Approach. *Buildings* **2022**, *12*, 204. https://doi.org/10.3390/buildings12020204

Academic Editor: Carlos Oliveira Cruz

Received: 10 January 2022
Accepted: 8 February 2022
Published: 11 February 2022

1. Introduction

In RC construction, cast in situ concrete is the most commonly used structural material in the world, including in Turkey [1], since it offers more flexibility, ease of handling, and cost-effective solutions when compared to other materials [2]. In addition, the cost of implementing labour intensive building methods, such as cast in situ concrete, in Turkey may be significantly less than the cost of introducing modern technology, such as precast concrete systems [3]. RC construction consists of three main elements: formwork, rebar, and cast in situ concrete [4]. The FWS provides the geometry and strength that concrete demands to obtain the shape and the structural design properties of the cured concrete [5]. In addition, FWSs have a significant impact on the time and cost performance of RC structures since formwork activities are performed continuously throughout the construction process [6]. Indeed, the FWS can account for up to two-thirds of the total cost of the RC structural frame [7] and it can have a major impact on the total duration of the project as the FWS affects the floor cycle time of building construction projects [8]. Therefore, selecting the most appropriate FWS can reduce project cost and time [9].

The FWS can be selected based on a number of compromising and conflicting criteria, most of which are interrelated and interdependent [10]. Thus, there may be quantitative relationships among them. The quantitative relationships between these FWS selection criteria groupings may indicate some critical effects. For example, the FWS selected based on the FWS selection criteria and its effects on the project time, cost, and quality performances can be studied quantitatively by considering the relationships among FWS selection criteria groupings. According to some studies, the FWS design and selection are mainly affected by the structural design criteria of the building construction project, e.g., [11,12]. Therefore, the structural design may also affect the project performance.

Although previous studies greatly contribute to the FWS selection problem, they do not provide insight on the quantitative effects between FWS selection criteria groupings. Therefore, the main objectives of this study are to identify the FWS selection criteria groupings quantitively and to investigate the effects among them. For this purpose, first, a questionnaire is developed; then, the data from the questionnaire is analyzed using statistical methods to identify the FWS selection criteria groupings. Finally, a SEM approach, which is used to investigate relationships among latent factors [13], is utilized to determine and quantify the effects among the identified groupings.

This study is considered to provide a substantial contribution to the body of knowledge regarding FWS selection criteria and is intended to serve as a guide for construction professionals who are involved in the FWS decision-making process. Since formwork related activities and the selected FWS affects the time, cost, quality, and safety of a building construction project [14], the findings of this study can be used to improve these project performance factors.

2. Literature Review

Previous studies have identified that a variety of quantitative and qualitative criteria may affect the selection of FWSs in building construction projects. While most of them have focused on identifying and/or ranking the FWS selection criteria, e.g., [15–17], the others have applied multi-criteria decision-making (MCDM) methods to solve the FWS selection problem, which is affected by several compromising and conflicting criteria, e.g., [8,18,19]. Some of these studies are summarized as follows.

2.1. Studies Related to the Identification and/or Ranking of FWS Selection Criteria

Hanna [15] identified 38 factors influencing the selection of FWSs for building construction projects in the United States and categorized them into four groups based on expert opinion: building design, job specification, local conditions, and supporting organization. Hanna and Sanvido [20] investigated the selection process for vertical FWSs utilizing the factors and FWS alternatives identified by Hanna [15]. The study by Hanna et al. [16] proposed a rule-based expert system to guide decision makers in selecting the most suitable FWS for building construction projects. In an expanded version of the previously developed rules and guidelines for selecting FWSs, Hanna [17] incorporated additional factors, such as labour productivity to the relevant literature. Proverbs et al. [21] analyzed the importance levels of nine factors affecting FWS selection and the degree of association between each selection factor for contractors from the UK, France, and Germany.

Most of the studies on the FWS selection problem from 1989 until 2012 considered the FWS selection criteria under the four main groups identified by Hanna [15]. The widespread use of industrial FWSs in building construction projects across the world, as well as new technological advancements in formwork engineering [22,23], necessitated the inclusion of additional criteria in the FWS selection process in the following years. For instance, Krawczyska-Piechna [24] and Krawczyska-Piechna [25] contributed to the relevant literature by introducing criteria, such as flexibility, durability, compatibility, safety, and weight of the FWS for building construction projects in Poland. Loganathan and Viswanathan [26] investigated how FWS alternatives affect the cost, time, and quality performance of building construction projects in India. In addition to the factors identified in the literature for the FWS selection problem, Safa et al. [5] included the degree of formwork material recycling and the degree of building information modelling (BIM) applications for FWSs in the United States. Most of these newly introduced criteria may be classified under a new category, namely, FWS characteristics, as they describe the different properties of the selected FWS. Pawar et al. [27] identified seven FWS selection factors in the Indian construction industry and determined their relative importance based on three FWS alternatives. Teja et al. [28] first determined the relative importance level of 17 factors affecting FWS selection. Then, Teja et al. [28] proposed a fuzzy rule-based system for the selection of FWSs using five selection factors and six FWS alternatives commonly used in India. Lohana [29] demonstrated that the productivity criteria for the selection of FWSs in building construction projects can be measured as a function of cost, cycle time, and the degree of repetition of FWS. Rajeshkumar and Sreevidya [30] and Rajeshkumar et al. [31] investigated the criteria influencing FWS selection in high-rise buildings in India by determining their relative importance level and grouped 40 selection criteria into five categories by utilizing factors analysis. In addition, transportation costs were added as a new criterion for selecting FWSs. These studies, however, did not analyse the relationships between the FWS selection criteria groupings.

Terzioglu et al. [10] conducted a critical review of the literature on FWS selection criteria for building construction projects, identified 35 FWS selection criteria in total, and revealed that some of the structural design criteria are interdependent with the criteria under the FWS characteristics category. Based on Terzioglu et al.'s [10] study, Terzioglu et al. [32] ranked the previously identified FWS selection criteria in the Turkish building construction sector using mean score analysis. In addition, Terzioglu et al. [32] compared the perspectives and perceptions of Turkish construction professionals utilizing statistical tests and determined the agreements and disagreements regarding FWS selection criteria among different groups of respondents.

2.2. Studies Related to the Application of MCDM Methods for the FWS Selection Problem

Kamarthi et al. [33] and Hanna and Senouci [34] developed neural network (NN) models for the vertical and horizontal FWSs selection processes, respectively, using factors and FWS alternatives identified by Hanna [15]. Tam et al. [35] and Shin [36] developed a probabilistic NN model and an artificial NN model, respectively, based on prior NN models and FWS selection factors, e.g., [33], used for the FWS selection problem. Some new FWS selection factors for building construction projects, such as floor area and number of floors, were introduced into the relevant literature. Elbeltagi et al. [9] and Elbeltagi et al. [37] proposed fuzzy logic models to select horizontal and vertical FWSs, respectively, based on five FWS selection factors determined to be the most significant in Egypt. Shin et al. [8] developed a boosted decision tree (BDT) model to select horizontal FWSs in building construction projects using the seven most significant selection factors reported by Shin [36] in Korea. Krawczyska-Piechna [38] employed the technique for order of preference by similarity to ideal solution (TOPSIS) method to select the most appropriate FWS utilizing nine criteria determined in the Polish construction sector. Martinez et al. [39] applied the choosing by advantages (CBA) method using 14 selection factors for the FWS selection problem in Ecuador, while additional FWS selection factors including FWS complexity and FWS size were added to the literature. Basu and Jha [18] performed factor analysis to group the FWS selection criteria identified by Hanna et al. [16] using analytical hierarchy process (AHP) to identify the most important FWS selection criteria groupings in India. Similarly, Hansen et al. [19] used AHP to select the most appropriate FWS based on eight FWS selection criteria determined to be the most important in the Indonesian building construction sector.

In summary, some studies identified and/or ranked FWS selection criteria, while others solved the FWS selection problem using MCDM methods. However, no study has identified the quantitative effects among FWS selection criteria groupings. Terzioglu et al. [32] suggested performing factor analysis and SEM technique on FWS selection criteria, which may reveal important quantitative effects among FWS selection criteria groupings. These quantitative effects, if any, can be used to improve the FWS selection process in building construction projects and, consequently, the project performance factors [32]. To the authors' knowledge, no studies involving formwork or FWS selection have employed the SEM approach. However, the SEM approach has been employed in numerous construction management studies, e.g., [40,41], and few studies utilized SEM to solve a specific selection problem in the construction sector. For instance, Song et al. [42] utilized the SEM approach to solve the supplier selection of prefabricated building elements in building construction projects. Similarly, Samee and Pongpeng [43] used the SEM approach for construction equipment selection to improve contractors' competitive advantages in construction projects. Hence, using the SEM approach for the FWS selection problem can be a useful and novel method in the field of formwork engineering. Moreover, although there may be quantitative relationships between the FWS-FWF characteristics, structural design, and project performance factors [10], none of the previous studies aim to determine the quantitative relationships and interdependencies among them. The main objective of this study is to fill the important knowledge gap by analyzing the FWS selection criteria using an SEM approach. For this purpose, first, exploratory factor analysis (EFA) and confirmatory factor analysis (CFA) will be conducted to identify the underlying FWS selection criteria groupings and their quantitative relationships. Then, based on the results of the EFA and CFA, several hypotheses will be developed and tested using an SEM approach.

3. Research Methodology

The objective of this study is to analyse the FWS selection criteria in building construction projects in Turkey using an SEM approach. To achieve the research goal, first, a comprehensive review of the literature was undertaken to identify the FWS selection criteria of building construction projects. Second, a questionnaire was developed to collect data from the Turkish construction sector for analyzing the FWS selection criteria. Following the data collection stage, EFA was applied to reveal the underlying groupings of the FWS selection criteria. In addition, a measurement model was adopted to conduct CFA, which is used to confirm that the constructs were adequately measured. Finally, the quantifiable interrelationships among the underlying groupings of the FWS selection criteria were explored. For this purpose, first, a hypothetical structural model was developed based on the results of the EFA and CFA. Then, the SEM approach was utilized as the primary research instrument to test the hypothetical structural model.

The research methodology adopted in this study is in accordance with prior construction management studies, in which EFA, CFA, and the SEM approach is undertaken sequentially using the same dataset [44,45]. EFA is utilized to identify the latent constructs and CFA is used to determine the adequacy of the measurement model, which is required before developing and evaluating the structural model [44]. In general, the measurement model is concerned with modelling the relationships between the latent constructs and the observed variables, whereas the structural model is used to analyse the relationships among the previously identified latent constructs [46]. Therefore, based on the results of EFA and CFA (i.e., the measurement model), a hypothesized structural model can be developed and analyzed using the SEM approach [46]. The flowchart of the research methodology is shown in Figure 1, which consists of five main stages: (1) identification of FWS selection criteria, (2) design of the questionnaire, (3) data collection, (4) data analysis, and (5) discussion.

3.1. Identification of FWS Selection Criteria

After an extensive literature review, a total of 35 FWS selection criteria for building construction projects were identified. Terzioglu et al.'s [10] study includes a complete discussion of each of these FWS selection criteria and a critical review of the relevant literature. The applicability of these FWS selection criteria was further checked and validated by face-to-face interviews with several experts, who have more than 20 years of international experience in formwork engineering (see Terzioglu et al.'s [10] study). In addition, Terzioglu et al. [32] contributed to the applicability and validation of the FWS selection criteria by conducting a questionnaire study in the Turkish building construction sector. Hence, the FWS selection criteria of this study are based on the findings by Terzioglu et al. [10] and Terzioglu et al. [32]. The identified FWS selection criteria from the literature review and their assigned ID numbers are presented in Table A1.

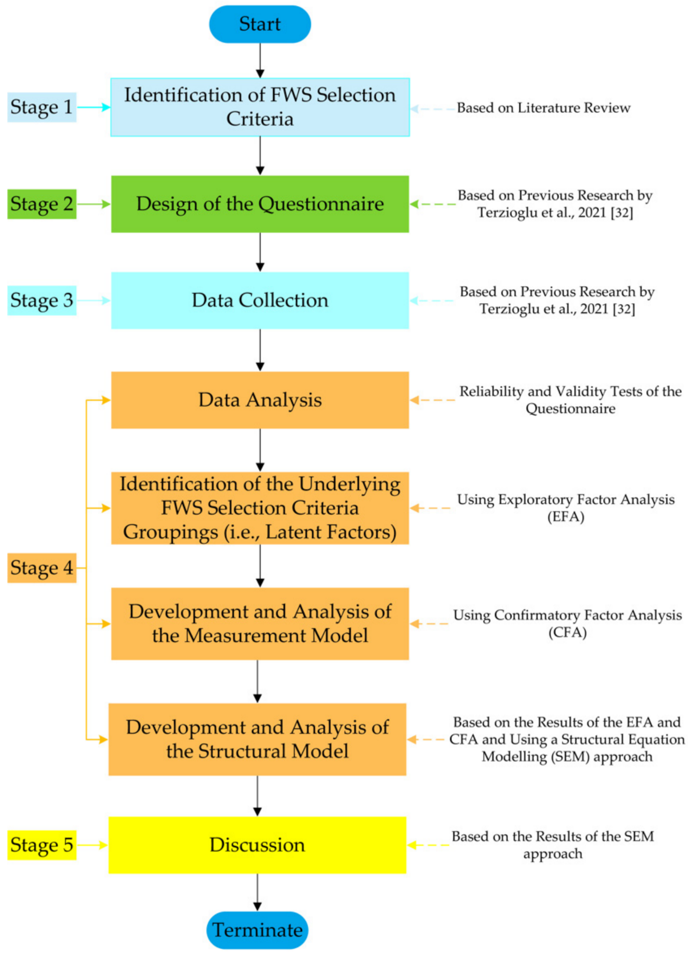

Figure 1. Research flowchart.

3.2. Design of the Questionnaire

The questionnaire was designed based on the identified FWS selection criteria from the literature review and expert evaluation. Prior to distribution, the questionnaire was examined by three experts with over 20 years of international experience in both technical and administrative areas of formwork engineering. The experts were tasked with validating the identified FWS selection criteria and approving the questionnaire structure and questions for applicability. The authors carefully analyzed the experts' suggestions regarding the applicability of the FWS selection criteria and the appropriateness of the questionnaire's structure and questions. When necessary, the questionnaire was revised. The questions were kept brief and there were no leading questions. The authors and these experts reviewed the language and arrangement of the questions to ensure that response bias was minimized. To understand the respondents' background and ensure reliable responses, the demographic information was presented at the beginning of the questionnaire. The main body of the questionnaire included two sections. The first section was designed to gather specific qualitative (e.g., building type) and quantitative information (e.g., total building area, total building height) of the building construction project in which the respondents are currently involved. In the second section, respondents were asked to evaluate the relative importance of each of the 35 FWS selection criteria considering the building construction project in which they are currently working. An ordinal six-point Likert scale was selected to measure the relative importance of each FWS selection criteria in the decision-making process (0—not considered, 1—not important, 2—slightly important, 3—moderately important, 4—very important, and 5—extremely important), which is commonly used in construction management studies, e.g., [47]. The questionnaire structure is shown in Figure 2.

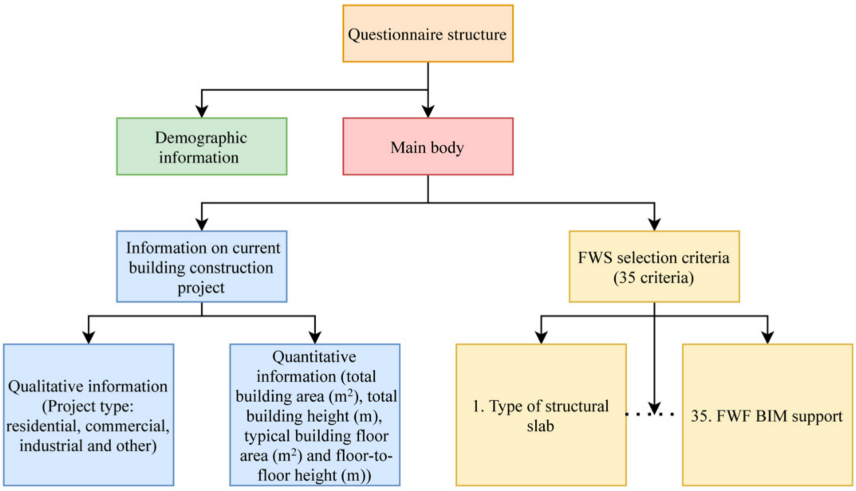

Figure 2. Questionnaire structure.

3.3. Data Collection

Target respondents were construction professionals who actively participate in the selection and decision-making process of FWSs in the Turkish construction sector. The professionals include company owners/partners, project managers, construction managers, site engineers, technical office and design engineers, planning engineers, procurement engineers, and tendering engineers. The participants in this study were selected using the random sampling technique, which is commonly used in the construction management field and in which a sample is randomly selected from the population with a non-zero probability [48]. This sampling technique is shown to be successful since the sample effectively represents the population while avoiding any voluntary response bias [49]. The questionnaire was developed using https://docs.google.com/forms (accessed on 10 October 2021), which is a common online survey system [50,51]. The survey link was sent to more than 2500 respondents through the Union of Chambers of Turkish Engineers and Architects (UCTEA) and the Association of Formwork and Scaffold Manufacturers (IKSD) in Turkey. A total of 222 valid responses were received. Since the sample size was greater than 100, it can be considered more than adequate for an SEM approach [52]. More information on the methods utilized in this study's questionnaire design and the data collection stages (e.g., validation of the questionnaire structure, minimization of the response bias, response rates, sampling techniques etc.) can be found in Terzioglu et al.'s [32] questionnaire study. The demographic information of the respondents is given in Table A2. In addition to the personal background information, respondents were asked about the profile of the company in which they are currently working. This information refers to the number of technical and administrative employees, the number of operating years in the construction sector, the field of specialization, and the market region. The demographic information of the respondents' company is given in Table A3.

3.4. Data Analysis

First, the collected data from the valid questionnaires were stored and analyzed using the Statistical Package for Social Sciences (IBM SPSS, Version 28.0). Non-parametric statistical tests were conducted to analyse the data from the questionnaire since the data were obtained on an ordinal measurement scale and had non-normal distribution [53]. CFA and SEM approach was implemented by the utilization of Analysis of Moment Structure (IBM SPSS AMOS, Version 26.0) software package, which is widely used in construction management studies [54,55]. The methods and statistical tests used in this study are briefly described below:

3.4.1. Reliability Test

The characteristics of a questionnaire as a measuring instrument can be evaluated by considering its reliability and validity. The degree to which a measurement instrument is biased or provides accurate and consistent data is referred to as reliability [56]. Cronbach's α is a measure of internal consistency and is often used in reliability testing [57]. The reliability of the questionnaire data in this study was tested utilizing Cronbach's α, and it was calculated using Equation (1):

$$\alpha = \frac{k}{k-1}\left(1 - \frac{\sum_{j=1}^{k} \sigma_{U_j}^2}{\sigma_X^2}\right) \tag{1}$$

where, k is the number of items (i.e., testlets), $\sigma_{U_j}^2$ is the variance of the j-th item, and σ_X^2 is the variance of the observed total test scores. The mean value for Cronbach's α was computed for the 35 FWS selection criteria. In general, the value for Cronbach's α ranges between 0 and 1, where an acceptable value is considered to be higher than 0.70 [58]. The mean value of Cronbach's α for all 35 FWS selection criteria is 0.973 (i.e., $\alpha > 0.70$), which indicates a satisfactory internal consistency.

3.4.2. Validity Test

The degree to which research is accurate is referred to as validity. Two of the most common types of validity in business research are content validity and construct validity [56]. Content validity is the extent to which a research topic is adequately covered [58]. Content validity in this study is provided by an extensive literature review on the research topic and empirical evaluation through face-to-face interviews with experts.

The degree to which items in a construct measure the same construct is known as construct validity, which can be revealed by factor analysis, which is a method for grouping variables in a dataset based on their significant correlations [57]. The Kaiser–Meyer–Olkin (KMO) method and Bartlett's test of sphericity were used in the factor analysis to evaluate the sampling adequacy of the questionnaire data. Kaiser [59] suggests a KMO value larger than 0.60 for further analysis. According to some studies, a KMO value larger than 0.50 may also be satisfactory for factor analysis, depending on the adequacy of the sample size [57]. SPSS Version 28.0 was used to conduct the factor analysis and determine the validity of the questionnaire data. The KMO value for the 35 FWS selection criteria is 0.942, which designates adequate intercorrelations. The Bartlett's test of sphericity is 6966.708, and the corresponding significance probability is $p = 0.000$, which shows that the correlation matrix is not an identity matrix and there are relationships among the FWS selection criteria [60]. Thus, the data from the questionnaire ensure construct validity and are appropriate for subsequent factor analysis.

3.4.3. Exploratory Factor Analysis (EFA)

The most common uses of EFA are to find structures and relationships between variables and categories, as well as to reduce the variables into smaller numbers [61]. Moreover, by identification of a set of unobserved latent factors, EFA can reconstruct the complex observed variables in an essential form [62]. In general, there are two steps involved in EFA: (1) factor extraction and (2) factor rotation. The identification of the underlying factor groupings (i.e., groupings of the FWS selection criteria) is performed through factor extraction, and determination of the number of the underlying groupings is revealed through factor rotation [60]. Hence, this study uses EFA to determine the underlying groupings for the FWS selection criteria by examining the factor loadings in the varimax rotation matrix. The criteria with a factor loading of greater than 0.50 were considered in EFA [63,64]. The reliability and validity tests were repeated for each revealed underlying grouping (i.e., latent factor) of the FWS selection criteria. These tests measure the degree of intercorrelations among the FWS selection criteria and the adequacy for conducting EFA.

3.4.4. Confirmatory Factor Analysis (CFA)

The relationships between the latent factors and their items (i.e., observed variables) can be examined by means of a measurement model, which is conducted before the development of the structural model [65]. First, CFA is provided by examining the standardized factor loadings (β) in the measurement model and by extracting the items with standardized factor loadings close to or less than 0.50 [13,60]. Second, composite reliability, Cronbach's α, convergent reliability, and discriminant validity were used to evaluate the measurement model [66]. In addition, the SEM approach requires validation of the model based on certain goodness-of-fit (GOF) measures. The following GOF measures were adopted for validation of the measurement model and the hypothesized structural model in this study from the various fit indices reported in the SEM literature:

1. The absolute normed chi-square (χ^2/df) is the ratio of chi-square (χ^2) to the degree of freedom (df), which compares the observed covariance and estimated covariance matrices under the assumption that the tested model is valid [67];
2. The goodness of fit index (GFI) is a measure of how well a hypothesized theory fits the data [67];
3. The incremental fit index (IFI) compares the chi-square to a baseline model and indicates how well the model fits compared with the baseline model [68,69];
4. The Tucker-Lewis index (TLI or NNFI) takes into account the correlation between model complexity and sample size [70];
5. The comparative fit index (CFI) measures the relative improvement in the fit of the hypothesized model, and it is less affected by sample size [67];
6. The root-mean-square error approximation (RMSEA) measures the difference between the observed covariance matrix and estimated covariance matrix compared to the unit degree of freedom [71];
7. The standardized root mean square residual (SRMR) is the standardized difference between the residuals of the observed correlation matrix and hypothesized covariance model [68];
8. The normed fit index (NFI), which is sensitive to sample size, compares the chi-square value of the hypothesized model to the chi-square of the baseline model and adjusts for the complexity of the model [72].

The GOF measures and their recommended values used to evaluate the validity of the SEM approach in this study are summarized in Table A4.

3.4.5. SEM Approach

The SEM is a statistical research method that can be utilized for the analysis of complex multi-variable research data [73]. Moreover, through a measurement model and a structural model, SEM is an effective methodology for assessing model constructs and hypothesized structural relations among latent factors [74]. Thus, SEM has been widely used in the field of construction management, e.g., [58,75–80]. The structural model can be developed and analyzed further after the measurement model has been evaluated satisfactorily [65]. In general, the primary purpose of the SEM is to explore the relationships among the latent factors in the structural model [13,75]. These relationships can be depicted from a SEM model by exploring the quantifiable direct and indirect effects between the latent factors [58,69]. For this purpose, first, a hypothetical structural model is developed based on the results of the EFA and CFA. Then, the direct and indirect effects among the latent factors in the structural model are tested for their statistical significance. In addition, the coefficient of determination or squared multiple correlation (i.e., R^2) value, which is a measure of the predictive strength of the construct in question and an indication of the degree of variance of the endogenous latent factors [81], are explored. R^2 values of 0.67, 0.33, and 0.19 are considered substantial, moderate, and weak, respectively [82]. In addition, the GOF measures are used as validation of the hypothesized structural model.

4. Results

4.1. Results of the Exploratory Factor Analysis (EFA)

Factor extraction is conducted by the principal component method (PCM), which identifies the latent factors. As for the factor rotation, varimax rotation is used, which maximizes the variance of the squared loadings for each factor [57]. The EFA was performed in IBM SPSS Version 28.0. The PCM and the varimax rotation matrix revealed that there were four items with a factor loading less than 0.50 (e.g., "type of concrete finish" (ID 11), "potential reuse of the FWS in other projects" (ID 22), "hoisting equipment" (ID 23), and "in-house capability" (ID24)), which were extracted from the analysis. In addition, the cumulative percentage of variance (CPV) of all 35 items was 0.69, whereas it was 0.71 (i.e., CPV > 0.60) after deleting four items, which is considered satisfactory [64,77]. The PCM was used to extract five principal components by specifying a minimum initial eigenvalue of 1.0 [31]. The eigenvalues and the variance explained by each latent factor (i.e., component) and the cumulative variance explained are presented in Table 1. The total variance explained was more than 60%, indicating that the five latent factors were sufficient to explain most of the variances [61]. In addition, the results of the varimax rotation matrix and EFA on the FWS selection are shown in Table 2. The values of factor loadings above the threshold value are in bold.

Table 1. Results of total variance explained.

Description of Latent Factors	Eigenvalues of Components	Variance Explained	Cumulative Variance Explained
Factor 1: FWS-FWF characteristics	18.505	52.871%	52.871%
Factor 2: Structural design	2.014	5.754%	58.625%
Factor 3: Local conditions	1.600	4.571%	63.196%
Factor 4: Cost	1.331	3.803%	66.998%
Factor 5: Performance indicators	1.010	2.887%	69.885%

Table 2. Results of the varimax rotation matrix and EFA.

	Latent Factors				
	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
Observed Variables	**FWS-FWF Characteristics**	**Structural Design**	**Local Conditions**	**Cost**	**Performance Indicators**
FWF logistical support	**0.755**	0.205	0.211	0.153	0.108
FWS complexity	**0.754**	0.250	0.333	0.209	0.080
FWF technical support	**0.744**	0.228	0.101	0.196	0.270
FWS size	**0.734**	0.315	0.208	0.244	0.088
FWS weight	**0.729**	0.223	0.237	0.256	0.149
FWF BIM support	**0.701**	0.111	0.391	0.092	0.074
FWS safety	**0.698**	0.180	0.225	0.181	0.353
FWS compatibility	**0.673**	0.354	0.118	0.253	0.044
FWS flexibility	**0.656**	0.300	0.171	0.135	0.329
FWS sustainability	**0.653**	0.167	0.371	0.079	0.271
FWS durability	**0.621**	0.391	0.051	0.248	0.422
In-house capability (deleted)	0.496	0.161	0.341	0.262	0.371
Hoisting equipment (deleted)	0.439	0.406	0.025	0.282	0.432
Degree of repetition of the FWS	0.288	**0.694**	0.128	0.284	0.111
Number of floors	0.157	**0.692**	0.159	0.404	0.059
Variation in column/wall dimensions and location	0.316	**0.639**	0.254	0.063	0.329

Table 2. *Cont.*

	Latent Factors				
	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
Observed Variables	**FWS-FWF Characteristics**	**Structural Design**	**Local Conditions**	**Cost**	**Performance Indicators**
Floor to floor height	0.257	**0.625**	0.395	0.183	0.158
Uniformity of building	0.182	**0.615**	0.295	0.235	0.262
Total building height	0.194	**0.595**	0.206	0.323	0.140
Floor area	0.256	**0.591**	0.458	0.160	0.040
Type of structural lateral loads-supporting system	0.328	**0.557**	0.217	−0.042	0.325
Type of structural slab	0.386	**0.541**	0.039	0.030	0.314
Site access	0.254	0.208	**0.775**	0.221	0.114
Weather conditions	0.306	0.221	**0.729**	0.227	0.198
Size of site	0.254	0.236	**0.698**	0.232	0.222
Variation in openings/inserts dimensions and location	0.302	0.430	**0.564**	0.010	0.110
Type of concrete finish (deleted)	0.228	0.207	0.410	0.120	0.402
Maintenance cost of the FWS	0.369	0.116	0.345	**0.717**	0.144
Labour cost of the FWS	0.243	0.308	0.162	**0.714**	0.301
Transportation cost of the FWS	0.286	0.188	0.424	**0.679**	0.021
Initial cost of the FWS	0.197	0.391	0.076	**0.655**	0.322
Potential reuse of the FWS in other projects (deleted)	0.389	0.377	0.027	0.473	0.404
Labour quality	0.307	0.231	0.356	0.214	**0.702**
Labour productivity	0.389	0.268	0.265	0.344	**0.594**
Speed of construction	0.162	0.477	0.207	0.340	**0.593**

The latent factors were named according to the characteristics of the variables within the underlying groupings and the literature review. EFA revealed five main latent factors: FWS-FWF characteristics, structural design, local conditions, cost, and performance indicators. These identified latent factors are briefly described below:

1. FWS-FWF characteristics: This latent factor includes the different FWS characteristic variables (e.g., FWS durability, FWS size) and the variables associated with the FWF's technical or logistical support capabilities. Each selected FWS will be supplied by a FWF with certain capabilities. Therefore, these variables are part of the selected FWS;
2. Structural design: This latent factor is represented by the different structural design variables (e.g., type of structural slab, number of floors), which are usually determined prior to the FWS selection;
3. Local conditions: The variables in this latent factor mainly address the local site conditions (e.g., weather conditions, size of site) of the RC construction project;
4. Cost: This latent factor is associated with the total cost of the selected FWS, which can be determined by considering the initial cost, transportation cost, maintenance cost, and labour cost of the FWS;
5. Performance indicators: All observed variables in this latent factor, including labour quality, labour productivity, and speed of construction, affect the time and quality performance of the RC construction project.

The reliability test on each latent factor was performed and the mean values of the corresponding observed variables were calculated as reported in Table 3. In addition, "variation in column/beam dimensions and location" (ID 5) was deleted from the analysis as extracting it increased Cronbach's α value of the corresponding latent factor. The value for Cronbach's α of each latent factor ($\alpha > 0.70$) indicated satisfactory internal consistency.

Table 3. Results of the internal consistency of the latent factors and mean values of the observed variables.

Latent Factors	Observed Variables	Mean	Cronbach's α
FWS-FWF characteristics	FWF logistical support	3.08	0.952
	FWS complexity	3.05	
	FWF technical support	3.28	
	FWS size	3.09	
	FWS weight	3.13	
	FWF BIM support	2.73	
	FWS safety	3.25	
	FWS compatibility	3.08	
	FWS flexibility	3.35	
	FWS sustainability	3.17	
	FWS durability	3.84	
Performance indicators	Labour quality	3.49	0.891
	Labour productivity	3.60	
	Speed of construction	3.91	
Local conditions	Site access	2.44	0.881
	Weather conditions	2.67	
	Size of site	2.64	
Cost	Maintenance cost of the FWS	2.97	0.893
	Labour cost of the FWS	3.49	
	Transportation cost of the FWS	2.95	
	Initial cost of the FWS	3.95	
Structural design	Degree of repetition of the FWS	3.85	0.910
	Number of floors	3.54	
	Variation in column/wall dimensions and location (deleted)	3.65	
	Floor to floor height	3.49	
	Uniformity of building	3.66	
	Total building height	3.49	
	Floor area	3.14	
	Type of structural lateral loads-supporting system	3.85	
	Type of structural slab	3.84	

4.2. Results of the Confirmatory Factor Analysis (CFA)

The CFA is performed by first developing the measurement model based on the results from the EFA. The measurement model, which comprises the five latent factors and 30 observed variables, is developed in IBM SPSS AMOS 26.0 software, shown in Figure 3.

The results of the CFA of the measurement model are shown in Table 4. In the measurement model, the standardized factor loadings range between 0.639 to 0.901 (i.e., $\beta > 0.50$), where the values above 0.70 demonstrate significant loadings [62]. In addition, the significance level of the standardized loadings of each observed variable was $p < 0.001$. Therefore, no deletion of an item is required from the measurement model. Furthermore, the composite reliability (CR) is above the minimum acceptable range of 0.70 for all latent factors [83]. The average variance extracted (AVE) of the observed variables was above the minimum value of 0.50, indicating adequate convergent validity [60,84].

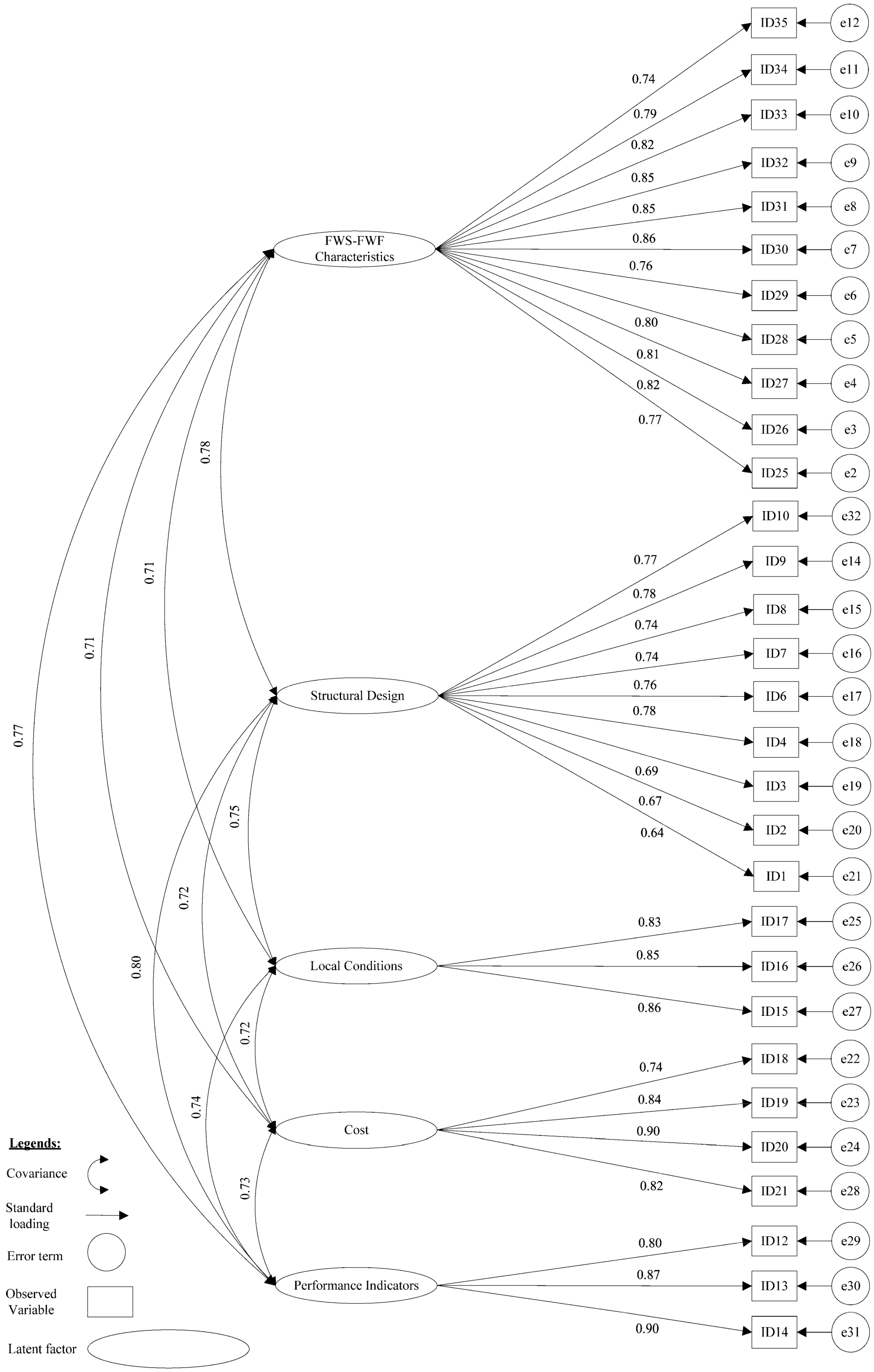

Figure 3. Measurement model.

Table 4. Results of the CFA of the measurement model.

Latent Factor	Observed Variable	Standard Loading (β)	S.E.	C.R.	p	Cronbach' α	CR	AVE
FWS-FWF characteristics	ID 25	0.768	-	-	-	0.952	0.953	0.650
	ID 26	0.818	0.077	13.330	***			
	ID 27	0.814	0.067	13.189	***			
	ID 28	0.796	0.072	12.843	***			
	ID 29	0.759	0.076	12.130	***			
	ID 30	0.862	0.074	14.267	***			
	ID 31	0.848	0.073	13.795	***			
	ID 32	0.851	0.074	13.854	***			
	ID 33	0.817	0.077	13.168	***			
	ID 34	0.790	0.079	12.674	***			
	ID 35	0.738	0.086	11.738	***			
Performance indicators	ID 12	0.805	-	-	-	0.891	0.894	0.737
	ID 13	0.867	0.073	14.735	***			
	ID 14	0.901	0.072	15.212	***			
Local conditions	ID 17	0.827	-	-	-	0.881	0.881	0.712
	ID 16	0.849	0.068	14.682	***			
	ID 15	0.855	0.071	14.503	***			
Cost	ID 18	0.744	-	-	-	0.893	0.895	0.682
	ID 19	0.836	0.110	12.015	***			
	ID 20	0.895	0.104	12.709	***			
	ID 21	0.821	0.094	12.513	***			
Structural design	ID 9	0.782	-	-	-	0.910	0.911	0.534
	ID 8	0.736	0.083	11.854	***			
	ID 7	0.736	0.083	11.520	***			
	ID 6	0.761	0.080	12.035	***			
	ID 4	0.777	0.074	12.432	***			
	ID 3	0.691	0.082	10.660	***			
	ID 2	0.670	0.077	10.318	***			
	ID 1	0.639	0.081	9.736	***			
	ID 10	0.769	0.078	12.343	***			

Note: "-" represents baseline parameter estimation, "***" indicates significance level $p < 0.001$, S.E. denotes for standard error, C.R. denotes for regression weight estimate, CR denotes for composite reliability, AVE denotes for average variance extracted.

Moreover, discriminant validity, which measures how distinct a latent construct (i.e., latent factor) is from the other constructs [85], should be evaluated. The square root of each latent construct's AVE value should be higher than any other construct's correlation value [84]. As shown in Table 5, discriminant validity of the constructs was provided in this measurement model.

Table 5. Discriminant validity evaluation of the latent constructs in the measurement model.

Latent Construct	FWS-FWF Characteristics	Performance Indicators	Local Conditions	Cost	Structural Design
FWS-FWF characteristics	**0.810** [a]				
Performance indicators	0.774 ***	**0.859** [a]			
Local conditions	0.710 ***	0.737 ***	**0.843** [a]		
Cost	0.710 ***	0.733 ***	0.716 ***	**0.826** [a]	
Structural design	0.778 ***	0.803 ***	0.747 ***	0.724 ***	**0.740** [a]

Note: "[a]" indicates the square root of AVE of each latent construct, and "***" indicates significance level $p < 0.001$.

Finally, the GOF measures of the measurement model are examined. Based on the recommended values for fit indices in the relevant literature (Table A4), the measurement model resulted in an acceptable overall fit (χ^2/df = 3.392, GFI = 0.713, RMSEA = 0.104, SRMR = 0.055, NFI = 0.785, TLI = 0.821, CFI = 0.837, IFI = 0.838, PNFI (parsimonious normal fit index) = 0.713, PGFI (parsimony goodness of fit index) = 0.606). While the RMSEA value is 0.104, it was regarded acceptable since it is very close to the recommended value of 0.10.

4.3. Results of the SEM Approach and Hypotheses Development

Initially, a conceptual framework was developed to illustrate the relationships among the five FWS selection criteria groupings based on the results of EFA and CFA. The conceptual framework is illustrated in Figure 4, and the following hypotheses are developed as part of the conceptual framework:

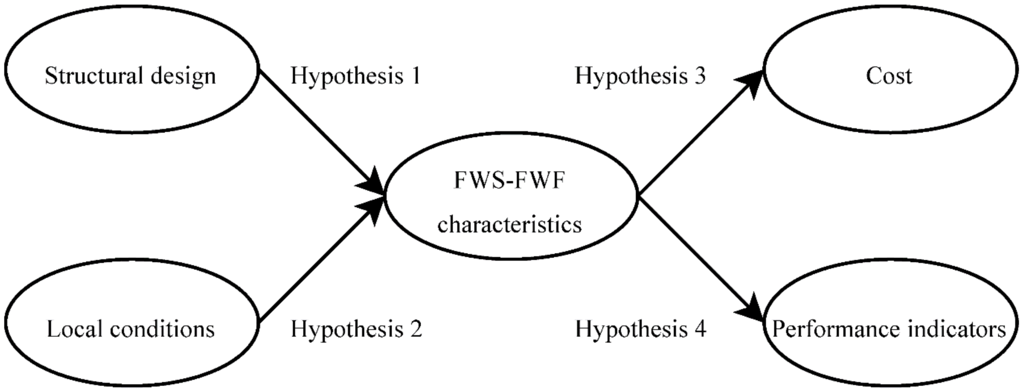

Figure 4. The conceptual framework for FWS selection criteria groupings and hypotheses.

Hypothesis 1 (H1). *Structural design has a positive and significant influence on FWS-FWF characteristics.*

Some building structural parameters related to the structural design of a building construction project (e.g., "total building height") may significantly affect other FWS selection criteria [32]. In addition, structural design-related FWS selection criteria, such as "type of structural slab" and "type of structural lateral loads-supporting system" may have the greatest impact on the selection process of a FWS [18]. The type of the selected FWS (e.g., aluminium FWS) can have different characteristics compared to other FWSs (e.g., traditional FWS) [19]. In addition, as there are many FWFs available with each fabricator planning, designing, detailing, producing, and supplying different FWSs [86,87], the selected FWS may vary depending on the capacity and characteristics of the FWF. Hence, the structural design may influence the FWS-FWF characteristics.

Hypothesis 2 (H2). *Local conditions have a positive and significant influence on FWS-FWF characteristics.*

Local conditions (i.e., "weather conditions", "site access", and "size of site") are environmental aspects of the building construction project, which may be an important factor in the FWS selection process [31]. The planning and selection of the FWS should be performed before the construction starts while considering the local site conditions [88]. For instance, the feasibility of using "flying FWS" is dependent on size access and the size of site in a building construction project [17]. Moreover, some FWSs are sensitive to severe weather conditions, such as "sliding FWS" or "slip FWS" as concrete must be delivered and poured continuously and without disruption in these types of FWSs [7,17]. Therefore, local conditions may influence the FWS-FWF characteristics.

Hypothesis 3 (H3). *FWS-FWF characteristics has a positive and significant influence on cost.*

The FWS-FWF characteristics (i.e., the criteria associated with the selected FWS and FWF) may significantly affect the cost of a building construction project [32]. For example, using a durable FWS (i.e., "FWS durability") may eliminate the need for replacement of the FWS and reduce unnecessary cost [10]. Moreover, utilizing industrial and modular FWSs with standard sizes and shapes (e.g., "FWS flexibility", "FWS size") may significantly reduce construction waste and cost [89]. The cost performance and constructability of the building construction project can be substantially improved using BIM applications in formwork engineering [90]. Therefore, “FWF BIM support”, one of the FWS-FWF characteristics, is another criterion that may affect cost. As a result, FWS-FWF characteristics may influence cost in a building construction project.

Hypothesis 4 (H4). *FWS-FWF characteristics has a positive and significant influence on performance indicators.*

“Labour quality”, “labour productivity”, and “speed of construction” (i.e., performance indicators) are criteria that may be affected by the selected FWS. For instance, as some heavy components of the FWS require the use of hoisting equipment [91] and other lightweight or self-climbing FWSs may not [92], the “speed of construction” may be affected by the type of the FWS selected (i.e., FWS-FWF characteristics), especially in high-rise building construction. In addition, as some FWS require less labour force and less cycle time, such as “Table FWS” [93], labour productivity and speed of construction can be greatly improved by selecting the appropriate FWS. Therefore, FWS-FWF characteristics may influence the performance indicators of a building construction project.

The conceptual framework was adapted into a hypothetical structural model and analyzed using IBM SPSS AMOS 26.0 software. The five latent factors (i.e., FWS selection criteria groupings) and 30 observed variables (i.e., FWS selection criteria) were considered in the analysis, with structural design and local conditions acting as exogenous latent factors and FWS-FWF characteristics, cost, and performance indicators acting as endogenous latent factors. As some GOF measures needed refinements and modifications, covariance and casual relationships among some error terms were added. These modifications are in line with the suggestions for model fit [69] and are widely used for improving the GOF measures [67]. It was verified that all refinements made theoretical sense [69] in terms of the FWS selection criteria interrelationships. The final SEM model on FWS selection in building construction projects is shown in Figure 5.

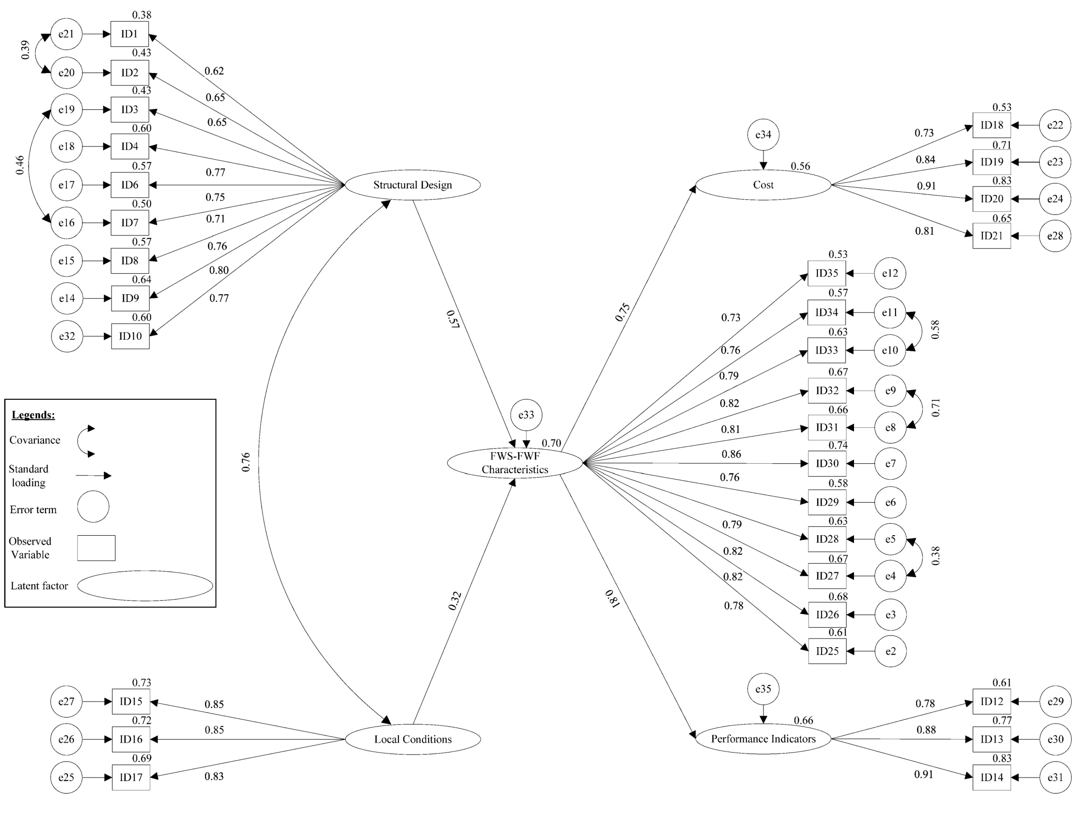

Figure 5. Final SEM model on FWS selection in building construction projects.

In the CFA (i.e., the measurement model), the overall model fit specifies the degree to which the observed variables represent the hypothesized latent constructs [94]. On the other hand, the structural model is tested by evaluating its adequacy [94]. As the CFA of the measurement model was shown to be satisfactory (i.e., composite reliability, convergent validity, and discriminant validity was verified) for the subsequent SEM approach [94], it is common practice in the SEM literature to evaluate and validate the hypothetical structural model (i.e., Figures 4 and 5) based on satisfactory GOF measures [41,94,95]. The structural model is adequate for interpretation, since it resulted in a satisfactory overall model fit ($\chi 2/df$ = 2.737, GFI = 0.753, RMSEA = 0.089, SRMR = 0.069, NFI = 0.827, TLI = 0.870, CFI = 0.882, IFI = 0.883, PNFI = 0.751, PGFI = 0.639). Moreover, the R^2 values for the endogenous latent factors (i.e., FWS-FWF characteristics, cost and performance indicators) were explored. The R^2 values for FWS-FWF characteristics ($R^2{}_{FWS\text{-}FWF\ characteristics}$ = 0.70) and performance indicators ($R^2{}_{Performance\ indicators}$ = 0.66) were both higher than 0.67, while the R^2 value for cost ($R^2{}_{Cost}$ = 0.56) was higher than 0.33, indicating that the structural model had substantial and moderate predictive power, respectively [82].

The Hypotheses H1–H4 were tested by exploring the standardized direct effects (i.e., the standardized path coefficients) and each hypothetical path's corresponding two-tailed significance level. Structural design had the highest positive influence on FWS-FWF characteristics (β = 0.565, p < 0.001) and FWS-FWF characteristics exerted the highest positive influence on performance indicators (β = 0.813, p < 0.001). The standardized path coefficient values for H1, H3 and H4 were all larger than 0.50, indicating a large effect, while the path coefficient value for H2 was larger than 0.30, suggesting a medium effect [69]. The results and conclusions for the hypotheses of this study are shown in Table 6.

Table 6. The results and conclusions for the hypotheses.

Hypothesis	Results	Conclusion
H1	Yes (β = 0.565, p < 0.001)	Supported
H2	Yes (β = 0.325, p < 0.001)	Supported
	Yes (β = 0.749, p < 0.001)	Supported
H4	Yes (β = 0.813, p < 0.001)	Supported

In addition to the direct effects between the latent factors, the indirect effects among the latent factors were investigated. For this purpose, the bootstrap estimation method in IBM SPSS AMOS was utilized (a bootstrap sample of 2000 and a 95% confidence interval was used). The indirect effects are supported if zero does not lie between the lower bound and upper bound of the bias-corrected confidence interval [96]. The results of the bootstrap estimation method concluded that all indirect effects among the latent factors were significant (p < 0.001 and p < 0.01) and therefore supported, as shown in Table 7.

Table 7. Results of the bootstrap estimation method for indirect effects.

Indirect Effect Path	Standardised Indirect Effect	95% Confidence Interval		p	Conclusion
		Lower bounds	Upper Bounds		
SD → FWS-FWF characteristics → PI	0.460	0.286	0.596	0.000	Supported
SD → FWS-FWF characteristics → Cost	0.423	0.226	0.509	0.000	Supported
LC → FWS-FWF characteristics → PI	0.264	0.084	0.363	0.004	Supported
LC → FWS-FWF characteristics → Cost	0.243	0.069	0.304	0.004	Supported

Note: "SD" indicates structural design, "PI" indicates performance indicators, and "LC" indicates local conditions.

5. Discussion

The structural design of the building and the selected FWS have a significant impact on the constructability of a RC construction project [97]. Furthermore, since most industrial FWSs are manufactured as modular and standard elements that may be modified to various structural design dimensions [98], there should be a relationship between the structural design and the FWS-FWF characteristics. Hypothesis 1, that the structural design has a positive and significant direct effect ($\beta = 0.565$, $p < 0.001$) on FWS-FWF characteristics, was supported by the SEM approach. In addition, structural design may have a significant impact on formwork labour productivity and labour cost [99–101]. This was supported by the positive and significant indirect effect ($\beta = 0.460$, $p < 0.001$) of structural design on the performance indicators and the positive and significant indirect effect ($\beta = 0.423$, $p < 0.001$) of structural design on cost. Moreover, the constructability performance of the building project can be improved significantly by jointly considering the structural design and the selected FWS during the design stage [11]. In light of the findings of this study, the structural design of the building has a direct effect on FWS-FWF characteristics and indirect effects on both cost and performance indicators. Hence, as the findings of this study suggest, structural design is one of the essential factors to be considered not separately but in tandem with the FWS-FWF characteristics.

Weather conditions may have a direct effect on the FWS selection as some FWS materials are less resistant to certain extreme temperatures than others, as well as wind speeds may become a critical factor in the selection of FWSs [102]. Moreover, some FWS may be large enough to be preassembled and transported to the construction site, while others may require a local assembly area [17]. Thus, local conditions (i.e., weather conditions, size of site, and site access) should have a positive and significant effect on the FWS-FWF characteristics, which is supported by the SEM results for Hypothesis 2. Although the direct effect of local conditions on FWS-FWF characteristics ($\beta = 0.325$, $p < 0.001$) is smaller than the direct effect of structural design on FWS-FWF characteristics, it can be an essential factor in extreme circumstances, such as hot or cold weather temperatures, or construction sites with limited access and assembly area for FWSs. Formwork labour productivity and formwork labour cost are partially affected by local conditions [101]. For instance, labour productivity of formwork related activities may be affected by weather conditions [103]. Hence positive and significant indirect effects of local conditions on both cost ($\beta = 0.243$, $p < 0.001$) and performance indicators ($\beta = 0.262$, $p < 0.001$) have been validated through the SEM approach.

Formwork may be the most critical factor in RC construction, accounting for up to 60% of the unit cost of the RC structure [25] and up to 15% of the entire construction cost [104]. As various FWSs have different characteristics (e.g., FWS weight, FWS size), the selected FWS may affect labour productivity and labour cost [105]. Furthermore, the early involvement of the FWF in the FWS supply chain and local logistical support from the FWF can shorten delivery times and save transportation costs [86]. As a result, there should be a direct relationship between the FWS-FWF characteristics and cost (i.e., initial cost of the FWS, transportation cost of the FWS, maintenance cost of the FWS, and labour cost of the FWS). The SEM approach validated Hypothesis 3, that FWS-FWF characteristics had a positive and significant direct effect ($\beta = 0.749$, $p < 0.001$) on cost. In addition, the direct effect of FWS-FWF characteristics on cost was found to be the second largest direct effect in the SEM model. This finding suggests that, in order to improve the cost performance of the building construction project, variables associated with the FWS characteristics and the FWF's support capabilities should be carefully evaluated during the FWS selection.

Activities related to formwork might take up to 75% of the overall time spent on the construction of RC structures [106]. Formwork activities are also a major source of time waste [107] and material waste [108] in building construction projects, which may affect the speed of construction. Furthermore, the type of FWS utilized in building construction projects may have a direct impact on productivity and quality performance factors [18]. Therefore, there should be a strong relationship between FWS-FWF characteristics and performance indicators (i.e., speed of construction, labour productivity, and labour quality).

Hypothesis 4, that FWS-FWF characteristics had a positive and significant direct effect ($\beta = 0.813$, $p < 0.001$) on performance indicators, was confirmed using the SEM approach. The direct effect between these two latent factors was also found to be the largest direct effect in the SEM model. As time, cost, and quality are the three important factors in a construction project [109], this study identifies the quantitative effects of FWS-FWF characteristics on these performance factors and validates the importance of FWS selection in building construction projects.

The FWS selection may be performed by different construction professionals, such as company owners/partners, project managers, construction managers, site engineers, technical office and design engineers, planning engineers, procurement engineers, and tendering engineers, which may have different perceptions and perspectives regarding the importance level of FWS selection criteria [32]. Most of the previous studies used MCDM methods to select the appropriate FWS based on the perspectives of contractors or a specific group of construction professionals, e.g., [18,19,38]. Moreover, these studies used certain MCDM methods (e.g., AHP, TOPSIS etc.) while assigning relative weights to the FWS selection criteria but neglected the interrelationships (i.e., direct effects and indirect effects) among the FWS selection criteria groupings. In recent years, combining the SEM approach with various MCDM methods has become a popular and useful technique in the literature for a certain selection and/or ranking problem [42,110,111]. The quantitative direct and indirect effects revealed through the SEM approach in this study can be used by construction professionals and practitioners in MCDM methods by conducting a combined SEM-MCDM method to select the most appropriate FWS. Hence, using the results of this study, the time, cost, and quality performance of a building construction project may be improved.

6. Conclusions and Recommendations

Previous research identified and utilized FWS selection criteria in MCDM to select the most appropriate FWS, with some of these studies also grouping FWS selection criteria according to expert's opinion or by using factor analysis. The effects of the FWS selection criteria groupings, such as structural design and the local site conditions on the FWS selection process studied in the literature are mainly based on experts' knowledge with no quantitative evidence or relationship to the identified FWS selection criteria. In addition, the effects of the selected FWS on the time, cost, quality, and productivity performance factors have mostly been studied based on data from case studies.

Although previous studies greatly contribute to the existing body of knowledge of the FWS selection process, none have identified the relationships and interdependencies quantitatively among the FWS selection criteria groupings and their quantitative effects (i.e., direct and indirect effects) on the performance factors. Therefore, the main objective of this study was to fill this important knowledge gap. For this purpose, first, 35 FWS selection criteria were identified based on the existing literature and face-to-face interviews with experts from the Turkish construction industry. Then, a questionnaire was designed and distributed to construction professionals who actively participate in the selection and decision-making process of FWSs in the Turkish construction sector. The data from the respondents were analyzed by statistical methods to identify and validate the FWS selection criteria groupings (i.e., latent factors).

The findings revealed five latent factors: FWS-FWF characteristics, structural design, local conditions, cost, and performance indicators. Finally, a conceptual framework and a structural model were developed to quantify and verify the relationships between these latent factors. Based on the conceptual framework and the structural model, four hypotheses (i.e., direct effects) among the five latent factors were tested utilizing SEM. Moreover, the indirect effects between these latent factors were evaluated. It was found out that the SEM approach supported all hypothesized direct effects and indirect effects with FWS-FWF characteristics having the highest direct effect on the performance indicators followed by its direct effect on cost. In addition, structural design had a major direct effect on FWS-FWF characteristics and indirect effects on performance indicators and cost.

The findings of this study can be used for making qualitative and quantitative validations and comparisons with previous research on FWS selection criteria. In addition, engineers, contractors, and FWFs may use the quantitative relationships and interdependencies among the FWS selection criteria groupings identified in this study to assist them in determining the most appropriate FWS. For instance, the quantitative effects among the FWS selection criteria groupings can further be used in MCDM methods by implementing a combined SEM–MCDM technique. Therefore, it is expected that this study will serve as a guide for construction professionals who actively participate in the decision-making process of FWSs, and will contribute to the improvement of project time, cost, and quality in building construction projects.

This study has several limitations. First, the data in this study was obtained from the Turkish construction industry. However, only 31.1% of the respondents' companies are involved in exclusively national projects, while 68.9% are involved partially or only in international projects. Therefore, the findings of this study may be used in other countries as well. Second, the FWS selection criteria were identified and analyzed based on building construction projects. As the FWSs used in construction projects may differ according to the type of construction, this study focused only on the FWS selection criteria for building construction projects. Based on the limitations of this study, the proposed SEM approach for analyzing the FWS selection criteria may be performed in other countries to validate this study's results. The quantitative effects of structural design and local conditions on FWS-FWF characteristics and the quantitative effects of FWS-FWF characteristics on cost and performance indicators can be evaluated and compared with the findings of this study. Furthermore, the FWS selection criteria for infrastructure and industrial construction projects may be identified and analyzed with the proposed SEM approach. Hence, different relationships and interdependencies among the FWS selection criteria groupings for other types of projects may be revealed.

Author Contributions: Conceptualisation, T.T.; methodology, T.T.; software, T.T.; validation, T.T., H.T. and G.P.; formal analysis, T.T.; investigation, T.T.; resources, T.T.; data curation, T.T.; writing—original draft preparation, T.T.; writing—review and editing, G.P.; visualisation, H.T.; supervision, G.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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

Ethics Statement: : The material presented in this study is the authors' own original work, which has not been previously published elsewhere. The article is not currently being considered for publication elsewhere. The article reflects the authors' own research and analysis in a truthful and complete manner. The article properly credits the meaningful contributions of co-authors and co-researchers. All sources used are properly disclosed. All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

Appendix A

Table A1. FWS selection criteria in building construction projects and their assigned ID numbers.

ID Numbers	FWS Selection Criteria	References
1	Type of structural slab	[8,16]
2	Type of structural lateral loads-supporting system	[33,35]
3	Total building height	[8,36]
4	Variation in column/wall dimensions and location	[17,20]

Table A1. *Cont.*

ID Numbers	FWS Selection Criteria	References
5	Variation in openings/inserts dimensions and location	[17,20]
6	Degree of repetition of the FWS	[5,18]
7	Number of floors	[8,31]
8	Floor area	[8,31]
9	Floor to floor height	[21,37]
10	Uniformity of building	[37]
11	Type of concrete finish	[20,21]
12	Speed of construction	[5,29]
13	Labour quality	[9,16]
14	Labour productivity	[28,31]
15	Weather conditions	[18,26]
16	Site access	[17,20]
17	Size of site	[18]
18	Initial cost of the FWS	[5,9]
19	Transportation cost of the FWS	[30,31]
20	Maintenance cost of the FWS	[26,28]
21	Labour cost of the FWS	[5,9]
22	Potential reuse of the FWS in other projects	[18]
23	Hoisting equipment	[16,17]
24	In-house capability	[24,34]
25	FWS sustainability	[5,26]
26	FWS safety	[27,38]
27	FWS durability	[24,39]
28	FWS flexibility	[5,38]
29	FWS compatibility	[25,38]
30	FWS complexity	[26,39]
31	FWS weight	[38,39]
32	FWS size	[39]
33	FWF technical support	[24,38]
34	FWF logistical support	[21]
35	FWF BIM support	[5]

Table A2. Demographic information of the respondents.

Category	Response	Frequency of Respondents (N = 222)	Percentage (%)
Educational level	Bachelor's or equivalent	136	61.3
	Master's or equivalent	82	36.9
	Doctoral or equivalent	4	1.8
Age	20–29	24	10.8
	30–39	74	33.3
	40–49	58	26.1
	$\geq$50	66	29.7
Work experience	1–10	59	26.6
	11–20	68	30.6
	21–30	39	17.6
	$\geq$31	56	25.2
Professional title	Company owner/partner	54	24.3
	Project manager/construction manager/site engineer	81	36.5
	Planning engineer	12	5.4
	Procurement/tendering engineer	10	4.5
	Technical office/design engineer	20	9.0
	Formwork design/sales engineer	45	20.3

Table A3. Demographic information of the respondents' company.

Category	Response	Frequency of Respondents (N = 222)	Percentage (%)
No. of technical and administrative employees	1–9	67	30.2
	10–49	54	24.3
	50–249	61	27.5
	≥250	40	18.0
No. of operating years in the construction sector	1-10	30	13.5
	11–20	45	20.3
	21–30	35	15.8
	≥31	112	50.5
Field of specialisation	Project management	66	29.7
	Engineering and design	43	19.4
	Formwork and scaffolding	48	21.6
	General contractor	53	23.9
	Subcontractor	12	5.4
Market region	Only national projects	69	31.1
	Mostly national and partially international projects	110	49.5
	Mostly international and partially national projects	38	17.1
	Only international projects	5	2.3

Table A4. GOF measures for SEM and recommended values for fit indices.

Goodness of Fit Measures	Parameters	Recommended Values	References
Absolute fit indices	χ^2/df	< 5.0 (preferably < 3.0)	[112]
	GFI	0 (no fit)–1 (perfect fit)	[72,113]
	RMSEA	<0.1	[58]
	SRMR	<0.08	[114]
Incremental fit indices	NFI	0 (no fit)–1 (perfect fit)	[72]
	TLI or NNFI	0 (no fit)–1 (perfect fit)	[72]
	CFI	0 (no fit)–1 (perfect fit)	[72,113]
	IFI	0 (no fit)–1 (perfect fit)	[72,113]
Parsimony fit indices	PNFI	>0.5	[115]
	PGFI	>0.5	[115]

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