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Article

Pythagorean Fuzzy AHP Based Dynamic Subcontractor Management Framework

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Abstract: In construction projects, a significant part of construction work is done by subcontractors (SCs). Therefore, their management by main contractors (MCs) becomes an important issue as the density of SCs is created at the construction sites. In recent years, more focus on SC evaluation and selection in bidding process has been on the agenda whereas the subject of SC performance appraisal on-site during the project execution phase has been untended in the literature. Thus, this study aims to focus on the measurement and evaluation of the performance of SCs in the project execution phase, and to provide a tentative performance-based dynamic management framework that MCs will use in the management of SCs in order to take proactive measures. In line with the aim, a total number of 23 performance measurement criteria (PMC) under 7 main groups were determined as a result of a comprehensive literature review and expert evaluations. Knowing that not every criterion will have the same effect in performance measurement, pairwise comparisons of the criteria were made using the Pythagorean Fuzzy Analytic Hierarchy Process (PFAHP) method and their importance weights were determined. The PFAHP method was obtained by integrating the Pythagorean fuzzy set into the AHP method and chosen with the aim of improving the fuzzy AHP method and obtaining more consistent results by eliminating the uncertainty since Pythagorean fuzzy sets is more capable than fuzzy sets at expressing and handling uncertainty in uncertain environments. Lastly, a framework for SC performance measurement and evaluation on project execution phase is presented. It is believed that the presented framework will allow for a proactive management style that will enable effective decisions to be made while the project is ongoing, and a dynamic way of working instead of static and conventional work.

Keywords: subcontractor management; performance measurement criteria; performance appraisal; Pythagorean Fuzzy Analytic Hierarchy Process (PFAHP); project execution phase

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1. Introduction

Construction projects are temporary businesses with multi-stakeholders, where different levels of education, culture and experience come together, and where conflicts often occur. Delays and failure to complete work within the given budget are the main causes of conflicts in construction projects. It is mentioned that disagreements between main contractors (MCs) and subcontractors (SCs) are often caused by incorrect estimation and insufficient information about risks [1]. Therefore, in order to both reduce the failure rate in the project and prevent conflicts, it is seen that there is an essential need to make the SC management more active and more foresighted [1]. Subcontracting in the construction industry is seen as intermediaries in the provision of a variety of construction-related services from the market to the MCs [2]. MCs divide the entire work they receive from the employer into parts and have SCs undertake these parts with the aim of reducing the workload and sharing the risks. The use of SCs has been adopted in the construction industry that requires special expertise, large-scale costs and advanced equipment [3]. Selecting SCs, making contracts, managing the relationships between various SCs, and maintaining their organization can be the summary of a project's success or failure. In construction projects, SCs are in a critical position for project success because project success is possible with the success of each element in the project [4]. Since the SC has a direct contribution to the project, it is essential to question, supervise and monitor their current status in the project. The performances of the SCs, who are evaluated and selected according to criteria such as their previous experience, the price offers they submit and their work volume, may show differences while the project is ongoing. They may exhibit a way of working other than their performance in previous projects. For this reason, it is important to track and evaluate the performance of the SCs as well as the selection. Appropriate SC selection without effective tracking cannot guarantee the success of a project [5].

The performance of SCs on issues such as time, cost and quality, which are crucial in construction projects, can shed light on how the whole project will progress. Many construction projects either fail to meet deadlines or exceed the budget allocated for the project [6]. Considering that the problems leading to these should be examined in every aspect, the influence of SCs, who undertake the construction of a significant part of the works, cannot be ignored. SCs play a key role in construction projects where time and budget are well used or well managed. Saving money is essential for the owner, contractor and SC involved in a project [7]. While thinking from budget perspective, negative effects such as lack of quality, work accidents and harming the environment may arise that will harm other objectives of the project. This reveals the necessity of holistic thinking in construction projects.

While the SC selection issues have been emphasized in the literature, the subject of measuring and evaluating SC performance in the project execution phase has not been given much attention. This study is aimed both to help fill this gap in the literature and to create proactive solutions with a more dynamic SC management in the construction industry. For this purpose, developing a dynamic SC management framework for SC performance measurement and evaluation on project execution phase constitutes the main aim of this study. For this dynamic framework, the measurement criteria were gathered in a broad perspective by adding not only the dimensions of time, cost, quality and resource adequacy but also different dimensions such as environmental protection, occupational health and safety, compatibility with different groups in the site of construction and leadership characteristics. In this context, unlike the existing literature, it is aimed to determine and bring together the criteria of different dimensions that MCs will use to measure the performance of SCs during the project execution phase, and then to determine the importance levels of the criteria for a decision support mechanism Thus, it is aimed to gain a perspective that aims to attract more attention to the literature on performance-based SC management during the project execution phase. With the help of this dynamic framework, it is expected that SC's continuous monitoring and effective decision-making process during the execution phase is ensured. At the same time, thanks to this dynamic framework developed, it is desired to contribute to the rapid development of both the current project and the SCs.

In the literature, too much weight is given to the selection of SCs in the bidding processes, but there has been no study in which the performance of the SCs is periodically measured, evaluated by combining the results and criterion importance weights and taking immediate action at the stage called the project execution phase or the construction phase. To draw more attention to the execution phase, where the most effort is spent and the most critical period of construction projects, this study aims to develop a dynamic SC management framework for a dynamic monitoring, auditing and decision-making process beyond the static control and monitoring outside of traditional methods. By sharing the evaluation results with the SCs, SCs can see their mistakes, deficiencies and features that need to be improved, without wasting much time, and where compensation can be made faster. At the same time, it is aimed to maintain the dynamic environment in this respect by determining the successful SCs, with the aim of maintaining their performance with the same activity and not experiencing any declines. This environment, which will directly enable the MCs and SCs to be more productive, will also indirectly become a mechanism that will benefit other stakeholders (material supplier, sub-employees, equipment service, technical personnel, etc.) involved in the project.

2. Literature Review

An in-depth literature review was conducted to gain a comprehensive insight into the SC management researches in construction industry. This literature review was carried out using Google Scholar, Web of Science and Scopus databases. By examining the studies on the topic of SC management, especially the last 20 years (2002–2022), it is aimed to reduce it to a more understandable level by categorizing the subjects related to SC management. Studies related to SC management, with the keywords 'subcontracting', 'Subcontractor', 'Subcontractor management', 'Subcontractor performance evaluation', 'Subcontractor selection' and 'on-site subcontractor performance', were investigated. In total, 322 documents that may be relevant to the subject were examined. Afterwards, the titles and abstracts of the studies were checked and elimination was carried out. A total of 62 documents were examined in depth through this scan. Studies that may be related to subcontractor selection, evaluation, and performance management were taken and studies suitable for the scope of this article were examined. Since the scope of this article is subcontractor performance evaluation during the project execution phase, studies that may be related to this scope have been examined. In the following two titles, the literature on these subjects is explained and 29 studies related to these two subjects are discussed. When the studies related to subcontracting practices in the literature within a 20-year timespan is examined, SC management, SC selection and evaluation and SC risk management are found among the main research areas. SC selection and evaluation, which is one of the frequently encountered subjects in the literature, consists of studies on the evaluation of SCs in the bidding processes according to their previous performance values. On the other hand, very few studies on measuring and evaluating SCs performance on-site during the project execution phase is encountered.

2.1. Subcontractor Evaluation and Selection Processes

Researchers have often emphasized that SC selection is the most important and first step in SC management in a project. Prior performance data is usually taken into account when making this selection. It is desired by everyone to have a fair selection that will provide more objective results for the selection of SCs, and will provide profit in terms of cost, time and quality. Many different decision support systems have been proposed by researchers from past to present that facilitate the decision-making of MCs. Emphasizing the importance of price and trust in SC selection, Hartmann and Caerteling [8] show that both price and trust are important mechanisms. Abbasianjahromi et al. [9] aimed to eliminate the stage of weighting criteria in SC selection, aim to develop a comprehensive model for SC selection based on fuzzy preference selection index. Cheng and Huang [10] stated that with the selection of inappropriate SCs, there will be a direct impact on the duration, cost, quality and safety of the project and that failures will occur in the project. Abbasianjahromi et al. [11] found that previous studies evaluated the selection of SCs on the basis of criteria but did not consider the number of tasks assigned to SCs and as a result of this proposed a hybrid model applying the continuous ant colony and fuzzy set theory.

In the SC selection model that Ulubeyli and Kazaz [12] developed, it has been seen that it can be used as a consultation system for MCs to reduce the risk in the selection of SCs. Shahvand et al. [13] have developed a model that reveals a significant increase in performance in construction companies, evaluating and selecting SCs and suppliers separately on three main criteria: Quality, cost and on-time delivery.

In the construction sector, where costs are at the forefront, the price offers they give when choosing a SC often precede their other features. Polat [14] stated that MCs generally tend to choose SCs that offer the lowest bid price, and that working with unqualified and underfunded SCs can lead to inefficiencies and failures. For this reason, it was proposed that a decision approach in which AHP and the preference ranking organization method for enrichment assessments (PROMETHEE) are used together, which considers the financial capacities and qualifications of the SCs in the SC selection process. In the article by Abbasianjahromi et al. [15] it is mentioned that there are multiple criteria that the project management team should evaluate during the SC selection process, and therefore a comprehensive decision-making process for SC selection based on Kano and fuzzy TOPSIS models is suggested. Shivam and Khasiyani [16] developed a conceptual model for SC selection in different construction projects by proposing an integrated decision approach that uses the relative importance index (RII) for the SC selection issue and PROMETHEE. Koçak et al. [17] have adopted an approach to create a new alternative to SC selection with the Additive Ratio Assessment Method, which is one of the multi-criteria decision-making (MCDM) techniques that can be more scientific, instead of traditional practices in the construction industry. Palha et al. [18] have developed a method for pre-tender selection based on a real case study that provides insight into the activities of SCs. El-khalek et al. [19] aims to identify, analyze and prioritize the most important criteria affecting the SC selection process using the statistical analysis approach.

The MCs need to set out with the right strategies for the works in the project to go well, and as the first step of this, they should pay attention to the selection of the appropriate SCs. Nov and Peansupap [20] stated that the MCs have wrong practices in selecting SCs and thereupon developed a new model using artificial neural networks to determine the type of relationship between MC and SC. Abdullah et al. [21] conducted a study aiming to develop the cause-effect diagram of the SC selection and as a result, showing that the "experience" criterion is the main factor affecting the SC selection. Afshar et al. [22] stated that SC selection is a very time-consuming element in cases where multiple projects are undertaken by the same contractor, and presented an optimized model that enables SC selection and projects to be scheduled and facilitated to be executed. Karaman and Sandal [23] aimed to develop a selection criteria model that could contribute to the pre-qualification conditions for SCs in the future SC selection process and to measure their impact on project success.

2.2. Subcontractor Performance Appraisal On-Site

The decrease in quality and efficiency in construction can be attributed to the performance of SCs assigned to complete actual works [24]. However, the number of studies focusing the SC performance appraisal on-site fall behind when it is considered with the number of studies focusing on SC evaluation and selection before construction execution start. Among those studies, Ko et al. [25] conducted a study aimed at improving existing practices to evaluate the performance of SCs. The appropriateness of adopting the Evolutionary Fuzzy Neural Inference Model (EFNIM) to ameliorate the disadvantages was examined. Maturana et al. [26] provided an on-site SC evaluation framework, stating that if SCs are only evaluated at the end of the project, they may only be useful in a future project. Mbachu [27] proposed a conceptual framework for SC management in which the prioritization of the criteria valid in the construction stage takes place. For this, a KPI list consisting of 10 holistic criteria, prioritized on the basis of the RII values of the criteria, was created. When these studies are examined, the deficiencies in these developed frameworks are seen as the comprehensiveness of the determined criteria and the incompleteness in detecting root causes of SCs' on-site performance and creating action plans related to root problems.

Ng [24] created a decision support system by performing SC performance evaluation with the balanced scorecard model. After this study, Ng and Tang [28] have defined performance evaluation criteria that will form the basis for the development of a new SC performance evaluation system and facilitate the viewing and comparison of performances. Stating that knowledge-based systems may be the right approach to make SC performance evaluation healthier and more attentive, Ng [29] mentioned the importance of monitoring the performance of SCs. Ng and Skitmore [30] then propose an approach to develop a balanced scorecard SC evaluation model through a survey study in which baseline and target performance levels are determined for large-scale skilled SCs. This model consists of ten SC evaluation criteria: labor, progress, safety, environment, relationship, resource control, attitude to claims, communication, promptness of payment and general obligations. In this study, 'workmanship', 'progress' and 'safety' are considered as the most important SC appraisal criteria. Yang et al. [31] in their research based on the concept of Total Quality Management (TQM) focused on the performance evaluations of employees and SCs. Chamara et al. [32] by investigating the performance of SCs in the project in terms of time, cost and quality, which are crucial issues in the industry, aimed to bring their current performance to the desired levels. MCs should consider how to develop different relationships with different SCs and how to protect cooperating SCs for the success of the project [33]. For this, SCs can contribute to the project by developing a dynamic and effective management model with continuous performance evaluations during the construction process. The performance of SCs is an important factor contributing to project success due to monitoring and proper execution of performance, which can result in better construction quality, time savings, and reduced costs for subcontracting work [34]. Poovitha et al. [35] emphasized the importance of performance measurement and performance evaluation in the construction industry and reviewed the main performance management studies. Gankhuyag and Tsai [36] prepared a study to determine the criteria for SC evaluation. For this purpose, they determined 16 criteria in 4 dimensions. These 4 dimensions are Management, Resources, Quality and On-site Performance. With the AHP method, the most important main criteria were determined as 'quality' with 0.346 and then 'management' with a weight of 0.336. Only 'Safety', 'Labor efficiency', 'Site arrangement' and 'Material usage' criteria were created in the On-site Performance group. Criteria such as cost, time, quality and communication were evaluated in other groups.

In summary, the literature reviewed is mostly on the measurement of performance in the bidding period and the selection of SCs according to this performance. While the prequalification and selection of SCs has been mentioned so frequently, it has been determined that the subject of SC performance evaluation during construction execution was not given much attention by the researchers. It is important to evaluate the performance of the SC not only before starting a project but also during the project execution phase. Based upon, the added value of on-site SC performance tracking would be: (1) providing a more controlled and far from traditional control method of the project; (2) keeping the success rate of the project at high levels with the motto of continuous improvement; (3) increasing the communication between MC and SC and eliminating the disconnections during the execution of the work; (4) rapid detection and correction of manufacturing defects; (5) foreseeing possible problems in terms of time of the project; (6) controlling cost overruns; (7) radically addressing problems by increasing communication and attention to SCs' sub-employees; (8) ensuring that occupational health and safety (OHS) performance is continuously determined and more effective in preventing possible occupational accidents; (9) increasing awareness towards the environment; (10) enable easier decisions in selecting SCs for subsequent projects. Thus, taken into consideration of the shortcomings identified in the literature regarding the measurement and evaluation of the performance of SCs during the construction execution phase and the contributions of on-site SC performance tracking, the determination of the new management approach determine the orientation of this research.

3. Research Methodology

The research methodology adopted in this study consists of two main parts: (1) Scope definition and problem detection; (2) problem evaluation and a framework proposal. Figure 1 presents the research methodology adapted within the study.

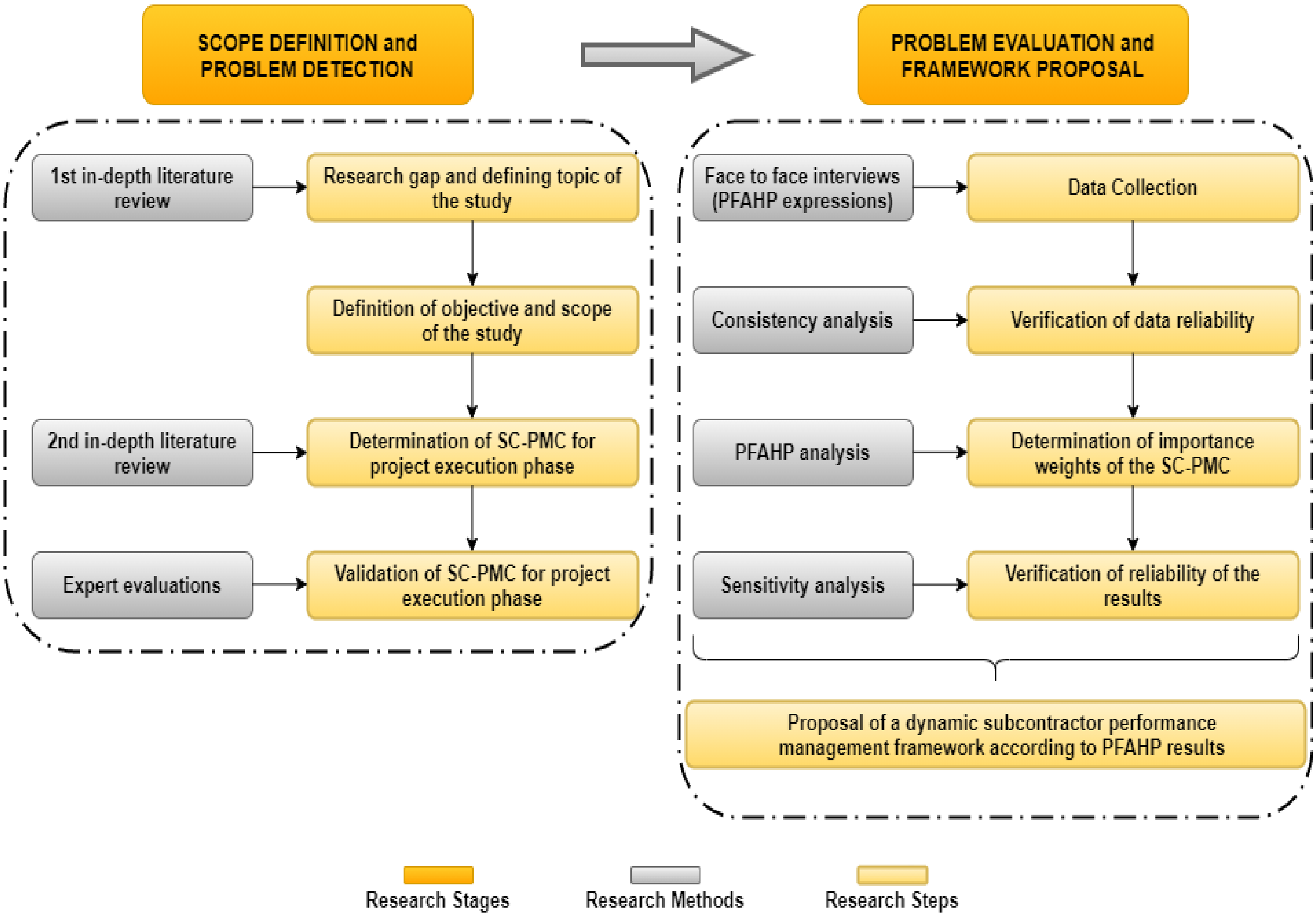

Figure 1. Research methodology.

In the 'Scope definition and problem detection' stage, an in-depth literature review was conducted firstly to identify the research gap and create the scope of the study. It is obvious that the most crucial stage in determining the success of the projects is the construction phase. At the same time, while a significant part of the work is done by SCs, there is a need for a dynamic monitoring, auditing and decision-making process beyond the static control and monitoring outside of traditional methods. Within the findings that there are deficiencies in onsite SC performance measurement and evaluation during the project execution phase, developing of a dynamic SC management framework that can be used in the performance measurement of the SCs in project execution phase constitutes the aim of the study. In line with this aim, the criteria that will be used for the on-site performance measurement of the SCs were investigated through a second in-depth literature review. Literature review was conducted using Google Scholar, Scopus and Web of Science databases with a time span of 2000–2022. While conducting the literature review, the keywords 'subcontractor management', 'subcontractor performance appraisal', 'subcontractor performance measurement criteria', 'subcontractor selection' and 'on-site subcontractor performance' were used. In the first round, a total number of 208 studies were found. As the second round, determined 208 studies were rescanned within the SC performance on execution phase perspective. Within the scope of the study, a total number of 24 studies that can shed light on the subject of SC performance measurement and evaluation during the project execution phase were taken into account among 208 studies. By examining those 24 studies, a total of 37 criteria were determined initially. The determined criteria were then evaluated by 14 experts currently working in MC companies with more than 10 years industry experience. Of the 14 experts, 6 of them are officials working in superstructure works, 3 in road construction works, 2 in dam construction works and 2 in natural gas pipeline construction. As a result of the interviews with the experts, the criteria that are more relevant to the selection of SCs during the bidding and tender phase (such as reputation, experience in the construction industry, experience in similar works, time accuracy in submitting bids, financial references, failure to complete contract, willingness to tender, etc.) were not included in this study since the main focus of this study is related to the SC's performance on execution phase of the construction project. While conducting literature review, it is seen that most of the criteria in the performance measurement literature are included in the SC selection processes. Although most of the criteria are related to the previous performance of the SCs before the project starts, it has been confirmed by the interviewed experts that these criteria are suitable for the project execution phase for a dynamic evaluation mechanism based on up-to-date data. Consequently, a total of number of 23 criteria under 7 main groups were validated as the SC-PMC for the project execution phase.

In the 'Problem evaluation and framework proposal' stage, with the idea that not every criterion will have the same degree of impact on performance measurement, the importance weights of the criteria were determined with PFAHP method by combining Analytic Hierarchy Process (AHP) with Pythagorean fuzzy sets (PFs) firstly. It has emerged as an important question to what extent these 23 SC-PMC will affect the success of the project on construction sites. By determining the importance levels of these criteria, it is aimed to use the performance measurement data more reliable and to use the effect levels more equitably. As a result of this, it is aimed to distinguish the criteria with low impact and the criteria with high impact, and to allow evaluation according to the importance level of the criteria. Therefore, a questionnaire based on the pairwise comparison method of SC-PMC was prepared to determine importance degree of these criteria. The importance weights of the criteria were determined with the PFAHP, an advanced AHP method, with the data obtained from 20 participants, who have worked in different construction projects for more than 10 years in their professional life and are now actively involved in the MC companies. Based on the ability to express thoughts linguistically, PFAHP is an effective method for removing ambiguity in language [37]. In order to perform PFAHP, face to face interviews were conducted with a total number of 20 participants who have worked in different construction projects for more than 10 years and are now actively involved in the MC companies. After that, consistency analysis was performed to measure the consistency of the answers received. Afterwards, the importance weights of the SC-PMC were calculated by providing the input of the obtained data to the MATLAB program in which the PFAHP steps were applied. As the last step of PFAHP analysis, sensitivity analysis was performed to demonstrate the reliability and applicability of the PFAHP method. The final step of "problem evaluation and framework proposal" stage consists of a tentative performance-based dynamic management framework proposal. The framework contains "performance measurement", "performance data appraisal" and "action plan" parts.

4. Subcontractor Performance Measurement Criteria (SC-PMC) for Project Execution Phase

Within the aim of the study, a total number of 23 performance measurement indicators under seven main groups were determined as a result of a comprehensive literature review and expert evaluations. The main groups, which should be kept under control in a project for a continual control, are of cost, time, and quality. Although cost, time, and quality are observed as priority targets in the literature, it is expressed that there is a need for other headings in different dimensions (such as adequacy, compatibility, environment and OHS) in the developing construction industry. These criteria have been presented in the literature by researchers [8,30,38–40] for different purposes. Within this background, determined SC-PMC were grouped under seven main topics that are Time, Cost, Quality, Resource Adequacy, Compatibility and Communication, OHS—

Environmental Protection and Leadership, respectively. Detailed explanations related to seven main groups are below:

- Time (C1): In the literature, this criterion has been identified under the names of timely completion of works, on-time delivery, process progress monitoring, and progress control. Shiau et al. [41] established 'progress control', 'work quality', 'cooperativeness', 'safety management' and 'material management' criteria for SC selection criteria. Ng [24] conducted a study with the criteria of, 'completion of job within the time' and 'adherence to program' sub-criteria. Hanák and Nekardová [40] created the SC selection criteria, and it is seen that these criteria are also important for performance measurement. The criterion related to time is 'meeting the delivery deadlines' and 'speed in remedying claim of defects'.
- Cost (C2): Some criteria have been found in the literature regarding cost for SCs. Eom et al. [42] proposed four groups for a SC management framework (financial, service, process and improvement) in their study. In the finance element, there are "profitability, growth, activeness, and stability" sub-titles are observed. Arslan et al. [43] also examined the PMC under the headings of cost, quality, time, and adequacy. It has created 'timely payment to laborers and 'completion of job within the budget' sub-criteria within the subject of cost. El-Mashaleh [44] mentioned the importance of cost control by making timely payments with the criterion of 'prompt payment to labor'. Hanák and Nekardová [40] included 'meeting the planned price' criterion related to cost dimension in their studies.
- Quality (C3): Another meaning of successful completion of construction projects is to reach the quality standards specified in the contracts and specifications, together with the desired time and costs of the product. For this reason, the performance of the SCs involved in the production of the products in the projects, in compliance with the quality standards, is important. Pallikkonda et al. [45] presented a SC preliminary evaluation framework for SC ratings with eight main titles: time, cost, quality, technical capability, management capability, health and safety, experience and reputation and adequacy. In the study, the criterion of 'quality assurance programs' was mentioned in the quality group. In the studies of Arslan et al. [43] under the main heading of quality, 'quality of production', 'quality of materials used', 'job safety' and 'number of qualified personal' criteria are seen. Jasim [46] outlines criteria as 'performance timelines', 'work quality', 'budget management', 'resource availability' and 'communication problems' in his study to classify and diagnose the causes of poor-quality management in construction projects.
- Resource Adequacy (C4): The researchers have gathered some important criteria here by opening the title of 'adequacy'. These were determined as 'adequacy of labor resources', 'adequacy of material resources', 'compliance with company image' and 'compliance with other employees on-site'. Hwang and Lim [47] identified four main categories of critical success factors for project success: project characteristics, contractual arrangements, project participants and interactive processes. The factors that concern SCs were as follows: capability, SC key personal, competency of SC proposed team, SC team turnover rate, SC top management support, SC track record and SC level of service.
- Compatibility and Communication (C5): The communication and compliance abilities of the SCs, with whom the MCs are in constant communication, also affect the performances in other categories for the projects. Mbachu [27] prepared a conceptual evaluation framework for evaluating the performance of SCs during the construction phase and has determined different PMC. Among these criteria, there is also the good communication network criterion. Afshar et al. [22] examined the evaluation criteria in two main groups (technical and behavioral) in a multiple decision-making method model that performed for SC pre-evaluation. The behavioral ones as SC's personality, respect to ethics, creativity, self-control, suitable teamwork, respect for others, honesty, work obligation, having discipline and orderliness, SC personal manner of communi-

cation and SC flexibility in interaction with the MC. It is always possible for changes to occur in the projects during the implementation phase of construction projects. How SCs will respond to this has also become an important question. Based on this, Hanak and Nekardova [40] mentioned the 'ability to flexibility respond to changes in the project' criterion in their work.

- OHS—Environmental Protection (C6): OHS and Environmental Protection issues are among the most important issues in construction projects, which are frequently encountered in addition to time, cost, and quality dimensions. Ng and Tang [28] obtain more qualified results for measurement by including the topics of 'health and safety', 'environmental protection', 'organization', 'general obligations', 'industry awareness' and 'attendance to emergency'. In the SC evaluation study conducted within the framework of lean construction principles, Maturana et al. [26] determined the criteria of 'quality', 'schedule fulfillment', 'safety' and 'cleanliness' developed lean principles in these matters. Cheng et al. [38] gathered the SC performance assessment factors under the following headings in their studies. 'Duration control abilities', 'material wastage', 'collaboration with other SCs', 'safe working environment', 'clean working environment' and 'financial condition'. Ng and Skitmore [30] considered criteria 'workmanship', 'progress', 'safety', 'communication' and 'environment' for SC evaluation. Cheng and Wu [39] listed the SC evaluation criteria in the concept of OHS and Environment as follows: Material wastage, safety and protection, tool usage habit, and workspace cleanliness.
- Leadership (C7): For holistic success in projects, it has become a necessity to examine and evaluate other characteristics of SCs apart from the above-mentioned criteria. Social structures, life views and personal characteristics of the parties can also have an impact in works where efforts are made for a common purpose. Akinshipe et al. [48] revealed that innovative thinking style, problem-solving skills, reliability, emotional maturity and control, and trust from project stakeholders are vital features required for the successful completion of projects. Ferdig [49] defines leaders as follows: Leaders are those who inspire and illuminate a common vision, help build consensus, create direction and create incentives among participants in the beliefs and actions needed by an organization. A more advanced concept, 'Transformational leadership', is a type of leadership that focuses on collaborators and the development of subordinates. Transformational leaders encourage the development of groups and organizations while raising followers' desire for success and self-development [50]. Zavari and Afhsar [51] evaluating the effect of the transformational leadership style of construction site managers on the success of construction projects, showed that the transformational leadership of a site manager is directly related to project success.

Description of the total 23 SC-PMC under these seven groups can also be found in Table 1. A frequency analysis was also performed to detect the frequently mentioned SC-PMC with the information gathered from 24 articles. The result of frequency analysis presented in Table 2.

Table 1. SC-PMC and definitions.

		SC-PMC	Definitions
Time (C1)	C11	Ability to adhere to the project schedule	Compliance with the determined work schedule
	C12	Speed in remedying defects and problems	The speed of faulty or forgotten production in rectifying the defect or deficiency upon warning.

Table 1. *Cont.*

		SC-PMC	Definitions
Cost (C2)	C21	Ability to adhere to the project budget	Staying within the budget limits agreed in the contract.
	C22	Timely payment to its workers	Payment performance to workers in each progress payment period.
Quality (C3)	C31	The quality of the material used	Material usage status in accordance with the standards specified in the contract and general specifications.
	C32	The quality of workmanship	The quality of the construction workmanship done during the application.
	C33	The quality of the resulting final product	Compliance status of the finished production with the project and specifications.
Resource Adequacy (C4)	C41	Technical competence of the employees	The experience, knowledge and competence of the technical personnel employed by the SCs.
	C42	Adequate labor resource availability	Number of workers, availability of machinery, equipment, and vehicles.
	C43	Adequate material resource availability	Whether the material to be used in the production is available at a sufficient level.
Compatibility – Communication (C5)	C51	Compliance with other SCs and employees on-site	Working situation in coordination with other SCs and employees on-site and not causing delay.
	C52	Communication and compliance with the MC	The use of coordinated work execution skills and information exchange in the execution of the project with the MC
	C53	SC's own team harmony	Compatibility and coordination within the SC's own team.
	C54	Ability to adopt and respond to changes in the project	When a change is requested in the productions in the projects, the reactions and analysis skills.
OHS—Environmental Protection (C6)	C61	Attitude towards OHS requirements	The state of adopting and complying with the OHS rules requested by the MC.
	C62	Environmental awareness capability (waste management, etc.)	The ability to re-evaluate the wastes generated as a result of its work or to dispose of the wastes with environmental protection awareness.
	C63	Ability to provide a clean and tidy work environment	A clean and orderly working situation that will not disturb other employees in the working environment and prevent them from doing their jobs.
	C64	Attitude towards material waste	The situation of avoiding unnecessary use and wastage in the use of materials, the ability to use the energy (fuel electricity, etc.) consumed by the vehicles they use efficiently.

Table 1. *Cont.*

		SC-PMC	Definitions
Leadership (C7)	C71	Transformational leadership	Showing leadership that focuses on collaborators and the development of subordinates.
	C72	Commitment	Commitment to the project, the effort it contributed to the solution of the problems with the MC, its contribution to the overall project, apart from his own work part, the ability to make sacrifices.
	C73	Critical analysis and judgment	Ability to accurately identify the advantages and disadvantages of situations, make sound judgments and make decisions based on factual information.
	C74	Vision and imagination	The ability to be creative and innovative and to set solid priorities for future work.
	C75	Strategic perspective	Ability to make short- and long-term assessments and anticipate opportunities and threats.

Table 2. The Frequency Analysis.

SC-PMC			Researchers																							
Main Criteria	**Sub-Criteria**		**Shiau et al. (2003) [41]**	**Ng, S.T. (2007) [24]**	**Ng and Tang (2008) [28]**	**Eom et al. (2008) [42]**	**Arslan et al. (2008) [43]**	**Mbachu, J. (2008) [27]**	**El-Mashaleh (2009) [44]**	**Maturana et al. (2009) [26]**	**Hartmann & Caerteling (2010) [8]**	**Cheng et al. (2011) [38]**	**Cheng and Wu (2012) [39]**	**Ng and Skitmore (2014) [30]**	**Chamara et al. (2015) [32]**	**Pallikonda et al. (2019) [45]**	**Hanák and Nekardová(2020) [40]**	**Jasim (2021) [46]**	**Afshar et al. (2020) [22]**	**Dulewicz and Higgs (2003) [52]**	**Wideman (2000) [53]**	**Mahfouz et al. (2019) [54]**	**Ferdig (2007) [49]**	**Limsila and Ogunlaga (2008) [55]**	**Zhang et al. (2018) [56]**	**Zavari and Afshar (2021) [51]**	**Frequency**
Time C1	**C11**	Ability to adhere to the project schedule	✔	✔		✔	✔	✔	✔	✔		✔	✔	✔	✔	✔	✔	✔	✔								**15/24**
	C12	Speed in remedying defects and problems			✔		✔	✔								✔	✔		✔								**6/24**
Cost C2	**C21**	Ability to adhere to the project budget	✔	✔		✔	✔	✔							✔	✔	✔	✔									**9/24**
	C22	Timely payment to its workers					✔		✔									✔									**3/24**
Quality C3	**C31**	The quality of the material used				✔	✔	✔	✔	✔	✔				✔	✔		✔									**9/24**
	C32	The quality of workmanship	✔	✔		✔	✔	✔	✔	✔	✔			✔	✔	✔		✔									**12/24**
	C33	The quality of the resulting final product	✔	✔		✔	✔	✔	✔	✔	✔				✔	✔		✔									**11/24**
Resource Adequacy C4	**C41**	Technical competence of the employees			✔	✔	✔				✔		✔			✔		✔	✔								**8/24**
	C42	Adequate labor resource availability		✔	✔		✔									✔		✔	✔								**6/24**
	C43	Adequate material resource availability	✔	✔	✔		✔									✔		✔	✔								**7/24**

Table 2. *Cont.*

SC-PMC			Researchers																								
Main Criteria		**Sub-Criteria**	Shiau et al. (2003) [41]	Ng, S.T. (2007) [24]	Ng and Tang (2008) [28]	Eom et al. (2008) [42]	Arslan et al. (2008) [43]	Mbachu, J. (2008) [27]	El-Mashaleh (2009) [44]	Maturana et al. (2009) [26]	Hartmann & Caerteling (2010) [8]	Cheng et al. (2011) [38]	Cheng and Wu (2012) [39]	Ng and Skitmore (2014) [30]	Chamara et al. (2015) [32]	Pallikkonda et al. (2019) [45]	Hanák and Nekardová(2020) [40]	Jasim (2021) [46]	Afshar et al. (2020) [22]	Dulewicz and Higgs (2003) [52]	Wideman (2000) [53]	Mahfouz et al. (2019) [54]	Ferdig (2007) [49]	Limsila and Ogunlaga (2008) [55]	Zhang et al. (2018) [56]	Zavari and Afshar (2021) [51]	**Frequency**
Compatibility and Communication C5	**C51**	Compliance with other SCs and employees on-site	✔	✔		✔		✔			✔	✔	✔	✔		✔		✔	✔								**11/24**
	C52	Communication and compliance with the MC	✔	✔	✔	✔		✔	✔		✔		✔	✔		✔		✔	✔								**12/24**
	C53	SC's own team harmony						✔			✔		✔			✔											**4/24**
	C54	Ability to adopt and respond to changes in the project			✔	✔		✔								✔	✔										**5/24**
Occupational Health & Safety - Environmental Protection C6	**C61**	Attitude towards OHS requirements	✔	✔	✔	✔	✔	✔	✔	✔		✔	✔			✔											**11/24**
	C62	Environmental awareness capability (waste management, etc.)		✔	✔			✔						✔		✔											**5/24**
	C63	Ability to provide a clean and tidy work environment								✔		✔	✔						✔								**4/24**
	C64	Attitude towards material waste	✔					✔				✔	✔			✔											**5/24**
Leadership C7	**C71**	Transformational leadership						✔												✔		✔	✔	✔	✔	✔	**7/24**
	C72	Commitment				✔		✔		✔	✔								✔	✔	✔	✔	✔	✔	✔	✔	**12/24**
	C73	Critical analysis and judgment																		✔							**1/24**
	C74	Vision and imagination				✔														✔			✔		✔		**4/24**
	C75	Strategic perspective				✔														✔			✔				**3/24**

Note: The symbol (✔) indicates that the mentioned criterion is included in the relevant study.

It is seen that in Table 2, the criteria with high frequency are 'Ability to adhere to the project schedule' (C11), 'Ability to adhere to the project budget' (C21), 'The quality of the material used' (C31), 'The quality of workmanship' (C32), 'The quality of the resulting final product' (C33), 'Compliance with other subcontractors and employees on-site' (C51), 'Communication and compliance with the main contractor' (C52), 'Attitude towards OHS requirements' (C61) and 'Commitment' (C72). There are criteria with a high frequency in almost every main group, and it is seen that there is a concentration especially in quality criteria.

5. Pythagorean Fuzzy Analytic Hierarchy Process (PFAHP)

To solve the multi-criteria decision-making method (MCDM) problem, using AHP under Pythagorean fuzzy sets, PFAHP process is revealed to determine the criterion weight of the evaluation criteria. In classical AHP, the linguistic variant of pairwise comparison is presented in terms of definite value. Classical AHP is not suitable for presenting the real state of the problems because it involves uncertainty in linguistic judgment [57]. Since classical AHP is not fully suitable for decision making under uncertainty and uncertainty in the decision-making process, fuzzy AHP is presented by combining AHP with fuzzy logic [58]. To overcome the compensatory approach and the inability of AHP to handle linguistic variables, a variant of AHP called fuzzy AHP has been introduced. The PFAHP method, which is obtained by integrating the Pythagorean fuzzy sets into the AHP method in order to eliminate the uncertainty, was developed with the aim of improving the fuzzy AHP method and obtaining more consistent results.

When the evolution of fuzzy sets was examined: Type-1 fuzzy sets were proposed firstly, and they only consist of the $\mu A(x)$ membership function, which takes values in the range [0, 1]. Then Zadeh [59] develops Type-2 fuzzy sets by expanding Type-1 fuzzy sets with a membership function range. Next, Atanassov [60] developed the intuitionistic fuzzy Set (Ifs) theory by extending the fuzzy set theory. In IFs theory, the degree of membership is given as well as the degree of non-membership. According to this theory, μ is the degree of membership of an element, and ν is the degree of non-membership. The equation $0 \leq \mu + \nu \leq 1$ must be satisfied. As one of the extensions of IFs, Smarandache [61] develops neutrophic fuzzy sets defined by degrees of truthiness, indeterminacy and falsity. Torra [62] prove that the envelope of the hesitant fuzzy sets is an IFs and multiple degrees of membership function are used in hesitant fuzzy sets. PFs were introduced by Yager [63] in some cases developed as a generalization to IFs, since IFs cannot fully express uncertainty [64]. There may be a situation where the sum of the membership degree and non-membership degree of the alternative provided by the decision maker is greater than 1 [65]. To overcome this shortcoming, according to Yager's proposed theory of PFs, $0 \leq \mu^2 + \nu^2 \leq 1$ equality condition is required to provide [66]. Thus, while ordinary fuzzy sets and IFs cannot explain this situation, PFs overcomes this situation. PFs provide greater autonomy to decision makers in expressing their assessment of the uncertainty in the MCDM problem under consideration [67].

In conclusion, Pythagorean fuzzy sets (PFs) is the generalization of the intuitionistic fuzzy sets (IFs) and is more capable than IFs at expressing and handling uncertainty in uncertain environments. PFSs have been developed so that experts can make clearer decisions over a wider area and express their assessment of the problem being addressed [68]. Lin and Chen, [69] as a result of their bibliometric analysis on Pythagorean fuzzy sets in the 2013–2020 period, determined that current research studies on PFSs mainly focus on developing addition operators, score functions, correlation coefficients, distance measures and also decision methods. Garg [70], who stated that the correlation coefficient plays an important role in statistics and engineering sciences, drew attention to the weakness of the existing correlation coefficients between IFSs. According to Garg [70], PFS theory can handle not only incomplete information, but also vague information and inconsistent information commonly found in real situations. Zhang and Xu [71] proposed an extended technique for sequence preference through analogy to the ideal solution method for efficient solutions of MCDM problems with PFs. Ma and Xu [72] have defined some new Pythagorean fuzzy weighted geometric/averaging operators to fit the existing score function and accuracy function for PFs for the pythagorean fuzzy number. Xiao and Ding [73] have proposed a new measure of deviation between PFSs using the Jensen–Shannon divergence.

The PFAHP method, which is obtained by integrating the PFs into the AHP method to eliminate the uncertainty, was developed with the aim of improving the fuzzy AHP method and obtaining more consistent results. Based on the ability to express thoughts linguistically, PFAHP is an effective method for removing ambiguity in language [37].

In the literature, the PFAHP method has been applied for different problems and successful results have been obtained. Karasan et al. [74] stated that PFs are superior to other extensions with a more flexible definition of the membership function and developed a new PFAHP method for a landfill selection problem for the city of Istanbul in Turkey. Song et al. [75] compared the traditional AHP and PFAHP results in their study for retail credit risk assessment and determined that the method of PFAHP could obtain reliable evaluation results and evaluate individual loans more accurately. Yildiz et al. [57] updated the criteria determined by the European Union to evaluate the quality of life of countries and determined the weights of these criteria with the PFAHP method. Çalık and Afşar [76] used the PFAHP to prioritize customers' bank selection criteria and aimed to provide more freedom to decision makers in expressing their opinions. On the other hand, it has also been seen that the use of the PFAHP method is not much used in the problems related to construction management [77]. Sarkar and Biswas [78] represented a combined approach consisting of AHP and TOPSIS to solve MCDM problems of unknown weights in a pythagorean fuzzy environment. Ayyıldız and Taskin Gumus [58] applied the PFAHP method to determine the critical risk factors and their weights for hazardous material transportation operations.

Based on all of these works, it is thought that interpretations can be flexible and variable, keeping in mind that the construction industry consists of temporary businesses that are constantly changing and developing. Stakeholders in the construction industry may have linguistic variability when expressing situations. It is desired to minimize the uncertainties caused by this variability. Because more reliable and accurate data can be obtained with less uncertainty. For these reasons, the PFAHP method has been deemed appropriate to measure the performance of the SC and to determine the importance levels of the aforementioned criteria, which are among our measurement inputs, for a related evaluation mechanism.

With the aim of determining importance weights of SC-PMC, pairwise comparisons of the criteria were made using the PFAHP method with 20 experts working actively in the MC companies. Detailed information regarding data collection, data analysis and steps of PFAHP can be found below.

5.1. Data Collection

A questionnaire was prepared to determine the importance weights of SC-PMC. Within the questionnaire, firstly, the main categories of PMC were compared with each other. Then, the sub-criteria within each main category were compared among themselves. The questionnaire in this study was answered by 20 experts with 10 years or more of technical experience working in different working groups (construction superstructure works, infrastructure works, road construction, natural gas pipe laying works, etc.) as the representatives of the MC companies of medium and large-scale projects. 13 of these experts are civil engineers. In total, 3 architects, 2 mechanical engineers and 2 electrical engineers participated in this study; 50% of the experts have 10–15 years, 20% 16–20 years and 30% more than 20 years of experience. The education levels of the experts were also asked, and there are 6 experts who have completed their master's degree, although they are generally undergraduate. The age information of the companies where the experts are currently working was also obtained. Accordingly, 30% of the MC companies are aged 30 years and over, 30% are between the ages of 16–29 years, and the remaining 40% are companies aged 10–15 years.

In PFAHP literature, it is acceptable that the sample size of participating experts between 5–10 would be sufficient [57,75]. For example, in Boyacı and Şişman [79], Yücesan and Kahraman [80], Mete [81] and Gül and Ak [82] studies number of expert participants for PFAHP analysis is under 10 whereas in Song et al. [75] and Yıldız et al. [57] studies, the number of expert participants for PFAHP analysis is 10. It was also found that a few studies involving more than 10 participants exist in the PFAHP literature [83]. Since it is known that the construction industry has a very large volume of different categories and stakeholders with different experience and working skills, the number of participants in this questionnaire was preferred to be over 10. Considering the diversity and variable structure of the construction industry, experts with SC management experience were sought. For this purpose, the owners of the MC companies or the MC officials who have decision-making authority and experienced people who previously worked as technical personnel or managers in the MC companies in the projects where SCs were employed were selected for the survey.

5.2. Data Analysis

The data obtained by 20 experts in total were entered into the MATLAB computer program in which the mathematical steps of PFAHP were applied. Then, importance weights of the criteria to be used in the performance measurement of the SCs were revealed.

In an environment where MCs will evaluate the performance of SCs on construction sites, not all criteria may be given equal importance. A high success rate in criteria with a high coefficient of importance will both ensure the success of the SC and increase the success of the project. Therefore, determining the importance levels of SC-PMC by the relevant experts in the sector will be a reference for the next steps.

5.2.1. Steps of PFAHP

The six steps of the PFAHP method can be found below.

Step 1. A pairwise comparison matrix $A = \left(a_{ij}\right)_{\cdot mxm}$ is created based on linguistic variables.

Step 2. Using Equations (1) and (2), the difference matrix $D = \left(d_{ij}\right)_{\cdot mxm}$ is formed.

$$d_{ij_L} = \left(\mu_{ij_L}\right)^2 - \left(\nu_{ij_L}\right)^2 \tag{1}$$

$$d_{ij_U} = \left(\mu_{ij_U}\right)^2 - \left(\nu_{ij_U}\right)^2 \tag{2}$$

Step 3. The multiplicative matrix $S = \left(s_{ij}\right)_{\cdot mxm}$ is calculated using Equations (3) and (4).

$$s_{ij_L} = \sqrt{1000^{d_{ijL}}} \tag{3}$$

$$s_{ij_U} = \sqrt{1000^{d_{ijU}}} \tag{4}$$

Step 4. The degrees of hesitation are determined using $H = \left(h_{ij}\right)_{\cdot mxm}$ Equation (5).

$$h_{ij} = 1 - \left(\mu_{ijU}^2 - \mu_{ijL}^2\right) - \left(v_{ijU}^2 - v_{ijL}^2\right) \tag{5}$$

Step 5. Un-normalized weights $T = \left(t_{ij}\right)_{\cdot mxm}$ are calculated with the help of Equation (6).

$$t_{ij} = \left(\frac{s_{ij_U} + s_{ij_L}}{2}\right) h_{ij} \tag{6}$$

Step 6. The criteria weights w_i are determined using Equation (7).

$$w_i = \frac{\sum_{i=1}^{m} t_{ij}}{\sum_{i=1}^{m} \sum_{j=1}^{m} t_{ij}} \tag{7}$$

The ten-point scale shown in Table 3 was used to express the experts' verbal statements about the criteria as fuzzy numbers.

5.2.2. Consistency Analysis

The consistency of the matrices is calculated by calculating the consistency ratio (CR) [84]. The matrix is considered consistent if the consistency ratio is less than 0.10. Consistency rate is found by dividing the consistency index (CI) by the random index (RI). RIs are constant coefficients that vary with the size of the matrix. The CI is calculated with the following formula:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{8}$$

$$CR = \frac{CI}{RI} \tag{9}$$

Table 3. Definition and interval-valued Pythagorean fuzzy scales of the linguistic variables.

Linguistic Variables	Interval-Valued Pythagorean Fuzzy Numbers			
	μ_L	μ_U	v_L	v_U
Certainly low important (CL)	0.0	0.0	0.9	1.0
Very low important (VL)	0.1	0.2	0.8	0.9
Low important (L)	0.2	0.35	0.65	0.8
Below average important (BA)	0.35	0.45	0.55	0.65
Exactly equal (EE)	0.1965	0.1965	0.1965	0.1965
Average important (A)	0.45	0.55	0.45	0.55
Above average important (AA)	0.55	0.65	0.35	0.45
High important (H)	0.65	0.8	0.2	0.35
Very high important (VH)	0.8	0.9	0.1	0.2
Certainly high important (CH)	0.9	1.0	0.0	0.0

Since the matrix size (n) of the sub-criteria of the main criteria C1 and C2 is two, consistency analysis is not performed. As a result of the operations, the CR values of the matrices of the sub-criteria of the main criteria are as follows. CR values of the matrixes can be found in Table 4.

Table 4. Consistency ratio (CR) values of the matrixes.

	Main Criteria	C1	C2	C3	C4	C5	C6	C7
Consistency Ratio (CR)	0.0089	-	-	0.0077	0.0596	0.0254	0.0164	0.0062

5.2.3. Sensitivity Analysis of the PFAHP Method

A sensitivity analysis is performed to demonstrate the robustness and applicability of the proposed decision-making methodology [58]. The weights of the main criteria obtained from the PFAHP are changed between the two main criteria, while the others are kept constant. The weight of the first main criteria is then replaced by the second (C1–C2), third (C1–C3), fourth (C1–C4), fifth (C1–C5), sixth (C1–C6) and seventh (C1–C7) main criteria, while the remaining criteria weights are fixed. This process is continued by performing among other main criteria. The sub-criteria weights according to the changes in the main criteria weights are given in Figure 2. According to the Figure 2, by considering the first main criteria as 'Time' and the second one 'Cost', these main criteria importance weights are exchanged. Then the final importance weight of 'Ability to adhere to the project schedule' (C11) increases from 0.1507 to 0.1711, the final weight of (C21) also decreases from 0.1818 to 0.1601. The process of sensitivity analysis is shown in Figure 2 whereas Figure 3 shows sub-criteria weight changes gained by the sensitivity analysis.

Figure 3 shows the final importance weights of the sub-criteria according to the sensitivity analysis. According to Figure 3, the highest weight changes are observed in the sub-criteria 'Ability to adhere to the project budget' (C21) and 'Ability to adapt to the project schedule' (C11). These sub-criteria are more widely affected by the importance of the main criteria. On the other hand, criteria such as C73, C74, C75, which have low importance, had less impact on the sensitivity analysis and showed the effectiveness of their importance levels.

5.2.4. PFAHP Analysis Results

According to the PFAHP analysis, both the order of main criteria importance weights and the sub-criteria importance weights are shown in Table 5.

	Local	Final	C1–C2	C1–C3	C1–C4	C1–C5	C1–C6	C1–C7	C2–C3	C2–C4
C11	0.7780	0.1507	0.1711	0.1417	0.0878	0.0641	0.1083	0.0543	0.1507	0.1507
C12	0.2220	0.0430	0.0488	0.0404	0.0251	0.0183	0.0309	0.0155	0.0430	0.0430
C21	0.8267	0.1818	0.1601	0.1818	0.1818	0.1818	0.1818	0.1818	0.1506	0.0933
C22	0.1733	0.0381	0.0336	0.0381	0.0381	0.0381	0.0381	0.0381	0.0316	0.0196
C31	0.3364	0.0613	0.0613	0.0651	0.0613	0.0613	0.0613	0.0613	0.0740	0.0613
C32	0.3359	0.0612	0.0612	0.0650	0.0612	0.0612	0.0612	0.0612	0.0739	0.0612
C33	0.3278	0.0597	0.0597	0.0635	0.0597	0.0597	0.0597	0.0597	0.0721	0.0597
C41	0.3761	0.0425	0.0425	0.0425	0.0728	0.0425	0.0425	0.0425	0.0425	0.0827
C42	0.4126	0.0466	0.0466	0.0466	0.0799	0.0466	0.0466	0.0466	0.0466	0.0907
C43	0.2113	0.0238	0.0238	0.0238	0.0409	0.0238	0.0238	0.0238	0.0238	0.0465
C51	0.2533	0.0209	0.0209	0.0209	0.0209	0.0491	0.0209	0.0209	0.0209	0.0209
C52	0.2263	0.0187	0.0187	0.0187	0.0187	0.0438	0.0187	0.0187	0.0187	0.0187
C53	0.2430	0.0200	0.0200	0.0200	0.0200	0.0471	0.0200	0.0200	0.0200	0.0200
C54	0.2775	0.0229	0.0229	0.0229	0.0229	0.0537	0.0229	0.0229	0.0229	0.0229
C61	0.3942	0.0548	0.0548	0.0548	0.0548	0.0548	0.0763	0.0548	0.0548	0.0548
C62	0.2608	0.0363	0.0363	0.0363	0.0363	0.0363	0.0505	0.0363	0.0363	0.0363
C63	0.1402	0.0195	0.0195	0.0195	0.0195	0.0195	0.0272	0.0195	0.0195	0.0195
C64	0.2048	0.0285	0.0285	0.0285	0.0285	0.0285	0.0397	0.0285	0.0285	0.0285
C71	0.1975	0.0138	0.0138	0.0138	0.0138	0.0138	0.0138	0.0382	0.0138	0.0138
C72	0.3891	0.0271	0.0271	0.0271	0.0271	0.0271	0.0271	0.0754	0.0271	0.0271
C73	0.1319	0.0092	0.0092	0.0092	0.0092	0.0092	0.0092	0.0255	0.0092	0.0092
C74	0.1333	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093	0.0258	0.0093	0.0093
C75	0.1483	0.0103	0.0103	0.0103	0.0103	0.0103	0.0103	0.0287	0.0103	0.0103

	C2–C5	C2–C6	C2–C7	C3–C4	C3–C5	C3–C6	C3–C7	C4–C5	C4–C6	C4–C7	C5–C6	C5–C7	C6–C7
C11	0.1507	0.1507	0.1507	0.1507	0.1507	0.1507	0.1507	0.1507	0.1507	0.1507	0.1507	0.1507	0.1507
C12	0.0430	0.0430	0.0430	0.0430	0.0430	0.0430	0.0430	0.0430	0.0430	0.0430	0.0430	0.0430	0.0430
C21	0.0682	0.1150	0.0577	0.1818	0.1818	0.1818	0.1818	0.1818	0.1818	0.1818	0.1818	0.1818	0.1818
C22	0.0143	0.0241	0.0121	0.0381	0.0381	0.0381	0.0381	0.0381	0.0381	0.0381	0.0381	0.0381	0.0381
C31	0.0613	0.0613	0.0613	0.0380	0.0277	0.0468	0.0235	0.0613	0.0613	0.0613	0.0613	0.0613	0.0613
C32	0.0612	0.0612	0.0612	0.0379	0.0277	0.0467	0.0234	0.0612	0.0612	0.0612	0.0612	0.0612	0.0612
C33	0.0597	0.0597	0.0597	0.0370	0.0270	0.0456	0.0229	0.0597	0.0597	0.0597	0.0597	0.0597	0.0597
C41	0.0425	0.0425	0.0425	0.0685	0.0425	0.0425	0.0425	0.0310	0.0523	0.0262	0.0425	0.0425	0.0425
C42	0.0466	0.0466	0.0466	0.0752	0.0466	0.0466	0.0466	0.0340	0.0574	0.0288	0.0466	0.0466	0.0466
C43	0.0238	0.0238	0.0238	0.0385	0.0238	0.0238	0.0238	0.0174	0.0294	0.0147	0.0238	0.0238	0.0238
C51	0.0557	0.0209	0.0209	0.0209	0.0461	0.0209	0.0209	0.0286	0.0209	0.0209	0.0352	0.0177	0.0209
C52	0.0498	0.0187	0.0187	0.0187	0.0412	0.0187	0.0187	0.0255	0.0187	0.0187	0.0315	0.0158	0.0187
C53	0.0534	0.0200	0.0200	0.0200	0.0443	0.0200	0.0200	0.0274	0.0200	0.0200	0.0338	0.0169	0.0200
C54	0.0610	0.0229	0.0229	0.0229	0.0505	0.0229	0.0229	0.0313	0.0229	0.0229	0.0386	0.0194	0.0229
C61	0.0548	0.0867	0.0548	0.0548	0.0548	0.0718	0.0548	0.0548	0.0445	0.0548	0.0325	0.0548	0.0275
C62	0.0363	0.0574	0.0363	0.0363	0.0363	0.0475	0.0363	0.0363	0.0294	0.0363	0.0215	0.0363	0.0182
C63	0.0195	0.0308	0.0195	0.0195	0.0195	0.0255	0.0195	0.0195	0.0158	0.0195	0.0116	0.0195	0.0098
C64	0.0285	0.0451	0.0285	0.0285	0.0285	0.0373	0.0285	0.0285	0.0231	0.0285	0.0169	0.0285	0.0143
C71	0.0138	0.0138	0.0434	0.0138	0.0138	0.0138	0.0360	0.0138	0.0138	0.0223	0.0138	0.0163	0.0275
C72	0.0271	0.0271	0.0856	0.0271	0.0271	0.0271	0.0709	0.0271	0.0271	0.0439	0.0271	0.0321	0.0541
C73	0.0092	0.0092	0.0290	0.0092	0.0092	0.0092	0.0240	0.0092	0.0092	0.0149	0.0092	0.0109	0.0184
C74	0.0093	0.0093	0.0293	0.0093	0.0093	0.0093	0.0243	0.0093	0.0093	0.0150	0.0093	0.0110	0.0185
C75	0.0103	0.0103	0.0326	0.0103	0.0103	0.0103	0.0270	0.0103	0.0103	0.0167	0.0103	0.0122	0.0206

Figure 2. The sensitivity analysis processes.

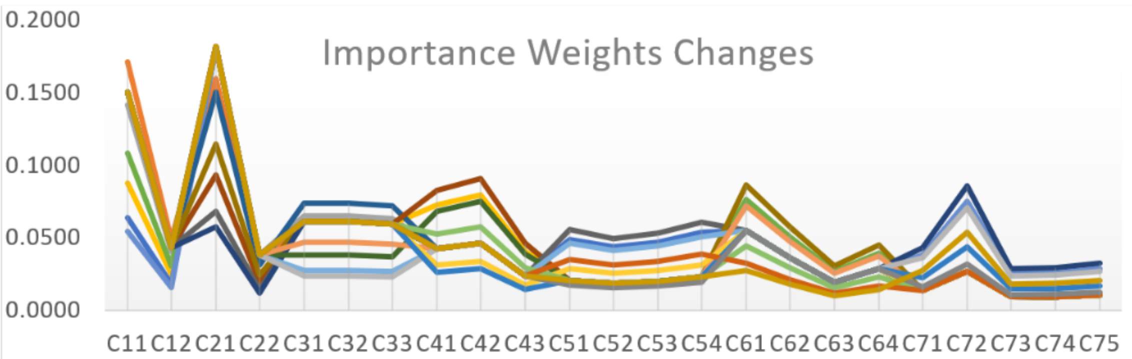

Figure 3. Sub-criteria importance weight changes gained by the sensitivity analysis.

Table 5. Final weights for main criteria and sub-criteria.

Main Criteria	Weight	Rank	Sub-Criteria	Local Weight	Final Weight	Rank
C1 Time	0.1937	2	C11 Ability to adhere to the project schedule	0.7780	0.1507	2
			C12 Speed in remedying defects and problems	0.2220	0.0430	8
C2 Cost	0.2200	1	C21 Ability to adhere to the project budget	0.8267	0.1818	1
			C22 Timely payment to its workers	0.1733	0.0381	10
C3 Quality	0.1822	3	C31 The quality of the material used	0.3364	0.0613	3
			C32 The quality of workmanship	0.3359	0.0612	4
			C33 The quality of the resulting final product	0.3278	0.0597	5

Table 5. *Cont.*

Main Criteria	Weight	Rank	Sub-Criteria	Local Weight	Final Weight	Rank
C4 Resource Adequacy	0.1129	5	C41 Technical competence of the employees	0.3761	0.0425	9
			C42 Adequate labor resource availability	0.4126	0.0466	7
			C43 Adequate material resource availability	0.2113	0.0238	14
C5 Compatibility-Communication	0.0824	6	C51 Compliance with other SCs and employees on-site	0.2533	0.0209	16
			C52 Communication and compliance with the MC	0.2263	0.0187	19
			C53 SC's own team harmony	0.2430	0.0200	17
			C54 Ability to adopt and respond to changes in the project	0.2775	0.0229	15
C6 OHS-Environmental Protection	0.1391	4	C61 Attitude towards OHS requirements	0.3942	0.0548	6
			C62 Environmental awareness capability (waste management)	0.2608	0.0363	11
			C63 Ability to provide a clean and tidy work environment	0.1402	0.0195	18
			C64 Attitude towards material waste	0.2048	0.0285	12
C7 Leadership	0.0698	7	C71 Transformational leadership	0.1975	0.0138	20
			C72 Commitment	0.3891	0.0271	13
			C73 Critical analysis and judgment	0.1319	0.0092	23
			C74 Vision and imagination	0.1333	0.0093	22
			C75 Strategic perspective	0.1483	0.0103	21

According to the PFAHP analysis, C21 (ability to adhere to the project budget) criterion, which is the sub-criterion of the 'Cost' was the most important criterion. C11 (ability to adhere to the project schedule) criterion, which is close to this value and included in the 'Time' category, took the second place. In addition to these, C61 (attitude towards OHS requirements) in the 'OHS-Environmental Protection' group became one of the most important ones. The criteria with low importance were generally gathered in the 'Compatibility-Communication' and 'Leadership' groups. C75 (strategic perspective), C74 (Vision and imagination) and C75 (critical analysis and judgment) criteria are in the last row.

5.2.5. Discussion of the PFAHP Analysis Results

According to the PFAHP analysis results, it is found that time, cost and quality criteria have the highest importance among all main criteria. Considering that construction success triangle is gathered around these three main criteria, these three basic criteria will lead the SC performance, thus increasing the project performance. Considering the final importance weights of C21 and C11, it has been seen that it is very important for the organizations serving as the MC in the construction industry to carry out the works within the desired budget and schedule period. El-khalek et al. [19] proved the importance of time and cost criteria in the study in which the effects of SC prequalification evaluation criteria on project success were determined. In addition to the 'time' criterion, it is stated that 'not being able to complete the contract due to financial reasons' is among the most important criteria. Findings of PFAHP analysis confirms that crucially of completing the construction works within agreed time, cost, and quality. The importance weights of the C31, C32 and C33 criteria, which are in the quality performance category, are very close to each other. It is understood that the MCs attach great importance to quality, along with time and cost dimensions, and give equal importance to material, workmanship and the quality of the resulting final product. The attention given to quality-related criteria in the literature [26,27,32,42–46] has been proven here as well, demonstrating its importance for the construction industry once. Issues such as resource adequacy, OHS, waste management, material waste as well are considered important by the experts in the industry. However, the traditional success basis of the construction industry, the fact that the works are done at the desired time, cost and quality has left these criteria in the background. Whereas, in order for the work to be done at the desired time, cost and quality, it actually depends on supporting conditions such as sufficient resources (labor force, material, personnel, etc.), reducing work accidents, giving importance to material recycling and using resources economically.

Mbachu [27] investigated key criteria to evaluate SCs' eligibility for an invitation to bid and their performance during the subsequent construction phase and used the multi-attribute technique in the data analysis. The quality criterion, among the 10 performance criteria determined for the construction phase, was at the highest level in the order of importance. 'High rate of productivity ensuring on-time delivery; efficient management and control of workforce', 'Cost control-waste minimization' and 'Good working relations with the main contractor's team, as well as good tolerance, loyalty and zero or minimal adversarial relation' criteria, were also determined as very important criteria in this study. It is seen that time, cost and quality criteria are similarly highly important in our study, but while quality is ranked first in this study in order of importance, it comes after time and cost criteria in our research. On the other hand, the importance of communication with the MC was a little behind in our research compared to this study.

C2 (cost) has the highest importance among all the main criteria as a result of this study. In addition, its sub-criteria C21 (ability to adhere to the project budget) is found out as the most prominent criterion (ranked at 1th place) that affects SC performance on-site while its other sub-criteria C22 (timely payment to its workers) is in the 10th place. Experts participating in the PFAHP analysis used expressions indicating that C21 is very important compared to C22 in general during the comparison between these two criteria. The reason for this difference is that the MCs are more concerned with the overall budget of the project. SCs' relationships with their own employees remain in the background for MCs. On the other hand, in the construction industry, where the labor cost is between 30% and 50% of the total project cost [85], MCs are more eager to consider the damages that may be caused by the disruptions in the labor payments, gave this criterion more importance than most criteria.

According to the PFAHP analysis results, the criterion of highest importance that was not included in the time, quality and budget criteria, was found to be C61 (Attitude towards OHS requirements) under OHS-environmental protection criterion. Lin and Mills [86] found that OHS is an important issue for companies, mainly because of fear of prosecution. Many OHS experts believe that better OHS performance is possible with the implementation of effective OHS management systems.

The importance of waste management needs to be understood to encourage stakeholders in this regard, as the construction industry cannot continue to implement if the environmental resources on which it depends are depleted [87]. The results of the study also reveal the necessity of environmental protection from the perspective of SCs. According to the PFAHP analysis results, environmental management-related criteria (C62 and

C64) have moderate importance in the overall ranking. It is understood that the effects of these criteria, which are neither considered too important nor too unimportant, on project performance in the construction industry are noticed by MCs. It is thought that the level of importance will gradually increase in the coming periods.

The difference between the importance weights of some criteria is high does not mean that low-value criteria are unnecessary. 14 experts who expressed their opinions during the determination of the 23 criteria and 20 experts who participated in the PFAHP study stated that the existing criteria are necessary and effective in measurement of the SC performance. If a holistic situation is aimed, it is also stated by experts that each criterion has a separate valuable contribution. Based on this, Famakin and Abisuga [88] express that effective leadership and employee engagement are the two main factors required for project success, suggest that the leaders of construction projects should prioritize the leadership style that affects employee commitment. Although the leadership dimension is not given much importance by the MCs, the sub-criteria of 'Commitment' (C72) stood out as a criterion that is given great importance in its own group. At the same time, when looking at the criteria that it left behind by taking the 13th place in the general ranking, it is understood that the MCs need SCs who dedicate themselves to the project and do not think only of their own interests.

The fact that the social dimensions are slightly behind compared to the technical dimensions shows that the companies have a high level of concerns about the time, cost and quality of the construction. These concerns often cause some benefits to be overlooked in projects that can assist in solving important problems. Eom et al. [42] pointed out the importance of communication and therefore harmony, stating that costly delays occur due to incorrect and untimely communication among the project members in the construction sector. Ofori and Toor [89] stated that the poor performance of projects in developing countries may cause serious problems for their countries and residents, because of completed projects affect long-term socioeconomic development. Therefore, they argued that construction processes and construction project features need effective leadership, and effective leadership can be the solution to the major problems of the construction industry, especially in developing countries. It is understood that for most construction managers, leadership is not a priority issue compared to other criteria in the study, and they ignore the benefits of this dimension, which has proven to be effective in reducing the different risks in the project. However, Rehman and Ishak [90] stated that active leadership is an important factor in dealing with complexities involving risk in terms of time, cost and quality in the construction project. Indeed, criteria related to leadership should not be underestimated by MCs considering their indirect effect on time, cost and quality that constitutes project success.

While it is aimed to increase the overall success rate by measuring the performance of the SCs on the basis of the aforementioned criteria, there are also targeted situations for each criterion. The targeted outputs of the criteria ranked in the top 10 according to their importance are shown in the Table 6.

Table 6. Targeted outputs by evaluating the top 10 criteria.

Sub-Criteria	Targeted Outputs
C21 Ability to adhere to the project budget	Anticipating budget overruns and taking action
C11 Ability to adhere to the project schedule	Preventing the project from exceeding the deadline by foreseeing possible delays
C31 The quality of the material used C32 The quality of workmanship C33 The quality of the resulting final product	Producing in accordance with quality standards by preventing all defects previously that may occur in the final product

Table 6. *Cont.*

Sub-Criteria	Targeted Outputs
C61 Attitude towards OHS requirements	Reducing occupational accidents and diseases by providing stricter follow-up of OHS rules
C42 Adequate labor resource availability	Preventing problems such as manufacturing errors and delays that may be caused by elements such as insufficient workers, equipment and machinery
C12 Speed in remedying defects and problems	Avoiding wasted time by taking more responsibility by SCs to quickly fix manufacturing defects
C41 Technical competence of the employees	Increasing the ratio of employees with more experience and suitable technical qualifications
C22 Timely payment to its workers	Reducing pull out of the work and dissatisfaction by tracking the payments of SCs to their employees

6. A Dynamic Subcontractor Management Framework for Performance Measurement and Evaluation on Project Execution Phase

It is obvious that the most crucial stage in determining the success of the projects is the construction phase. At the same time, while a significant part of the work is done by SCs, there is a need for a dynamic monitoring, auditing and decision-making process beyond the static control and monitoring outside of traditional methods. Within the findings that there are deficiencies in onsite SC performance measurement and evaluation during the project execution phase, developing of a dynamic SC management framework that can be used in the performance measurement of the SCs in project execution phase constitutes an important necessity.

In Figure 4, 'a dynamic SC performance management framework during the project execution phase' is proposed. This proposed framework is based on the idea that regular periodic performance measurements will be made using the SC-PMC created for the project execution phase and some decisions will be made with the data obtained. The framework consists of 'performance measurement', 'performance data appraisal' and 'action plan' parts.

6.1. Performance Measurement

Construction projects frequently suffer from the consequences of poor performance in terms of time delays, cost overruns and quality flaws [91]. In construction projects, it has become an important issue to constantly supervise SCs, to whom a significant part of the time, cost and quality dimensions of the works are entrusted. In the proposed framework, 'performance measurement' is the stage where regular performance measurements will be made by providing the inspection mechanism not only in time, cost and quality dimensions, but also in resource adequacy, OHS and environmental protection, compatibility and communication and leadership dimensions. While the project continues, using SC-PMC and a scoring system, performance evaluation will be carried out after performance measurement. It is recommended that measurements be made periodically on a weekly or monthly basis. It is necessary to use data and documents such as schedule of the work and progress payment documents, quality standard and control documents, technical personnel, worker, equipment, and vehicle information, OHS inspection reports, environmental waste recycling reports, daily and weekly site reports of the construction project. To be able to score criteria such as communication and leadership, it is necessary that the official who will make the measurement must be someone who has command of the field and SCs, and personal comments must be as objective and fair as possible. It is recommended to use a measurement scale with scores from 1 to 10 for measurement.

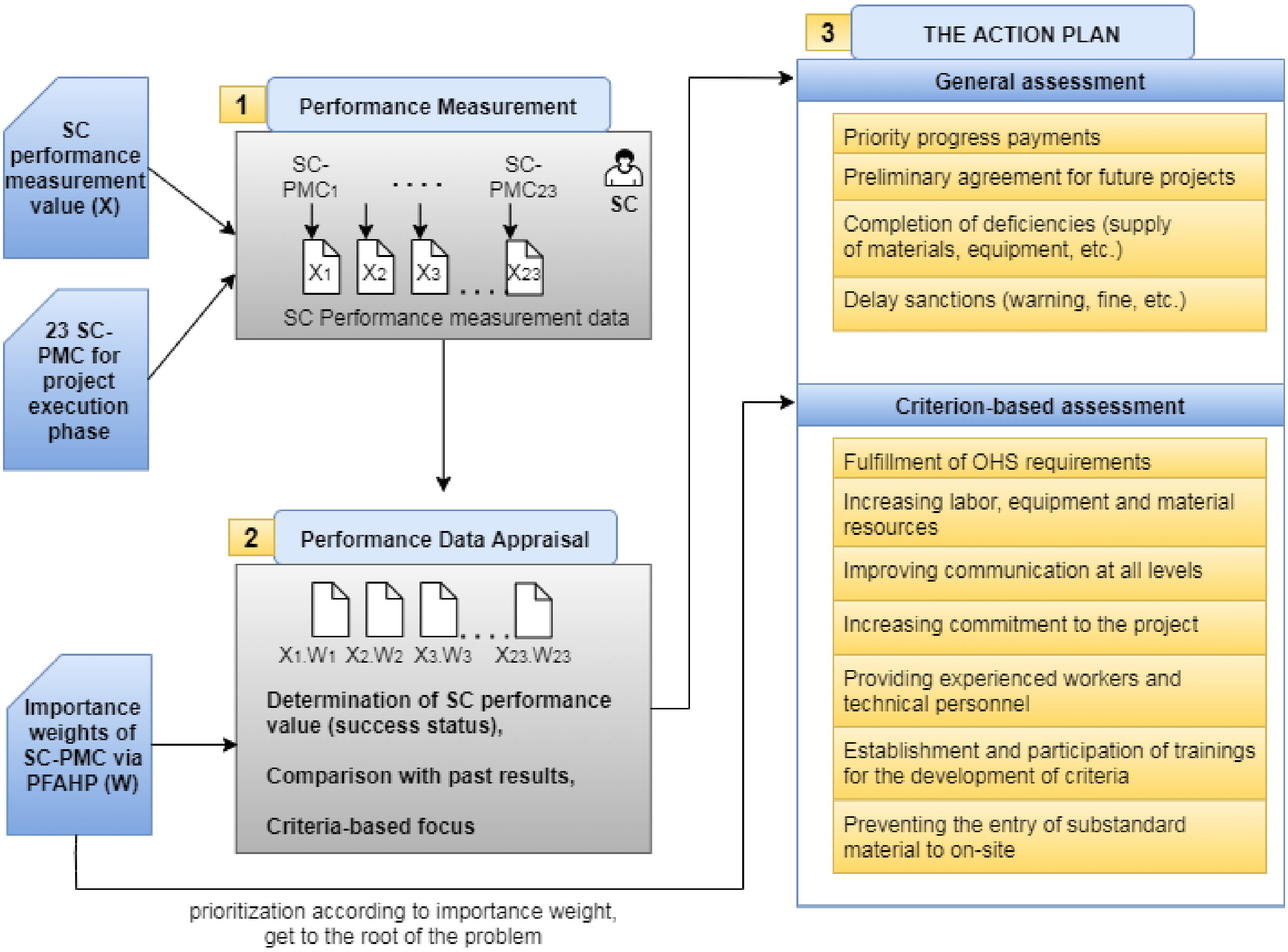

Figure 4. A dynamic SC performance management framework during the project execution phase.

6.2. Performance Data Appraisal

In the second step, the importance weights obtained as a result of PFAHP analysis will be used as the importance effect coefficient for SC-PMC. Thus, general on-site performance value of SCs will be created. This importance effect factor will come into play in the evaluation and action phases after the performance measurement of the SC during the project execution phase. As a result of this process, which will be carried out periodically (monthly or weekly), the results will be compared, and the progress of SCs will be monitored. In addition, this criteria-based focus approach will enable underperformed SCs to focus on the criterion/criteria that cause poor performance, and the root causes can be addressed in this way.

6.3. The Action Plan

The scope of the dynamic framework is that the decisions to be taken faster and more accurately by taking the actions faster. For this, it is aimed to take actions in the form of both criteria-based and general evaluation. SCs will be expected to make an effort to increase performance measurement values, while close supervision of MCs will be ensured to be multidimensional. SCs aiming to increase their performance values will move towards different working styles and will support the concept of dynamism by getting out of stagnation.

In the 'Action Plan' part, an overall evaluation of the general performance value will be in question. This proposed framework is based on the idea that some corrective and/or precautionary actions can be applied in terms of the actual performance of SCs. It may be possible to warn low-performing SCs, to impose penal sanctions, or to take remedial interventions such as material, equipment, vehicle, worker payments by the MC. In this way, it is aimed to contribute to the solution of possible quality defects, delays and financial problems in the project. On the other hand, to keep these performances of high-performing SCs up to date and reward them, actions such as progress payment priority and pre-agreement for future projects have been suggested.

The action plan part that strengthens the concept of dynamism of the tentative SC performance management framework, enables taking of different decisions at different times and going beyond the conventional rules in the contracts that will guide the course of the project. In this way, a management model can be applied that will enable MCs to be more dynamic and proactive when managing SCs. This will allow the elimination of some uncertain situations in future projects and the formation of sustainable partnerships.

Success in construction projects depends on the correct and timely good performance of stakeholders. Even if these performances are bad, it is necessary to observe and take immediate action. Otherwise, delays, cost overruns, quality deficiencies, OHS risks, workforce inadequacies, communication gaps and incompatibilities may occur. In order to prevent all these and similar problems, the temporary framework we propose allows the performance of SCs to be periodically measured and evaluated with criteria of different dimensions while the works are in progress, and to take action according to the results. In the action plan section, actions such as warning, applying, or bringing up on the agenda penal sanctions in contracts, making rewards (progress payment priority, etc.), making remedial interventions (material supply support, workforce support and training support, etc.) are generally recommended. In this context, at the point of decision making, a fair, very meticulous, and multidimensional follow-up and evaluation is essential in order to base the decisions on solid grounds.

7. Conclusions

This study aimed to determine the criteria to be used in the performance measurement of SCs in the project execution phase and to determine the criteria that will contribute more and directly to the success of the SC work performance by calculating their importance weights. Thus, a dynamic SC management was aimed by creating the action plans of the MCs. In this context, 23 sub-criteria were determined in 7 main groups by examining and collecting the criteria that were previously included in different studies separately in the literature and blending them with expert evaluations. While measuring performance, the importance weights of these criteria, obtained as a result of the PFAHP analysis, are suggested as the effect values of these criteria on success.

In construction projects, the performance of the SCs to stay within the budget agreed in the contract has been the most important criterion for the MCs. Immediately after, the criterion regarding the completion of the works at the desired time listed. The quality of workmanship, materials and the final product have the same weights of importance, and the quality criteria, together with the cost and time dimensions, have formed the most important performance criteria of the SCs. MCs also attach great importance to the performance of SCs in terms of OHS in order not to deal with serious criminal sanctions. In the 'leadership dimension', which includes sub-criteria that will add value to the projects, and which is handled to evaluate SCs in a different dimension, the criteria of dedication and transformational leadership attracted attention. Even though it is in the last place in the general ranking, it is estimated that this group will take place more frequently in future studies.

The contribution of the study to the literature can be listed as follows: (1) While the literature generally focuses on the evaluation and selection processes of the previous performances of the SCs before the SCs are included in the project, this study focuses on the current and continuous performance measurement of the SCs for the project execution phase. In this way, it is aimed to develop a proactive management model while the project continues. (2) While the criteria obtained were scattered in previous studies in the literature, the effective criteria were discussed collectively in this study. (3) While there are hardly any studies on PFAHP in the literature in the field of construction management, the use of the PFAHP method in this study contributed to the literature and thus the use of this method was encouraged. (4) It is aimed to address the criteria frequently encountered in the literature in a different dimension, thus, new sub-criteria have been defined under the name of 'leadership'.

This study offers practitioners a multidimensional evaluation method in construction projects execution phase, while managing the SCs of MCs, due to the combination of both technical and social criteria. It creates awareness of how proactive measures should be taken by aiming to increase the focus on the moment when the project is carried out rather than the previous performance or future performance of the SCs. This study will also help to determine the road maps of the MC companies in the projects, as a result of the determination of the contribution of the SC-PMC to the success with the participation of the experts in the sector.

In future studies, new dimensions and criteria can be added that will contribute to the project success of the SCs. The action plan in the proposed framework can be differentiated by taking it to advanced levels. This framework is initially suggested as a tentative framework in which the criteria obtained will be used to use input data that will enable action to be taken in the management of SCs. The criteria in the study can be evaluated in different ways by the relevant researchers as input data in future new management models that include SC performance measurement and evaluation. This study, which focuses on the construction project execution phase, aims to make the decisions to be taken fast, accurate and effective. Therefore, for a more dynamic and proactive study, performance measurement data can be analyzed with artificial intelligence in future studies to allow faster and more accurate evaluation.

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