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Determination of criteria for preventing construction waste in construction projects at the architectural design phase

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Abstract

Rapidly increasing population and urbanization worldwide lead to the continuous growth of the construction sector. In addition to meeting the need for construction, this growth also brings environmental problems. While the increase in construction projects accelerates the consumption of natural resources, it also leads to the generation of large amounts of construction waste. Waste management, especially during construction and demolition, has become a vital issue for environmental sustainability. Reducing construction waste is critical to minimizing environmental impacts, preventing economic losses, and increasing energy efficiency. In the existing literature, most studies on construction waste management (CWM) focus on the construction and demolition stages. However, it is known that the decisions to be taken at the design stage are decisive in preventing construction waste before it occurs. Despite this, studies on managing construction waste during the design phase are limited in the literature. In this context, this study aims to identify kits for the design process to minimize construction waste in construction projects. Within the scope of the study, comprehensive research was conducted using a systematic literature review and survey method. As a result of the literature review, a total of 57 criteria for minimizing construction waste in the design process were identified. These criteria were categorized into 10 groups within the framework of specific themes, and the researchers created a questionnaire form. The questionnaire was applied to the sample group online. The research sample group consisted of architects, civil engineers, contractors, and suppliers operating throughout Turkey. In total, 148 sector participants answered the questionnaire. The obtained data were analyzed using SPSS 29.0.2.0 software, and criteria for minimizing construction waste during the design phase were determined. As a result of the study, it was determined that designing with attention to material dimensions can significantly reduce the generation of construction waste. This research aims to contribute to environmental sustainability in the construction sector by revealing to what extent the decisions to be taken during the design process affect the generation of construction waste. The findings are instructive for professionals in the sector and show that the amount of waste in construction processes can be significantly reduced with the measures implemented at the design stage.

1. Introduction

The construction industry is recognized as one of the most critical sectors in the modern world, contributing to the global economy and playing a crucial role in human life. While construction meets individuals' housing needs through housing projects, it also serves vital areas such as transportation, health, and education through infrastructure projects. The construction sector continues to grow globally with the acceleration of industrialization and urbanization, emerging as a key driver of economic development, especially in developing countries [1].

This growth in the construction sector brings with it significant environmental problems. Increasing building production in line with population growth and urbanization trends leads to rapid depletion of natural resources, while at the same time generating large amounts of construction waste. Construction wastes result from construction, renovation, and demolition [2]. Construction wastes, which constitute a large portion of solid wastes, have a share of up to 40% in total waste, although it varies from region to region [3]. Studies reveal that the construction industry consumes about 40% of the raw materials used worldwide yearly [4, 5]. Countries such as China, the US, Brazil, and Australia also generate similarly large amounts of construction waste. High quantities of construction waste accelerate the consumption of natural resources, leading to environmental degradation and economic losses.

Construction waste management (CWM) is an integrated approach that systematically handles and processes waste generated from construction, renovation, and demolition activities [6]. It encompasses waste reduction, recycling, reuse, and responsible disposal strategies to mitigate adverse environmental, social, and economic impacts. From both financial and ecological perspectives, reducing construction waste is vital. Addressing waste reduction at the design stage leads to cost savings and efficient resource use and supports existing structures' future expansion and adaptability [7, 8]. Effective CWM practices can significantly reduce natural resource consumption, enhance energy efficiency, and lower construction costs.

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Most studies on CWM focus on construction processes and the demolition phase. A literature review shows efforts to minimize construction waste during the design phase in developed countries [9]. High-income countries, including Australia, are significantly contributing to the problem of construction waste generation by including the design process in CWM [10]. On the other hand, in developing countries such as Turkey, studies on construction waste minimization during the design phase are limited. Although the construction sector in Turkey is one of the sectors with the largest share of the economy, low awareness of sustainable waste management leads to high levels of waste generation in the sector.

Studies in the literature show that the decisions taken during the design phase are a determining factor in terms of the generation of construction waste throughout the life cycle of buildings [2, 11-17]. According to estimates, about 33% of wasted materials are caused by insufficient consideration of waste minimization in the design process [18, 19]. Most of the research on CWM focuses on the construction process, but the design phase is not adequately addressed in this context [20]. Although some studies have examined reducing waste generation during the design process [9, 21-25], waste minimization strategies and tools used have not been comprehensively elaborated and are under-researched [26].

This study addresses CWM from a preventive and strategic perspective, specifically during the design stage of construction projects. While traditional CWM practices focus on post-generation waste handling (e.g., during construction or demolition), this study highlights early design decisions' critical but underexplored role in reducing waste before it occurs. The primary reason for this focus is rooted in a widely acknowledged but under-researched reality in the literature: a significant portion of construction waste originates from decisions made during the design phase, well before any physical construction begins. Previous studies estimate that approximately 33% of construction waste results from insufficient consideration of waste minimization during design [26]. While most research on CWM concentrates on the construction and demolition phases, the design stage is often overlooked. However, key decisions made during design, such as material selection, modularity, detailing, and coordination, directly impact waste generation in later phases. By focusing on the design process, this study adopts a preventive approach to address waste generation before it occurs.

In Türkiye, awareness and implementation of waste minimization practices during the design phase remain limited. Therefore, this study specifically focuses on the design stage to address this gap in the literature and provide practical guidance to professionals on how early-stage decisions can contribute to more sustainable construction practices.

Unlike previous studies, this study aims to identify the criteria that cause construction waste generation in the design phase. For effective waste management, knowing the variables that may cause construction waste generation at every stage of the building production process is crucial to developing effective strategies. For this reason, this study aims to determine the criteria that cause construction waste in the design process. In this context, the questionnaire was prepared through a systematic literature review and was applied to the sample group, and data were collected from the participants. The study only analyzes the Turkish construction sector, and the practices in other countries are not directly included in the evaluation. The data obtained were analyzed with quantitative methods. This study aims to determine the variables that cause construction waste in the design phase of construction projects and to develop strategies for waste generation in the design process.

2. Existing Studies on Construction Waste

Numerous scholars worldwide have investigated the barriers associated with CWM to improve its effectiveness within the construction sector. Many of these studies have provided broad assessments of the challenges involved [27-41]. In contrast, other researchers have narrowed their focus to address specific aspects of CWM. For instance, studies have examined issues such as material wastage Al-Hajj and Hamani and Idowu et al. [42, 43], efficiency in waste practices Ajayi et al. [44], integration of circular economy principles [45-51] and managerial challenges [52, 53]. Additional research has delved into environmental repercussions Chen et al. [52], generation and handling of CWM Fatta et al. [54], material flow dynamics Guo and Huang [55], practical strategies and technological tools Gupta et al. [56]; Han et al. [57]; Porwal et al. [58], behavioral patterns of construction professionals toward waste Hao et al. [59]; Kulatunga et al. [4]; Li et al. [16], and the influence of regulatory frameworks and policies Lv et al. [60]; Ma et al. [61].

The causes of construction waste in the construction industry have been examined worldwide; notably, the subject has attracted the attention of scholars in the construction industries of developing countries, such as Pakistan Nawaz et al. [53], Egypt Daoud et al [31], Bangladesh Hasan et al. [33], Iran Khoshand et al. [62]. In Türkiye, scholars have also explored the topic of construction waste from a broad perspective. Salgın et al. [63] explored architects' views on reducing construction and demolition waste. Polat et al. [64] identified the root causes of construction and demolition waste. Erdal [65] highlighted the critical risk factors affecting waste generation in the Turkish construction industry.

While previous studies on construction waste have primarily focused on waste quantification, management strategies, environmental impacts, and applying various assessment tools such as life cycle assessment (LCA), there remains a critical gap in identifying the criteria preventing the construction waste at the design phase. Most recent studies emphasize sustainability or waste reduction during the construction or demolition phases. Unlike former research, this study explores the criteria for preventing construction waste during the architectural design phase.

3. Materials and Methods

The study's methodology, which aims to determine the criteria for the design process to minimize construction waste in the construction sector, consists of five successive stages. These stages are systematic literature review, organizing the questionnaire, applying the questionnaire form to the sample group, statistical analysis of the data obtained from the questionnaire form, and evaluation of the findings. Figure 1 shows the general summary and flowchart of the research method in detail.

3.1. Systematic Literature Review

A literature review aims to obtain the data needed for the research. Systematic literature review (SLR) is a research method developed to collect data by critically evaluating the literature [66]. To systematically collect data in a transparent, critical, unbiased, and reproducible manner, a systematic literature review recommended by [67], [68], and [69] was used in this study. The findings obtained from the systematic literature review should be subject to the inclusion and exclusion criteria agreed upon within the protocol [70]. Applying the inclusion and exclusion criteria is critical to obtaining the most reliable and nonjudgmental results on the studied subject [71].

Within the scope of this study, the main research question was "What are the factors that cause construction waste in the design process in the construction industry?". A systematic literature review was conducted through the "Web of Science" database. WOS database was searched using the keywords "construction waste, construction waste management, waste minimization, and design phase" from the "ALLFIELDS" field. The document types were refined as "article, review article, and early access". Conference proceedings and book chapters were excluded due to their inadequate peer review process. The search was limited to articles published between 2000 and 2024.

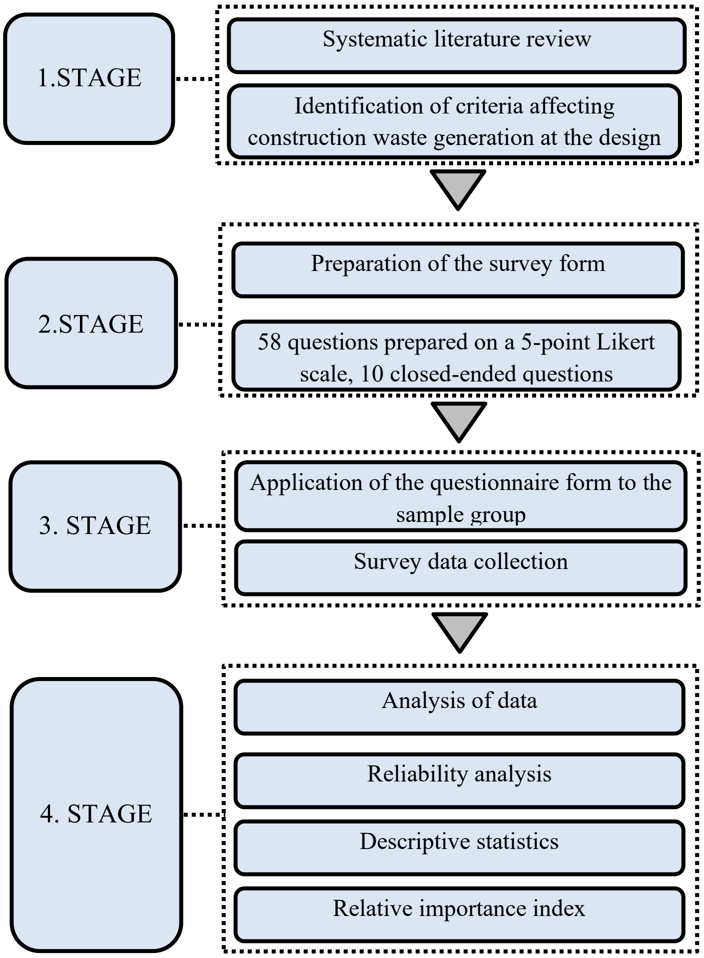

Figure 1. Research method stages

As a result of the SLR conducted with the protocol mentioned above, 32,574 articles were obtained. To ensure the relevance and quality of the retrieved literature, it is essential to define clear criteria for inclusion and exclusion. This study establishes criteria to filter the collected publications and retain only those directly related to the research focus. The inclusion parameters consist of: (1) studies that specifically examine challenges associated with construction waste in construction projects, and (2) papers published in peer-reviewed academic journals. Focusing on peer-reviewed sources within the domain is considered reliable for maintaining high research standards, as noted by Shi et al. [72]. On the other hand, the exclusion criteria include: (1) studies written in languages other than English; (2) research that centers mainly on technical details; and (3) publications for which full-text access is unavailable.

The titles and abstracts of all the articles obtained were examined, and the number of articles was reduced to 156 by excluding studies that were not directly related to the subject. In the next stage, the abstract, method, and results sections of all 156 studies were examined. Forty-two more studies were excluded, and 114 articles were included. The 114 articles were reviewed by the researchers and used to create an article pool of criteria that may cause construction waste generation during the design phase. As a result of detailed reading and inferences, 57 criteria that cause construction waste generation in construction projects at the design stage were identified. The codes, criteria definitions, and sources of these criteria are presented in detail in Table 1.

Table 1. Criteria and sources of construction waste in the design phase were obtained from the systematic literature review

Criteria for construction waste generation in construction projects based on decisions taken during the planning process		
PP1	Frequent Design Changes and Last-Minute Customer Requirements	[4, 9, 11, 13-14, 17-18, 21, 24-25, 39-40, 43, 63-64, 73-113]
PP2	Design Errors, Gaps, and Complexity	[4, 7, 9, 11, 13, 14, 17, 18, 21, 23, 24, 26, 43, 63, 73, 75-86, 88, 90-97, 99, 102-104, 108-126]
PP3	Incomplete and Inconsistent Contract Documents	[4, 10, 11, 13, 17, 23, 64, 75, 76, 81, 84, 90, 93, 95, 96, 99, 102, 109, 112, 117, 119, 122-124, 127]
PP4	Poor Design Quality	[9, 13, 17, 19, 43, 76, 84, 91, 97, 102, 105, 112, 116, 117, 119, 126, 128-130]
PP5	Ambiguous Features and Lack of Information in Drawings	[7, 9, 17-18, 63, 64, 74, 76, 78, 84, 85, 90, 92, 93, 95, 99-101, 103, 108, 110, 112, 116, 119, 122, 126-128, 131-134]
PP6	Inadequate Research and Inappropriate Planning	[11, 13, 17, 18, 43, 73, 76-78, 82, 84, 88, 91-93, 95, 104, 108, 110, 117, 128, 131, 135-137]
PP7	Errors in Construction Drawings and Detailing	[4, 9, 11, 13, 18, 21, 24, 26, 43, 63, 73, 76, 78, 81, 84, 85, 90, 91, 93-97, 99, 100, 102-104, 108, 109, 111, 114, 117, 119, 120, 122, 124, 125, 131]
PP8	Design without Considering Material Dimensions	[9, 17, 18, 21, 25, 26, 63, 78, 94, 97, 102, 105, 111, 114, 131, 133, 134, 138-142]
PP9	Defective Technical Drawing and Detail Production	[13, 17, 18, 43, 73, 76, 78, 85, 90, 91, 95, 99, 100, 103, 108, 113, 117, 119, 120, 124, 131]
PP10	Detailing Simple and Understandable Structural Elements for Field Use	[9, 23, 64, 90, 97, 99, 101, 102, 119, 133, 134, 140]
PP11	Overly Complex Designs Leading to Confusion and Interruptions	[13, 17, 18, 21, 24, 26, 64, 78, 79, 94, 96, 97, 99, 101, 102, 108, 111, 112, 117, 119, 120, 122-124, 131]
Criteria for coordination and communication in the design process		
CC1	Poor Coordination and Communication among Project Stakeholders	[17, 18, 21, 23, 26, 43, 63, 73-76, 78, 79, 84, 85, 88, 90, 91, 93, 96, 97, 102, 105, 109, 112, 114, 117, 119, 120, 122-125, 131, 143, 144]
CC2	Lack of Stakeholder Engagement and Commitment	[14, 21, 24, 96, 97, 105, 109, 111, 122, 125, 130, 145-147]

CC3	Delays caused by Drawing Revision and Distribution	[9, 11, 13, 17, 64, 76, 84, 91, 123, 128, 132]
CC4	Slow Information Flow Between Parties	[11, 13, 91, 132]
CC5	Lack of Clear Delegation of Responsibilities	[26, 91, 93, 148]
CC6	Disputes and Conflicts between Project Stakeholders	[84, 109, 112, 119, 125]
CC7	Lack of Coordination between Departments and Contractors	[21, 24, 26, 40, 91, 93, 97, 105, 122, 130]
Criteria for education and awareness in the design process		
EA1	Inexperienced Designers and Project Teams	[11, 13, 17, 18, 63, 64, 76, 78, 84, 88, 91-94, 96, 105, 108, 109, 115, 119, 120, 125, 128, 137, 138, 147, 149]
EA2	Lack of Education and Training for Employees	[9, 17, 18, 94, 105, 109, 114, 119, 125, 150-152]
EA3	Insufficient Knowledge on Construction and Waste Management	[9, 17, 18, 21, 23, 39, 63, 73, 92-96, 103, 105, 108, 110, 114, 120, 122, 150-152]
EA4	Lack of Environmental Awareness	[9, 17, 18, 64, 102, 105, 122, 150-152]
EA5	Designers Not Familiar with Alternative Products and Standard Sizes	[9, 17, 25, 26, 63, 76, 78, 94, 97, 102, 105, 111, 114, 121, 122, 133, 134, 138, 140, 142, 143]
EA6	Failure to Consider Waste Minimization at Planning and Design Stages	[10, 17, 18, 23, 44, 92, 93, 95, 102, 103, 108, 110, 122, 139, 141, 152-155]
Criteria for legal regulations in the design process		
LR1	Non-Compliance with Regulations and Specifications	[9, 10, 13, 16, 17, 24, 64, 74, 75, 94, 96, 100, 113, 122, 123, 131, 156]
LR2	Inadequate Regulatory Support and Enforcement	[7, 43, 126, 150, 152, 154, 155, 157, 158, 159]
LR3	Lack of Sector Norms or Performance Standards for Waste Management	[38, 149, 160, 161]
LR4	Increasing stringency of Waste Management Regulations	[43, 44, 154]
Financial and economic criteria in the design process		
EC1	Insufficient Financial Resources and Late Payments	[11, 44, 109, 125, 151, 154, 155, 157, 158, 162]
EC2	Lack of Financial Incentives and Support from the Client	[17, 18, 109, 125, 150, 154]
EC3	Time, Cost, and Quality Prioritized	[4, 111, 116, 145, 152, 155, 163, 164]
Level of influence of technological and methodological criteria in the design process		
TC1	Lack of BIM (Building Information Modeling) Implementation:	[23, 44, 97, 102, 127]
TC2	Improved Waste Information Sharing and Coordination Using BIM	[23, 26, 97, 102]
TC3	Embedding Waste-Related Information into the Building Model	[23, 44, 165, 166]
TC4	Using Computer-Aided Simulation for Visualization of Waste Performance	[23, 167]
TC5	BIM and Integrated Project Delivery (IPD) Techniques for Design Coordination	[26, 44]
TC6	Improved Overlap Detection in Building Models to Reduce Waste	[23, 168]
TC7	Design Documents Provide All Necessary Information, Legible and Easily Interpretable	[26, 169, 170]
TC8	Design Documents Include Site Conditions and Topographical Information	[26, 91]
TC9	Design for Standard Sizes and Units to Ensure Reusability of Spaces	[26, 43, 78, 136, 138, 171]
Criteria for material selection and standardization in the design process		
MS1	Promote the Application of Modular Design to Promote Standardization of Building Materials and Elements	[19, 26, 138, 157, 171-175]
MS2	Material Selection Considering Future Disassembly for Durability and Reuse	[9, 10, 14, 16, 21, 23, 24, 26, 63, 78, 79, 94, 102, 105, 114, 122, 157, 158, 171, 176]
MS3	Use of Long-Lasting, Lightweight, Modular, and Standardized Components	[19, 26, 94, 138, 157, 171-173, 175]
MS4	Choosing the Right Material Considering Environmental Aspects	[85, 171]
MS5	Lack of knowledge about standardization (e.g., size of material on the market	[9, 17, 21, 25, 26, 63, 78, 94, 97, 102, 105, 114, 122, 134, 138, 142]
Criteria for waste management in the design process		
WM1	Establishing Reward and Punishment Systems to Encourage Material Savings	[4, 9, 17, 21, 23, 24, 26, 94, 105, 114, 122, 137, 151, 174, 177-179]
WM2	Improving Regulations on Construction Waste	[14, 44, 154]
WM3	Awareness and Education on Waste Management	[9, 17, 18, 56, 78, 82, 97, 102, 105, 118, 122, 143, 150-152], 154, 159, 179-183]
WM4	Cooperation and Communication among Project Team Members for Waste Management	[24, 26, 64, 84, 93, 97, 105, 109, 119, 122, 125, 130, 171, 184]
WM5	Integration of Operators' Expertise and Experience into the Waste Management Process	[147, 163]
WM6	Lack of Appropriate Waste Management Plans and Practices	[4, 11, 13, 14, 17, 39, 73, 75-77, 84, 88, 117, 128, 132, 135]
Other decision criteria taken during the design process		
OC1	Poor Field Management and Supervision	[13, 14, 43, 64, 73-77, 84, 85, 88, 90-93, 95, 96, 103, 108, 110, 120, 123, 128]
OC2	Inadequate Monitoring and Control	[11, 13, 14, 43, 64, 73-77, 79, 84, 85, 88, 90-93, 95, 96, 103, 108, 110, 117, 118, 120, 123, 128, 132]
OC3	Wrong Planning and Timing	[11, 13, 14, 17, 73, 75-77, 84, 88, 91, 108, 110, 117, 128, 132, 135, 137]
OC4	Lack of Supplier Involvement	[14, 96, 113]
OC5	Sustainable Building Education and Lack of Awareness	[9, 17, 18, 43, 94, 105, 114, 150-152, 159, 183]
OC6	Insufficient Demand for Sustainable Buildings	[143, 161]

3.2. Research Population and Sample Selection

Within the scope of the research, the sample group was limited to 4 different occupational groups. This study's sample group consists of architects, civil engineers, contractors, and suppliers who are experienced in the construction sector. The sample group was not restricted according to the field or project type.

3.3. Questionnaire Preparation and Data Collection

While preparing the questionnaire, short, clear, and closed-ended questions were used so that the respondents could answer quickly and easily without spending too much time. A 5-point Likert scale was used in all these closed-ended questions. In the first part of the questionnaire, in order to measure the level of knowledge of the sample group on the subject of the study, the impact of the decisions taken during the design process in construction projects on the generation of construction waste was asked to the participants on a 5-point Likert scale

In the second part of the questionnaire study, 57 criteria, which were determined as a result of the literature review in order to determine the impact levels of the decisions taken in the design process on construction waste generation, were transformed into questions with a 5-point Likert scale and included in the questionnaire form. In this context, there are 11 questions about the decisions taken in the planning process, 7 about coordination and communication, 6 about education and awareness, 4 about legal regulations, 3 about financial and economic criteria, 9 about technological and methodological criteria, 5 about material selection and standardization, 6 about waste management and 6 about external factors.

The third and final section of the questionnaire included demographic questions. Nine questions were asked to determine the demographic characteristics of the participants. These questions measured gender, age, educational status, occupation, place of work, field of work, working position, working time in the sector, and working time in the current workplace.

Within the framework of the principles of scientific research and publication ethics, after obtaining the ethics committee's approval for the questionnaire form, the questionnaire, prepared to reach a wider group of participants, was delivered to the sample group online. Between August 19, 2024, and October 18, 2024, it was delivered online to architects, civil engineers, contractors, and suppliers operating in the Turkish construction sector via e-mail. In this process, 148 participants returned the questionnaire, and the data collected were analyzed quantitatively.

Table 2 gives the percentage (%) and frequency (f) distributions of the demographic characteristics of the sample group, which consisted of 148 participants who answered the questionnaire completely.

Table 2. Demographic characteristics of the sample group

General Information		f	%
Gender	Woman	68	45.9
	Male	80	54.1
Age	20-30 years old	58	39.2
	31-38 years old	33	22.3
	39-46 years	23	15.5
	47-54 years	23	15.5
	55 and above	11	7.4
Education Status	Primary/Secondary Education	-	-
	High School	-	-
	License/University	67	45.3
	Master's degree	26	17.6
	PhD	55	37.2
Profession	Architect	70	47.3
	Civil Engineer	71	48.0
	Contractor	3	2.0
	Supplier	4	2.7
Employed Institution/Company	Public institution	70	47.3
	Private company	78	52.7
Working Site	Office	71	48.0
	Construction Site	8	5.4
	Office + Construction Site	69	46.6
Position in the Organization/Company	Administrator	52	35.1
	Employee	96	64.9
Duration of Experience in the Construction Industry	1-5 years	48	32.4
	6-10 years	37	25.0
	11-15 years	14	9.5
	16-20 years	15	10.1
	21 years and above	34	23
Duration of Employment in the Institution/Company	1-5 years	74	50
	6-10 years	32	21.6
	11-15 years	21	14.2
	16-20 years	4	2.7
	21 years and above	17	11.5

3.4. Data Analysis

Data were analyzed quantitatively using SPSS (Statistical Package for Social Sciences) 29.0 and Office 365 Excel programs. The methods used in the study are reliability analysis, normality test, descriptive statistics analysis, and relative importance ranking.

In analyzing the data obtained, the internal consistency of the questionnaire was tested first. In questionnaires with 5-point Likert scale questions, the reliability of the questionnaire form should be questioned to evaluate the internal consistency of the questions before proceeding to other analyses [185]. According to Tavakol and Denick [186], Cronbach's alpha (α) coefficient is the most widely used reliability measure for assessing internal consistency. The alpha (α) coefficient takes a value between 0 and 1 according to the formula developed by Cronbach [187]. Data with a Cronbach's alpha (α) value of 0.7 and above 0.7 is reliable, and it is accepted that the reliability of the data increases as the alpha (α) value approaches 1 [186].

In the second data analysis stage, a normality test was performed to determine whether the data obtained within the study conform to the normal distribution. Skewness and kurtosis values were examined to evaluate the data's conformity to the normal distribution; the range of -3 to +3 was accepted as an indicator of normal distribution [188].

After determining whether the data set has a normal distribution, the frequency, percentage, mean, and standard deviation values were analyzed using descriptive statistics to examine the data distribution.

To objectively interpret the calculated mean values of the answers received according to the five-point Likert scale scoring, it is necessary to determine the score interval widths and the corresponding effect levels of the data. The interval width is calculated by dividing the series width by the number of groups to be formed, as suggested by [189, 190] (Equation 1).

$$\text{Range width} = (\text{array width}) / (\text{number of groups to make}) \quad (1)$$

The series width is calculated by subtracting the smallest (1) value from the highest value (5) in the Likert scale. Because a 5-point Likert scale was used, the number of groups to be formed was determined as 5. In this case, the score range of the study was calculated as 0.80 according to the formula. According to the range width in the survey study, the impact levels corresponding to the answers received and the score ranges are expressed in Table 3.

Table 3. Scoring criteria used in the evaluation of mean values obtained from the survey data

Likert Scale	Score Ranges	Impact Level
1	1.00 – 1.79	Not Affecting at All
2	1.80 – 2.59	Does Not Affect
3	2.60 – 3.39	Moderately Affects
4	3.40 – 4.19	Affects
5	4.20 – 5.00	Very Impressive

In this study, the index of relative importance (IRI) was used to determine the criteria' importance levels and to rank them among themselves [191]. To determine the criteria for minimizing construction waste in construction projects, an IRI was made based on the answers given by the participants according to the 5-point Likert scale scoring.

According to the participants' responses, the equation (Equation 2) developed by [192] was used to evaluate their perceptions of the importance level of the criteria affecting the generation of construction waste at the design stage. Accordingly, to determine the criteria affecting the formation of construction waste in the construction sector at the design stage, the IRI values for each criterion in the data set were calculated according to the participants' knowledge level.

$$IRI_{\mathrm{k}}\,(\%) = \frac{5(n_5)+4(n_4)+3(n_3)+2(n_2)+n_1}{5(n_5+n_4+n_3+n_2+n)_1} \times 100 \qquad (2)$$

After calculating the IRI of the criteria that contribute to construction waste during the design phase in the construction sector, the overall relative importance index (The Overall IRI) was then determined using the formula (Equation 3) developed by [193].

$$Genel\ (Overall) IRI_{\mathrm{k}}\,(\%) = \frac{\sum_{k=1}^{k=5}(k \times IRI_k)}{\sum_{k=1}^{k=5} k} \times 100 \qquad (3)$$

Finally, one-way ANOVA was used to compare the means of the sample group from different professions [194]. Since all variables have a normal distribution, we can conduct a parametric test.

4. Research Findings

4.1. Reliability Analysis

The internal consistency of the data obtained within the scope of this study was tested using reliability analysis based on Cronbach's alpha coefficient. The reliability analysis determined that the data's alpha value was 0.967, revealing that the measurement tool used in the study had very high internal consistency.

4.2. Evaluations of the Sample Group on the Level of Influence of Decisions Taken in the Design Process on Construction Waste Generation

According to the sample group, one of the study's objectives is to determine to what extent the decisions made during the design process affect the level of waste generation. Table 4 shows the participants' answers to this question.

Table 4. Sample Group's Assessment of the Level of Influence of Decisions Taken in the Design Process on the Generation of Construction Waste

To what extent do the decisions taken during the design process affect the generation of construction waste?	Frequency	Percentage (%)	Average (X̄)	Standard Deviation
	f	%	X̄	σ
No effect at all	4	2.7		
Does Not Affect	14	9.5		
Moderate affects	26	17.6	3.83	1.026
Affects	63	42.6		
Very affects	41	27.7		

When the values in Table 4 are analyzed, 87.9% (17.6+42.6+27.7) of the sample group stated that the decisions taken during the design process significantly affected the generation of construction waste.

4.3. Normality Analysis

The skewness and kurtosis values of the data set were examined to determine whether the data have a normal distribution. In this context, to say that the data set has a normal distribution, the values should take a value between +3 and -3 [188]. The normality test results of the data set are presented in Table 5. When the skewness and kurtosis values of the variables in Table 5 are examined, it is seen that the skewness and kurtosis values of all variables take values between -3 and +3. In other words, the data set of this study has a normal distribution.

4.4. Evaluation of Criteria Causing Construction Waste in the Design Process

The second part of the questionnaire investigated which decisions and criteria were taken during the design stage that caused construction waste to be generated in construction projects. Table 5 gives the relevant variables' percentage, frequency, mean, and standard deviation values.

Table 5. Impact levels of decisions taken during the design process on construction waste generation

Criteria Causing Construction Waste	Mean (X̄)	S.D. (σ)	Skewness	Kurtosis	Impact Level	IRI	Order of Importance	Mean of Architects	Mean of Civil Engineers	Mean of Contractors	Mean Suppliers'	One-way ANOVA test (p-value)
PP1	4.15	0.817	-0.825	0.711	H	80.65	15	4.28	4.07	3.67	3.75	0.233
PP2	4.34	0.736	-1.045	1.053	VH	84.71	3	4.42	4.33	3.33	3.75	0.057
PP3	3.90	1.005	-0.705	-0.171	H	74.65	43	3.97	3.86	4.00	3.25	0.543
PP4	4.03	0.938	-0.683	-0.216	H	77.93	30	4.29	3.83	3.67	3.50	0.015[a]
PP5	4.05	0.981	-0.866	0.158	H	82.79	7	4.25	3.91	3.67	3.50	0.120
PP6	4.22	0.943	-1.253	1.209	VH	81.75	12	4.42	4.11	3.00	3.50	0.009[b]
PP7	4.10	0.953	-0.962	0.503	H	80.76	14	4.36	3.89	3.67	3.50	0.011[a]
PP8	4.41	0.844	-1.459	1.486	VH	85.87	1	4.58	4.27	4.33	4.00	0.130
PP9	4.10	0.981	-0.876	-0.074	H	80.20	17	4.32	3.97	2.67	3.75	0.008[b]
PP10	3.88	1.047	-0.641	-0.463	H	75.91	35	4.09	3.80	2.00	3.25	0.002[b,c]
PP11	4.01	1.014	-0.779	-0.148	H	78.05	29	4.12	3.97	2.67	3.75	0.093
CC1	3.97	0.813	-0.418	-0.367	H	77.16	31	4.04	3.94	3.33	3.75	0.432
CC2	3.65	0.889	-0.206	-0.378	H	72.63	52	3.67	3.63	4.00	3.50	0.885
CC3	3.81	0.949	-0.440	-0.249	H	73.86	46	3.97	3.67	3.67	3.50	0.266
CC4	3.81	0.938	-0.373	-0.499	H	74.06	45	3.91	3.71	4.00	3.50	0.558
CC5	3.91	0.967	-0.616	-0.133	H	75.84	36	4.12	3.71	4.67	3.25	0.058
CC6	3.90	0.938	-0.353	-0.869	H	75.51	38	4.07	3.77	3.67	3.25	0.123
CC7	4.02	0.875	-0.479	-0.626	H	78.89	25	4.16	3.90	4.33	3.50	0.182
EA1	4.26	0.806	-0.659	-0.664	VH	81.89	11	4.28	4.24	4.33	4.00	0.919
EA2	4.04	0.892	-0.682	0.027	H	78.57	26	4.13	3.99	4.00	3.50	0.487
EA3	4.43	0.752	-1.189	0.840	VH	85.19	2	4.56	4.33	4.67	3.75	0.076

EA4	4.34	0.960	-1.601	2.208	VH	84.42	4	4.51	4.21	4.33	3.75	0.175
EA5	4.30	0.909	-1.196	0.802	VH	82.62	8	4.46	4.19	3.67	4.00	0.161
EA6	4.37	0.888	-1.393	1.426	VH	83.53	6	4.50	4.27	4.00	4.00	0.319
LR1	3.77	1.062	-0.516	-0.393	H	74.69	42	3.74	3.74	5.00	4.00	0.230
LR2	4.20	0.940	-1.124	0.873	VH	80.96	13	4.29	4.07	5.00	4.25	0.244
LR3	4.26	0.866	-1.057	0.731	VH	82.07	10	4.34	4.17	5.00	4.00	0.282
LR4	4.37	0.904	-1.422	1.429	VH	83.88	5	4.41	4.30	5.00	4.25	0.558
FE1	3.56	1.076	-0.296	-0.811	H	70.43	56	3.58	3.54	4.00	3.25	0.835
FE2	3.49	1.106	-0,223	-0.989	H	68.52	57	3.63	3.36	4.00	3.00	0.316
FE3	4.06	0.944	-0.677	-0.314	H	79.27	21	4.12	3.99	5.00	3.75	0.253
TC1	3.78	1.003	-0.513	-0.234	H	71.52	55	3.87	3.72	3.33	3.50	0.650
TC2	3.90	0.988	-0.645	-0.368	H	74.27	44	4.00	3.84	3.67	3.50	0.623
TC3	4.00	0.964	-0.765	-0.106	H	76.77	32	4.12	3.93	4.00	3.25	0.283
TC4	3.87	1.037	-0.593	-0.478	H	73.60	48	4.04	3.78	3.67	2.75	0.064
TC5	3.83	1.007	-0.454	-0.692	H	73.64	47	3.97	3.75	4.00	2.75	0.091
TC6	3.94	0.966	-0.586	-0.402	H	75.34	40	4.15	3.79	4.00	2.75	0.012[d]
TC7	3.79	0.952	-0.365	-0.550	H	72.21	53	3.91	3.70	4.33	2.75	0.057
TC8	3.77	0.987	-0.415	-0.627	H	71.60	54	3.91	3.67	4.00	2.75	0.088
TC9	3.89	0.900	-0.486	-0.209	H	73.57	50	4.01	3.79	4.33	3.00	0.079
MS1	3.98	0.879	-0.404	-0.716	H	75.36	39	4.12	3.87	3.00	4.25	0.073
MS2	4.26	0.840	0.954	0.234	VH	79.99	18	4.43	4.10	3.67	4.25	0.083
MS3	4.23	0.897	-1.007	-0.475	VH	78.99	23	4.39	4.07	4.00	4.25	0.233
MS4	4.32	0.853	-1.033	0.125	VH	79.14	22	4.47	4.20	4.00	4.25	0.280
MS5	4.06	0.950	-0.838	0.274	H	76.33	34	4.33	3.78	4.00	4.50	0.006[a]
WM1	3.87	1.023	-0.660	-0.146	H	73.59	49	3.96	3.82	4.33	2.75	0.109
WM2	4.24	0.798	-0.629	-0.637	VH	80.36	16	4.32	4.15	4.33	4.25	0.652
WM3	4.26	0.799	-0.584	-0.925	VH	79.82	19	4.44	4.09	4.00	4.25	0.081
WM4	4.16	0.833	-0.757	-0.024	H	78.12	28	4.24	4.09	4.00	4.00	0.714
WM5	4.12	0.829	-0.611	-0.319	H	76.54	33	4.22	4.00	4.33	4.25	0.473
WM6	4.33	0.797	-1.001	0.347	VH	82.17	9	4.43	4.22	4.00	4.50	0.396
OC1	4.27	0.812	-1.028	1.054	VH	78.54	27	4.38	4.20	4.00	3.75	0.318
OC2	4.25	0.888	-1.008	0.469	VH	79.42	20	4.36	4.15	4.00	4.00	0.499
OC3	4.21	0.824	-0.643	-0.584	VH	78.95	24	4.33	4.14	3.50	3.75	0.195
OC4	3.86	0.923	-0.322	-0.804	H	72.72	51	3.93	3.82	3.50	3.50	0.706
OC5	4.14	0.953	-0.845	-0.077	H	75.73	37	4.23	4.09	3.00	4.00	0.301
OC6	4.04	1.014	-0.619	-0.686	H	74.92	41	4.16	3.92	4.00	3.75	0.546

Notes: [a]Significant difference between mean architect and civil engineers' responses; [b]Significant difference between mean architect and contractors' responses; [c]Significant difference between mean civil engineers and contractors' responses; [d]Significant difference between mean architect and material suppliers' responses. (H:High, VH: Very high)

According to the data in Table 5, 20 of the 57 criteria that cause construction waste generation in the design process are at a very high level, and 37 of them cause construction waste generation at a high level. When the data in Table 5 are analyzed in detail according to the processes, 3 of the 11 criteria related to the planning process are at a very high level and eight at a high level; all seven criteria related to the coordination and communication process in the design process are at a high level; 5 of the six criteria related to training and awareness in the design process are at a very high level and one at a high level; 3 of the four criteria related to legal regulations are at a very high level and one at a high level; all of the financial and economic criteria (3 criteria) are at a high level; all of the 9 criteria related to technological and methodological aspects are at a high level; 3 of the 5 criteria related to material selection and standardization are at a very high level and two at a high level; 3 of the 6 criteria related to waste management are at a very high level and 3 at a high level; 3 of the 6 criteria related to other decisions taken in the design process are at a very high level and 3 at a high level.

4.5. Importance of Ranking of Criteria Causing Construction Waste in the Design Process

The 57 criteria that cause construction waste generation in the design process were ranked according to the responses of 148 survey participants on a five-point Likert scale (Table 5).

When the importance rankings of the criteria that cause construction waste generation during the design process are analyzed (Table 5), it is determined that the top 5 most important criteria are as follows.

1. Design without Considering Material Dimensions (PP8)
2. Insufficient Knowledge on Construction and Waste Management (EA3)
3. Design Errors, Omissions, and Complexity (PP2)
4. Lack of Environmental Awareness (EA4)
5. Non-Binding nature of Waste Management Regulations (WM4)

On the other hand, the last two criteria in the importance ranking are financial and economic criteria.

4.6. Perceived Importance of the Criteria Among Participants in the Profession

The sample group consisted of four groups, which were considered in the analysis: "architects," "civil engineers," "contractors," and "material suppliers." Each participant was asked to rate each of the 57 criteria for preventing construction waste during the design phase in terms of importance and relevance. Based on the results of the previous section, a one-way ANOVA test was performed on the mean scores of the dependent variable to explore divergences among the different groups. A significant level of 5% was considered (Table 5).

50 of the 57 criteria presented the significance levels higher than 0.05. The results imply a consistent opinion among architects, civil engineers, contractors, and material suppliers. However, the perceptions of the four respondent groups differed for six criteria (PP4, PP6, PP7, PP9, PP10, TC6, MS5) with a significance level of less than 0.05. Thus, a Tukey post-hoc test

was performed to evaluate which groups differed and to categorize their differences. Four significant-group differences are present, particularly in the “architect vs civil engineer”, “architect vs contractor,” “civil engineers vs contractor,” and “architect vs material supplier” groups.

Architects provided higher mean responses than civil engineers to PP4, PP7, and MS5.

Moreover, architects demonstrated significantly greater attention than contractors to PP6, PP9, and PP10, while civil engineers also devoted considerably more attention than contractors to PP10.

Finally, architects provided higher mean responses than material suppliers for TC6.

Five of the seven criteria show significant differences within the sample group classified under the planning process.

5. Conclusions and Discussion

With the rapidly increasing global population, construction is also growing significantly. The rise in construction projects results in more construction waste, which causes severe damage to the environment. Reducing construction waste has become essential to creating a more livable environment for future generations.

Waste management at every stage of the building production process is essential to reducing the amount of construction waste. Studies on waste management in building production mainly focus on the construction and demolition stages. However, the decisions taken during the design process also greatly affect the generation of construction waste. For this reason, knowing the criteria that cause construction waste generation during the design phase plays a critical role in effective waste management.

In this study, a comprehensive literature review was conducted to determine the criteria that cause construction waste generation in the design process, and 57 criteria that may cause construction waste generation in the design process were determined. The questionnaire prepared with the criteria obtained was applied to the sample group, and 148 data points suitable for evaluation were obtained from the determined sample group.

The results obtained from this study's findings show that out of 57 criteria that cause construction waste generation in the design process, 20 cause a very high level of construction waste generation, and 37 cause a high level of construction waste generation.

When the importance ranking of the criteria that cause the formation of construction waste in the design process is analyzed, it is seen that the three most important criteria are

1. Design without Considering Material Dimensions (PP8)
2. Insufficient Knowledge on Construction and Waste Management (EA3)
3. Design Errors, Deficiencies, and Complexity (PP2).

Concerning PP8, materials play a crucial and complex role in architectural design, yet they are frequently underappreciated during the early planning phases. Studies have shown that overlooking materials' physical attributes and dimensions can contribute to considerable waste. According to Niazy et al. [195], understanding material characteristics and sizes is essential for developing design strategies to reduce waste. A lack of attention to these factors can result in mismatches between the intended material use and actual needs, often causing excessive purchasing or inaccurate estimations, thereby increasing material waste [196]. To combat this, architectural planning should embrace a material-conscious approach, where an in-depth understanding of material dimensions forms a core part of the design process [197].

About EA3, a deep comprehension of construction methodologies combined with effective waste management is essential for reducing material waste. When architects and professionals lack sufficient knowledge about material properties and applications, it generates unnecessary waste. Hassan et al. [196] highlight that a frequent challenge stems from limited awareness of material types and dimensions during the design stage, which can result in errors and excessive waste due to inaccurate estimations and poor planning. Additionally, frequent alterations in design and the absence of well-integrated waste management frameworks tend to lower overall efficiency [195]. The situation is further aggravated by a general deficiency in training and knowledge surrounding sustainable waste reduction methods [198]. Strengthening education and awareness in construction waste management is therefore vital, as it enables stakeholders to implement waste-minimizing strategies from the early phases of a project.

Regarding PP2, the architectural design process is inherently intricate, and flaws or oversights at this stage can substantially contribute to material waste. Misalignments in communication between design and construction teams frequently lead to execution errors, often requiring rework or resulting in discarded materials. Research by Hassan et al. [196] identifies design-related mistakes as a key contributor to construction waste. Furthermore, overly complicated architectural plans can impede contractors’ ability to handle materials efficiently, leading to excess or unused supplies due to insufficient planning and foresight [199]. To mitigate this, adopting simpler design solutions when appropriate and encouraging stronger collaboration between architects and builders can help minimize waste generation [200]. Additionally, implementing Building Information Modeling (BIM) has been recommended to address these issues, as it enhances coordination and information sharing across project stakeholders, thereby reducing design flaws that often result in waste [198].

Several underlying factors must be considered when examining the discrepancies in mean responses provided by architects compared to civil engineers regarding issues such as design quality, construction drawing errors, and knowledge of standardization. These differences can largely be attributed to the distinct educational backgrounds, professional responsibilities, and inherent nature of the design and construction processes associated with each profession.

Architects primarily focus on a project's creative and aesthetic aspects, necessitating a thorough understanding of design principles. They often engage in the early phases of project development where conceptual designs are formed, leading to their heightened sensitivity toward design quality issues. Their reliance on creative innovation can make them more attuned to recognizing and addressing subpar design quality as it directly impacts their core competencies and project outcomes [201]. In contrast, civil engineers generally concentrate on the practical implementation of these designs, emphasizing structural integrity and adherence to technical standards, which can make them less critical of design issues if they assume that the architect has developed a satisfactory plan.

The differences in educational frameworks and professional focus significantly contribute to the observed professional responses. For instance, some studies indicate that architects may receive extended training regarding legal and ethical design considerations, which can influence their perception of project standards and quality [202]. This perspective can foster a prioritization of adherence to these standards among architects, contrasting with civil engineers who may focus more on functionality when faced with errors in construction documents.

Additionally, collaborative dynamics between architects and civil engineers can exacerbate the perceived disparities in quality issues. El-Gammal [203] noted that the effectiveness of cooperation between architects and civil engineers significantly influences project efficiency and quality outcomes. When relationships are strained or roles are unclear, it can increase construction document errors [204]. As architects typically lead initial design discussions, their insights profoundly impact project timelines and stress levels when quality issues arise, reflected in their higher mean responses in these areas.

The observation that architects show significantly greater attention than contractors to issues such as inadequate research and planning, defective technical drawing, and detail production, and detailing structural elements for field use can be attributed to several interrelated factors inherent in the professional responsibilities and training of architects compared to those of contractors.

Firstly, architects play a pivotal role in the design process. Their focus is primarily on creating viable solutions that address aesthetic and functional requirements, necessitating adequate research and planning. As Marisa and Yusof [205] noted, architects engage deeply with clients during the planning and design phases, making their input critical to project success. This involvement fosters a proactive approach to potential design pitfalls, as inadequacies in research or planning can directly impact the overall quality of the building outcome.

The relationship dynamics between stakeholders also affect how attention is allocated to these issues. Contractors, whose primary responsibility lies in executing the plans provided by architects, may less frequently engage in the initial planning stages, prioritizing logistical and operational aspects of construction over the nuanced factors of design fidelity. This divergence can result in scenarios where architects perceive a higher responsibility for ensuring that all drawings and specifications are foolproof, as errors can lead to significant setbacks or resource wastage on-site [206]. In contrast, contractors often focus on the feasibility and practical execution of designs, potentially leading to less emphasis on upfront planning mistakes.

Lastly, cultural aspects of the architecture profession further reinforce this focus. Architect training often emphasizes collaboration, communication, and the clarity of ideas presented to various stakeholders, including clients and contractors, enhancing their focus on usability and clarity [207]. This exposure fosters an acute awareness of the need for effective communication in passing detailed instructions and information, as any miscommunication can lead to defects or misunderstandings in execution on-site.

The findings reveal that the decisions taken during the design process are one of the key elements of CWM and directly affect all stages of the project process. In this context, early design decisions play a critical role in reducing waste by preventing unnecessary material consumption during construction. Therefore, integrating sustainable strategies into the design process will contribute to a more environmentally, economically, and socially efficient building production process by minimizing construction waste generation.

Minimizing construction waste at the design stage requires adopting sustainable construction practices. Increasing material efficiency is crucial in this regard, and waste can be reduced by preferring modular systems and using standard-sized and recyclable materials. Modern methods such as prefabrication will provide both environmental and economic benefits. The dissemination of digital tools, especially BIM-based project design systems, will help prevent design errors, optimize material use, and minimize revisions during the project process. Furthermore, effective communication and coordination among stakeholders should be ensured to avoid design errors and, consequently, construction waste. Approaches such as the integrated project delivery (IPD) model can effectively enhance collaboration. Promoting an environmentally friendly design approach will be feasible by increasing the use of sustainable materials in line with green building certification systems (LEED, BREEAM, etc.), energy-efficient buildings, and integrating renewable energy systems. Additionally, strengthening existing legal regulations, expanding policies that encourage the use of environmentally friendly materials, and making waste management strategies mandatory will accelerate the adoption of sustainable practices in the sector. Finally, training programs on sustainable design, recycling techniques, and waste management should be organized for sector professionals, and awareness campaigns and information-sharing platforms should be established to promote the sustainable design approach.

Author Contributions

Hakan Yılmaz: conceptualization, literature review, writing – original draft. Gülden Gümüşburun Ayalp: methodology, data analysis, writing – review & editing, supervision.

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