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Assessing the impact of construction material waste drivers on project cost overrun across material processing stages: a structural equation modeling approach

Lobna Kamal, Mohamed S. Yamany✉ & Hossam E. Hosny

A considerable quantity of materials supplied to construction sites becomes waste, hence escalating project costs. Nevertheless, research lacks a thorough assessment of the intricate, indirect, and non-linear correlation between material waste drivers at different processing stages and project cost overruns. This research study investigates this correlation using an advanced multivariate statistical technique known as structural equation modeling (SEM). Data were collected through a questionnaire survey to evaluate the construction material waste factors (CMWFs) and their association with cost overruns in construction projects in Egypt. An exploratory factor analysis was conducted to categorize CMWFs into material processing phases: (1) design and documentation, (2) material procurement, (3) material handling, storage, and transportation, and (4) on-site management. An SEM model was developed to uncover the impact of latent material processing phases on project cost overruns. The model's consistency, reliability, and accuracy were verified employing various performance metrics, including Cronbach's Alpha, composite reliability, and root mean squared error. The results demonstrate that factors related to material handling, storage, and transportation exhibit the highest correlation and impact on project cost overruns, as reflected by an R^2 value of 0.441 and a p-value below 0.05. This research helps decision-makers prioritize mitigation strategies for material waste and cost overruns, hence enhancing construction project performance.

Keywords Construction projects, Material waste, Cost overruns, Structural equation modeling, PLS-SEM

Notwithstanding the significance of construction projects, they often encounter substantial waste, as well as cost and time overruns^{1,2}. Construction waste can be classified into two primary types: tangible and intangible. Physical waste refers to the material debris produced from activities such as building, excavation, demolition, renovation, and similar undertakings. It is recognized as the leftover remnants generated by construction activities³. Conversely, unnecessary operations, delays, budget excesses, and quality deficiencies are sources of nonphysical construction waste⁴. Although material waste is factored into the calculation of material quantities and costs, the actual waste frequently surpasses these estimates². This variation in material waste adversely affects project performance regarding time and cost⁵. Consequently, constructors strive to acquire the estimated quantity of construction supplies plus an additional allowance⁶ to account for inaccuracies in waste estimation, potentially imposing extra financial pressures on them.

Several construction projects, particularly in developing countries, exceed their original budget by over 100%⁷. Cost overruns (COR) can lead to ineffective resource management decisions, affecting materials and workmanship, thus compromising the quality and safety of construction projects. This may result in diminished durability, functionality, and aesthetics of structures, jeopardizing their long-term performance and safety⁸. COR in construction projects can be ascribed to various factors, such as inadequate planning and scheduling, financial challenges encountered by contractors, insufficient communication among stakeholders, shortages of

Department of Construction Engineering, Faculty of Engineering, Zagazig University, Zagazig 44519, Egypt. ✉ email: mohamedyamany9@gmail.com; msyamany@eng.zu.edu.eg

skilled labor and technical personnel, defective designs, contractors' limited experience, and on-site waste^{9,10}. revealed that an increase in material waste volume results in a corresponding increase in project COR. Therefore, minimizing material waste contributes to mitigating COR and can provide significant financial benefits for both construction companies and national economic stability¹¹.

This study, alongside the work by¹², underscores the research gaps in the existing literature about construction material waste and project COR. Despite the growing interest in this study domain, there is a scarcity of research in developing nations examining the generation, causes, impacts, and reduction of construction material waste. Although several research studies examine construction material waste and its influential factors, they often overlook the impact of different phases of material processing, such as the procurement stage. Material waste negatively affects construction project performance in terms of time, cost, quality, and other performance metrics. Consequently, prior studies investigated the association between construction material waste and cost escalation utilizing traditional analytical methods, including regression analysis and Pearson correlation^{11,13}. These conventional techniques assume direct and observable correlations between variables and error-free measurements, rendering them unreliable for modeling unobservable interactions, particularly between material waste and project COR throughout distinct stages of material processing.

Study objectives and contributions

This research analyzes the latent relationship between material waste drivers and COR during various phases of material processing in construction projects in Egypt. The primary objectives of the research are (1) to identify and evaluate the key factors contributing to construction material waste, (2) to categorize these factors according to material processing phases based on their correlation with each phase, and (3) to examine the underlying association between material waste factors and project COR across different material processing phases.

This study contributes to classifying construction material waste factors (CMWFs) according to material processing phases using a questionnaire survey and exploratory factor analysis, rather than considering all factors as a singular construct. This study additionally evaluates the potential relationship between waste factors and project COR, as well as among latent variables, utilizing the structural equation modeling (SEM) technique. This facilitates the assessment of the correlation between CMWFs and COR throughout different material processing phases and times. Besides, this assists in revealing the complex interrelationship among material processing phases to eventually identify the root causes of material waste. Furthermore, assessing the importance and extent of relationship between waste factors and project cost performance helps identify the business impact of these waste factors, thereby enabling decision-makers to promptly and effectively mitigate those that most significantly influence project cost performance and manage project costs.

Literature review

The pertinent literature emphasizes four themes: factors contributing to the generation of construction material waste, methodologies for assessing the significance of these factors, impact of construction material waste, and the relationship between construction material waste and project cost performance.

Factors influencing construction material waste

A significant amount of material waste generated in construction projects is associated with several factors that have not been thoroughly analyzed¹⁴. This facilitates the identification of root causes of material waste, hence enabling stakeholders to implement effective waste reduction strategies¹⁴. A thorough understanding of these factors significantly aids in the effective management and minimization of construction waste¹⁵, which is essential for minimizing environmental impact, promoting sustainable construction practices, and improving project profitability.

Prior research investigated factors affecting construction material waste, including material procurement and handling, planning and documentation, on-site management practices, supervision of work activities, and site operational and environmental concerns. Design modifications, adverse worker attitude, and insufficient planning and scheduling were recognized as the primary contributors to material waste in construction projects¹⁶. In other research, frequent design changes were deemed the most critical factor influencing construction material waste^{3,17–20}. Nevertheless, certain other studies did not corroborate comparable results, either due to being conducted in different geographical regions or concentrating on various types of construction projects. Poor supervision was recognized as the primary variable correlated to construction material waste in Nigeria¹⁶. A separate study highlighted labor errors, insufficient on-site material management, and material quality as the principal drivers of construction material waste in Ethiopia^{21,22}. identified the main issues correlated to construction material waste in Turkey, which include deficiency of competent workers, poor coordination and communication, frequent rework stemming from insufficient supervision, and excessive material supply.

On the other hand, numerous research studies have pinpointed the least influential variables contributing to construction material waste⁵. revealed that the utilization of suboptimal equipment may not result in significant material waste. In addition, the factors that marginally contribute to construction material waste include ignorance of specifications, underutilized resources, bureaucratic inefficiencies, and theft¹⁷. Other insignificant factors encompass unavailability of equipment, insufficient instructions about handling, wrong order, improper material storage¹³, insufficient worker supervision, ineffective material management²³, absence of site waste manager, lack of a waste management plan, and managerial negligence²⁴.

Despite the existing literature, there is a paucity of research in developing nations investigating construction material waste, its influential factors and causes, as well as its effects¹². Previous research examined the CMWFs without considering material processing phases or focusing on select phases of its lifecycle (e.g., design or procurement)^{25,26}. This prevents accurate identification of the timing and location where factors most

significantly impact material waste generation, hence affecting the timely decision making and effectiveness of mitigation strategies for material waste.

Methodologies for assessing factors' significance

Previous research explored the factors affecting material waste in construction projects using various methodological approaches. Questionnaires surveys and personal interviews approaches were mostly utilized for primary data collection in the prior research²⁷. The majority of studies employed ranking and descriptive statistical techniques to evaluate the significance of factors influencing construction material waste. Descriptive statistical techniques include the computation of the mean score^{14,28–31}, the relative importance index^{21,32–36}, and the importance index^{18,37} pertaining to material waste factors. Additional methods include correlation analysis, analysis of variance³⁸, and regression analysis³⁹. Furthermore, the analytical hierarchy process (AHP) was employed to identify factors contributing to construction material waste⁴⁰. These conventional methods assume direct and observable correlations among variables and presume error-free measurements, rendering them inadequate for modeling unobservable relationships. These traditional techniques fail to elucidate the intricate interconnections among the latent variables or material processing phases that affect construction material waste. This may oversimplify the correlation between the CMWFs and material waste by disregarding hidden interrelationships among the material processing phases, hindering the identification of root causes of issues.

Impact of construction material waste

Construction material waste imposes considerable strain on the environment, society, economy, and construction industry due to pollution, resource depletion, health hazards, and elevated expenses^{41–43}. Material waste creates safety risks, resulting in community conflicts and dissatisfaction⁴⁴. Material waste negatively affects both construction corporates and project outcomes. Construction material waste escalates costs, hence diminishing profitability, particularly influencing small contractors with limited liquidity and financial resources. Companies possessing strong financial resources can improve waste management, thus securing profitability at both corporate and project levels²¹. At the project level, material waste frequently results in COR due to associated disposal expenditures and delays. As a result, minimizing construction waste can enhance efficiency, schedule reliability, and overall project value. Previous research reported that implementing a material recycling approach reduces project costs by approximately 15%⁴⁵.

Relationship between construction material waste and project cost overruns

Cost overruns occur when actual expenses exceed the allocated budget, occasionally leading to financial challenges⁴⁶. Previous research indicates that over 90% of global construction projects had experienced COR¹⁰. A large percentage of construction projects in the United Kingdom encounter difficulties in surpassing budgetary constraints¹. A research was undertaken by¹⁰ to examine the influence of material waste on project COR in Nigeria. This study analyzed data from 31 public and private projects, sourced from site inspections and archival records about material waste and COR. The findings demonstrate a substantial correlation between material waste and COR.

Another study was conducted to examine the relationship between material waste and cost escalation in Palestinian construction projects¹³. The research employed a questionnaire survey to gather necessary data and investigate the potential correlations of waste in particular construction materials, such as ceramic and bricks. The findings reveal that a 1% increase in material waste results in a 1.25% increase in project cost. The robust linear correlation between material waste and cost escalation was confirmed by the high R-squared value (> 0.7), underscoring the significance of material waste management in enhancing the cost performance of construction projects. Several other studies confirmed the significant impact of construction material waste on project delivery and expenses^{11,47}. Although numerous studies have investigated the link between construction material waste and COR worldwide, limited relevant research was undertaken in developing countries. Moreover, it was noticed that most prior research examined the waste factors or CMWFs independently from their correlations with project cost performance^{48,49}. This disregards the economic consequences of waste factors and reduces their practical relevance. It also affects the decision-making process aimed at mitigating the waste factors that most directly or indirectly impact COR.

Research methodology

A methodological framework was designed to accomplish the objectives of this research study, as illustrated in Fig. 1. The methodology has four major stages: literature evaluation, data collection, data analysis, and SEM development. The ensuing subsections provide a comprehensive discussion of each level.

The preliminary phase of methodology entails examining relevant literature to ascertain the factors affecting or contributing to construction material waste or CMWFs. This investigation identified 195 CMWFs, rendering it impractical to evaluate all of them when assessing or determining material waste mitigation strategies. Therefore, this compilation of CMWFs should be synthesized to a manageable list of the most influential elements.

Data collection

Relevant research often uses two data collection methods: expert interviews and questionnaire surveys^{27,50}. This study employs two sequential approaches to collect the necessary dataset from the Egyptian construction sector: a pilot study using expert interviews and a questionnaire survey.

Informed consent

The study was conducted through interviews and a questionnaire survey with the fully informed consent of all participants. Consent information was clearly provided within the questionnaire and interview materials.

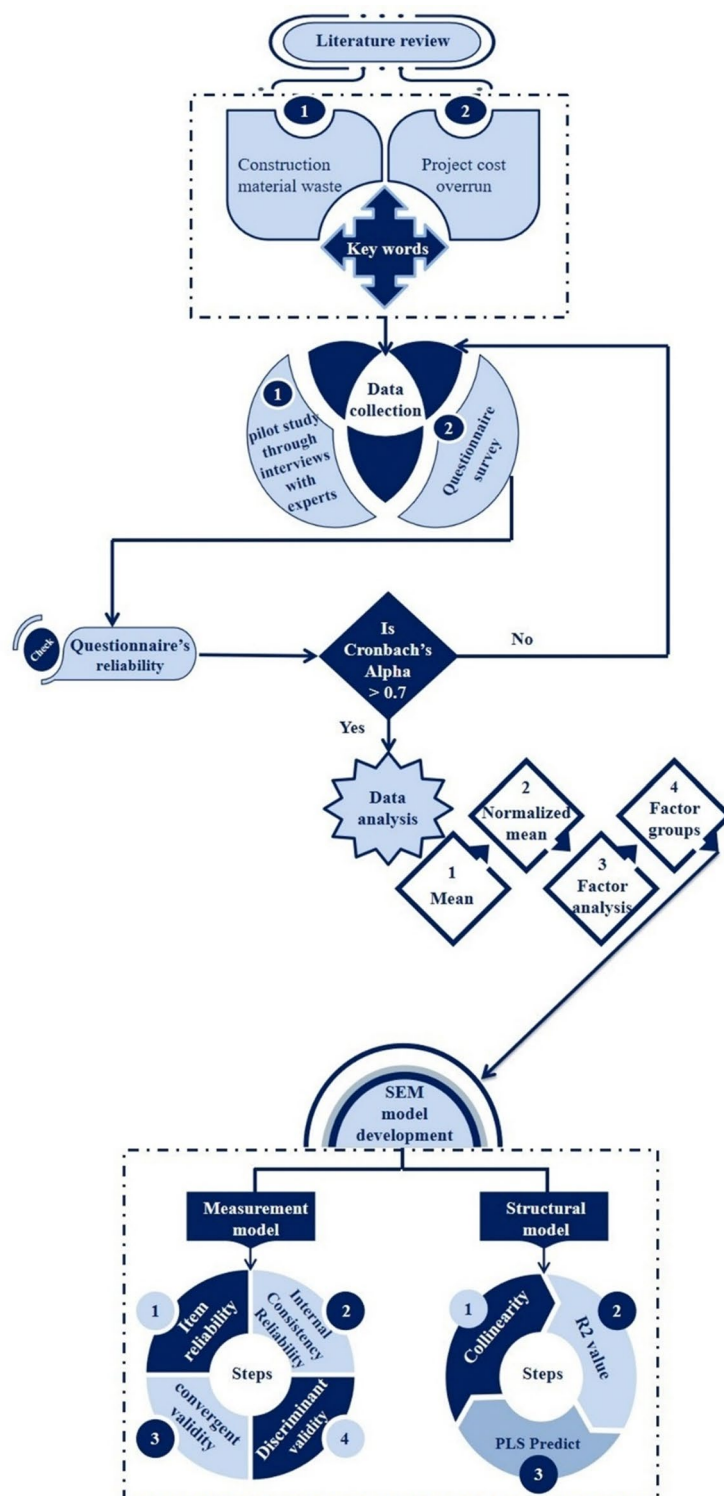


Fig. 1. Research methodology.

Participation was entirely voluntary, and participants could withdraw from the study at any time. All collected data were used solely for scientific research purposes, and participant responses were kept confidential and anonymous.

Ethical and compliance approval

Formal ethical approval for this study was waived by the Faculty of Engineering at Zagazig University, Egypt, in accordance with institutional guidelines for questionnaire-based survey research involving voluntary

and anonymous participation. Written informed consent was obtained from all participants prior to their participation in the study. All procedures performed in this study were conducted in accordance with recognized ethical standards for research involving human participants and complied with relevant institutional and national regulations.

Pilot study

A pilot study was conducted to primarily shortlist the 195 CMWFs identified from the relevant literature to a more manageable number appropriate for the subsequent questionnaire survey. It was conducted to preliminarily evaluate the significance of the found CMWFs and to unearth any overlooked factors. This pilot study was not intended for statistical analysis, but rather for refinement of the survey instrument by assessing factors' relevance and potential significance. It was conducted through interviews with eight subject matter experts, comprising four construction professionals and four academics in construction engineering. Integrating viewpoints from varied professional experiences and backgrounds enhances the credibility of gathered perspectives⁵¹. The interviewees were asked to assess the significance of each CMWF on a scale from 1 to 5, with 1 indicating low importance and 5 representing highest importance.

The Relative Importance Index (RII) was utilized to rank the 195 CMWFs. The RII was calculated as outlined in Eq. 1.

$$RII = \sum W / (A \times N) \quad (1)$$

- W is the score (range from 1 to 5) provided by each respondent to each factor.
- A is the highest score (5).
- N signifies the total number of participants, totaling 8.

Evaluating all 195 factors in any application is impractical; therefore the 80/20 Pareto principle was adopted to prioritize the 20% most significant factors. The Pareto principle posits that 80% of results stem from 20% of the contributing factors. This is a recognized, empirical prioritization strategy widely used in previous research. It helps identify the essential few factors that collectively account for the majority of the impact, while disregarding the insignificant many⁵². In the context of the current research, it may be argued that 80% of construction material waste is correlated with 20% of the contributing factors. Therefore, the top 20% of CMWFs, ranked by their RII values and encompassing 39 factors, were selected for inclusion in the questionnaire survey.

Questionnaire survey

The objective of the questionnaire survey is to investigate the significance of the shortlisted 39 CMWFs by leveraging extensive and diverse insights from subject matter experts. The questionnaire was crafted to be straightforward, concise, and unambiguous, using appropriate language for the intended respondents. The questionnaire was structured into three logical sections. The first section gathers demographic information on the respondents' professional backgrounds and experiences. The second section assesses the importance of the 39 CMWFs. The factors were clearly defined according to the study's conceptual framework and research questions. Participants were asked to evaluate the significance of the factors using a Likert scale from one to five, with 1 indicating very low or no contribution to material waste, 2 denoting low contribution, 3 representing moderate contribution, 4 signifying high contribution, and 5 reflecting very high contribution. At the end of this section, participants were given blank fields to identify additional factors they believe contribute to material waste. The third section of the questionnaire seeks to gather data on the percentage of COR in construction projects. The COR of construction projects was assessed using a Likert scale from 1 to 5, where 1 indicates a COR $\leq 5\%$, 2 signifies $5\% < \text{COR} \leq 15\%$, 3 denotes $15\% < \text{COR} \leq 25\%$, 4 signifies $25\% < \text{COR} \leq 35\%$, and 5 reflects $\text{COR} > 35\%$. Sections 2 and 3 employed a consistent response scale (five-point Likert scale) to ensure comparability across questionnaire items. The questionnaire was tested to ascertain the clarity of its content and time necessary for completion. This was conducted by three experts who confirmed that the questionnaire is adequately prepared for distribution to the target population.

The minimum population required for the survey was computed using the following Eq. (2)^{53–55}:

$$N = Z^2 \times P(1 - P) / e^2 \quad (2)$$

- N represents the minimum sample size.
- Z denotes the statistical value at a prespecified confidence level, specifically 1.645 at a 90% confidence level.
- P is the population proportion, set at 0.5.
- e indicates the sampling error, quantified at 10% within the predefined 90% confidence level.

Upon substituting into Eq. (2), the requisite minimum sample size to derive reliable inferences from the questionnaire survey was determined to be 68. The questionnaire was disseminated to all prospective respondents with experience in construction projects and material waste, either in paper format or via online Google forms. The experts were requested to respond to any inquiries based on their experiences from previous and current projects.

Data analysis

Descriptive statistics

To verify the consistency of respondents' perspectives regarding the significance of the 39 CMWFs, the mean rating score of each CMWF was computed and subsequently normalized to improve data organization and

clarity, thereby reducing redundancy and enhancing integrity⁵⁶. CMWFs are deemed critical if their normalized mean scores equal 0.5 or above⁵⁷.

Reliability assessment

The reliability of the gathered expert opinions was assessed utilizing the reliability test offered by the Statistical Package for Social Sciences (SPSS) software, version 26. Cronbach's Alpha indicates reliability by reflecting the consistency of respondents' evaluations. It measures the degree of agreement among expert viewpoints on a standardized scale from 0 to 1, where elevated values signify greater consistency⁵⁸. Data is regarded reliable when the Cronbach's Alpha value exceeds 0.7⁵⁹.

Exploratory factor analysis (EFA)

Exploratory Factor Analysis (EFA) was performed to detect the latent relationships among the CMWFs^{60,61}. EFA was employed to categorize the factors based on expert evaluations and the calculated correlations among them, with the ultimate objective of reducing the problem's dimensionality to manageable constructs^{49,62}.

To evaluate the suitability of the gathered data for conducting EFA, it is essential to analyze the Kaiser-Meyer-Olkin (KMO) measure and the p-value derived from Bartlett's test of sphericity. Data is considered suitable for EFA if the KMO exceeds 0.7 and the p-value is below 0.05⁶³. The KMO value and p-value of Bartlett's test of sphericity values were found to be equal to 0.844 and 0.01, respectively, demonstrating the data's appropriateness for conducting EFA.

In the EFA, the principal component analysis (PCA) technique was employed to transform correlated variables into a reduced set of components. The eigenvalue was established at 1.0 to guarantee the extraction of significant factors⁶⁴. The retrieved factors were subsequently rotated using the Varimax method. The Varimax rotation is utilized to improve the clarity and interpretation of extracted components⁶⁵. The EFA's findings were employed to investigate the association between CMWFs and COR through the development of the SEM model.

Development of structural equation model (SEM)

The SEM outperforms traditional analytical methods in numerous respects. The SEM enables a priori specification of connections among variables grounded in theoretical frameworks. Unlike conventional approaches, the SEM explicitly accounts for measurement errors, facilitating more realistic and accurate control over measurement quality. Traditional techniques lack graphical representation, whereas SEM uses a visual path-diagram approach, effectively depicting the complex relationships among variables⁶⁶. Therefore, SEM has garnered heightened interest from researchers across several disciplines, including social science and psychology⁶⁷. The SEM assesses the relationships and interactions among the underlying components or latent variables within a model. This approach allows the exploration of the intricate interplay among various factors and their influence on the overall system under investigation⁶⁸.

SEM can be developed using two approaches: Partial Least Squares SEM (PLS-SEM, or PLS path modeling) or Covariance-Based SEM (CB-SEM)⁶⁹. The PLS-SEM is utilized to uncover latent structural correlations among various variables, whereas CB-SEM is employed to validate theoretical frameworks. Previous research reported that PLS-SEM exhibits superior performance compared to CB-SEM in terms of predictive capabilities^{70–72}. In this study, the PLS-SEM was selected over the CB-SEM for specific methodological considerations. The PLS-SEM is particularly suitable for predictive research⁷³, which aligns with the objectives of this work. The PLS-SEM does not necessitate normally distributed data, making it suitable for data obtained from questionnaire surveys utilizing Likert scales⁷⁴. The PLS-SEM produces reliable results with smaller sample sizes and handles complex models with multiple constructs more effectively than CB-SEM⁷⁵.

The PLS-SEM approach encompasses two main models: measurement and structural. The measurement model (outer model) delineates the relationship between constructs and their corresponding observable indicators. The structural model (inner model) examines the links among the latent variables or constructs⁷⁶. This study employs Smart PLS software, version 4, to create the PLS-SEM model and reveal the correlation between the CMWFs and the COR of construction projects.

Results and discussion

Respondents' demographics

Of the 250 questionnaires distributed to specialists in the Egyptian construction sector, 234 were completed, resulting in a response rate of 93.6%. This study assesses potential non-response bias by comparing early respondents with late respondents who represent the non-respondents. The initial 25% of responses were analyzed against the last 25% of responses using the statistical paired t-test. The results showed no statistical difference between the two groups regarding the study variables, implying that the non-response bias is not a concern in the obtained data.

Figure 2 displays the demographic distribution of respondents according to organizational affiliation, years of experience, job position, types of construction projects, and academic qualifications.

Figure 2a illustrates the demographic distribution of respondents based on their organizational affiliation. The responses include perspectives of the three main stakeholder groups: contractors, consultants, and owners, with the majority of respondents being employed by contractors. A multi-group analysis (MGA) was conducted to examine the differences among the three stakeholder groups concerning their viewpoints of the CMWFs and their impact on COR. The analysis reveals that the owners group possesses perspectives markedly distinct from the other two groups, with a p-value less than 0.05. In contrast, consultants and contractors demonstrate a degree of agreement about the significance and effect of CMWFs on COR; however, their viewpoints differ significantly with respect to few factors, with a p-value less than 0.05.

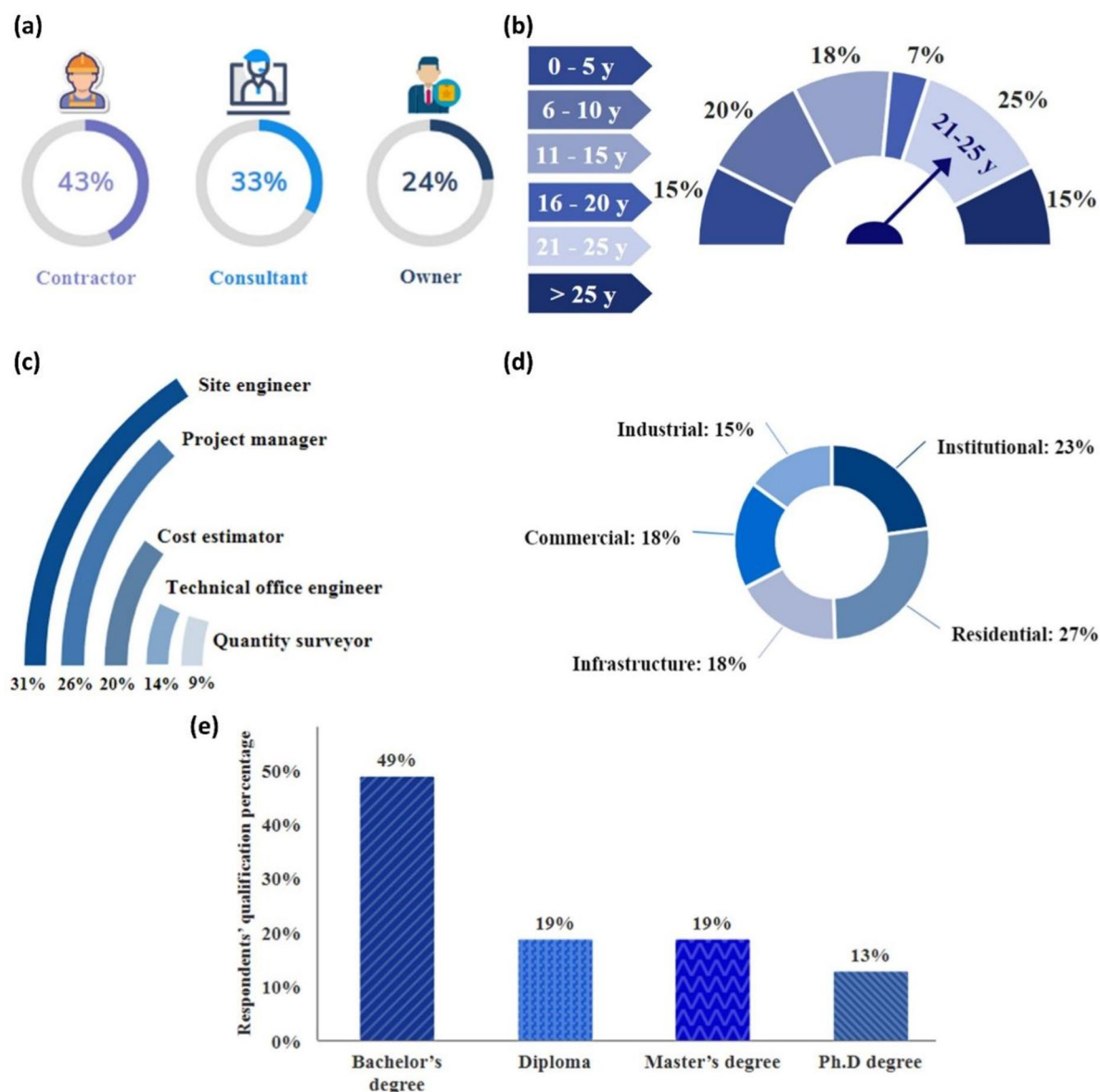


Fig. 2. Demographic distribution of respondents according to: (a) organizational affiliation, (b) years of experience, (c) job position, (d) construction projects they typically work on, and (e) academic qualifications.

Figure 2b illustrates that most participants have over 21 years of experience, thereby affirming the credibility of the respondents' perspectives. Figure 2c illustrates that the primary contributors are site engineers and project managers with direct experience in waste on construction sites. The remaining participants consist of quantity surveyors, cost estimators, and technical office engineers, who also manage material waste during the design and construction phases. Figure 2d signifies that the experts engage nearly uniformly across various categories of construction projects: residential, industrial, commercial, institutional, and infrastructure. This suggests that the findings of this study are relevant to all project types, making this research a distinctive contribution, as most studies focus on specific project categories. Additionally, approximately 50% of the participants pursued post-graduate studies (Fig. 2e), demonstrating their comprehension of the importance of research and the relevance of this study to the existing body of knowledge and practice.

Descriptive statistics

The calculated mean, standard deviation, and normalized mean values of the importance of the 39 CMWFs are presented in Table A1 in the appendix. Only 21 CMWFs have normalized mean values of 0.5 or higher and were hence retained for the following EFA.

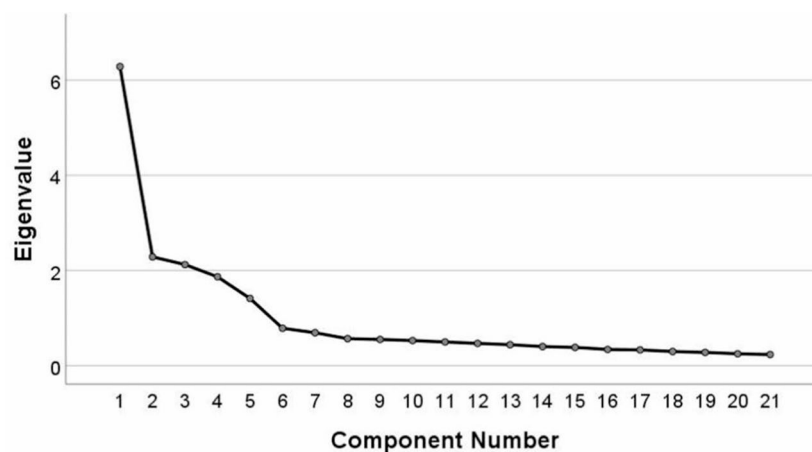


Fig. 3. Scree plot of eigenvalues by component number.

Total Variance Explained									
Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	5.666	28.331	28.331	5.666	28.331	28.331	3.199	15.997	15.997
2	2.273	11.367	39.698	2.273	11.367	39.698	3.040	15.198	31.195
3	2.122	10.609	50.306	2.122	10.609	50.306	2.672	13.361	44.556
4	1.856	9.280	59.587	1.856	9.280	59.587	2.228	11.140	55.695
5	1.395	6.977	66.563	1.395	6.977	66.563	2.174	10.868	66.563
6	0.784	3.918	70.481						
7	0.688	3.442	73.923						
8	0.562	2.812	76.736						
9	0.549	2.745	79.481						
10	0.526	2.630	82.111						
11	0.496	2.480	84.592						
12	0.441	2.205	86.797						
13	0.427	2.134	88.931						
14	0.401	2.003	90.934						
15	0.376	1.881	92.815						

Table 1. Results of explanatory factor analysis.

Reliability of internal consistency

The reliability of the collected data was assessed utilizing the variance-based approach in SPSS software, version 26. Cronbach's Alpha, an indicator of internal consistency, was determined to be 0.83 for all questionnaire items, signifying a satisfactory level of internal consistency among survey participants.

EFA results: factor structure, loadings, and explained variance

The EFA revealed the interrelationships among the 21 CMWFs. Following the initial round of EFA, 20 of the 21 CMWFs were kept, as their factor loadings exceeded the cut-off of 0.40 specified in⁶³. After a second round of EFA using the 20 retained key factors, the KMO measure and p-value of Bartlett's test improved to around 0.84 and 0.00, respectively, signifying increased variability across the factors and so ensuring a robust EFA.

Subsequent to the EFA, the Scree plot illustrated in Fig. 3 was analyzed to observe the decline in eigenvalues corresponding to the increase in the number of components. The inflection point occurs at the fifth component, suggesting that the CMWFs can be classified into five distinct groups. Components beyond the 5th exhibit eigenvalues less than one, indicating a negligible contribution to the variation.

Table 1 shows the five components derived from the EFA, which collectively account for 66.56% of the total variance, demonstrating that the reduced solution preserves substantial information from the original set of factors⁶⁴.

The five components were designated according to the contained factors and correspond to the stages of material processing as follows: Component 1 – On-site management (M), Component 2 – Others (O), Component 3 – Material handling, storage, and transportation (HST), Component 4 – Material procurement (P), and Component 5 – Design and documentation (D). Table 2 outlines the five components together with

Code	Description	Components (Factor Grouping)				
		1	2	3	4	5
Component 1. On-site management (M)						
CMWF025 (M01)	Inventory records don't accurately on-site materials	0.78				
CMWF024 (M02)	Inability to effectively handle congestion in your project	0.77				
CMWF023 (M03)	Recycled and reused materials aren't taken in consideration in your project	0.77				
CMWF020 (M04)	Lack of a clear and consistent flow of information between site supervisors, workers, and project stakeholders	0.73				
CMWF028 (M05)	Absence of effective knowledge management practices (such as lack of workshops, or communication networks within construction firms)	0.64				
Component 2. Others (O)						
CMWF09 (E01)	Insufficient security workers may contribute to theft of materials		0.79			
CMWF010 (E02)	Occurrence of accidents off-site leads to disruptions in workflow		0.77			
CMWF016 (E03)	The quality of road surface leading to the project isn't satisfactory		0.77			
CMWF013 (E04)	Extreme weather conditions impede work in your project		0.72			
CMWF014 (E05)	The process of applying for a work permit isn't direct	0.30	0.64			
Component 3. Material handling, storage, and transportation (HST)						
CMWF031 (HST01)	Lack of material storage close to the construction location			0.84		
CMWF032 (HST02)	Incorrect or unsuitable storage of materials in your project (Temperatures and moisture of stored materials aren't regularly monitored)			0.79		
CMWF033 (HST03)	Instructions about material handling isn't sufficient	0.37		0.76		
CMWF029 (HST04)	Improper transport of materials from storage to use			0.67		
Component 4. Material procurement (P)						
CMWF036 (P01)	Suppliers have a weak history and reputation in supplying the required materials				0.87	
CMWF035 (P02)	Late arrival of construction materials on site in your project				0.86	
CMWF037 (P03)	The suppliers frequently deliver materials don't meet the specific quality standards				0.82	
Component 5. Design and documentation (D)						
CMWF05 (D02)	Frequent design changes occur in your project					0.88
CMWF08 (D03)	The project drawings are incomplete and missing certain information					0.82
CMWF04 (D04)	The designer is unfamiliar with available product options					0.81

Table 2. Factor loadings of CMWFs across five components.

their associated CMWFs and the respective rotated factor loadings, illustrating the relationship between each factor and its corresponding component. The elements of groups 4 and 5, namely material procurement and design and documentation, have the most association with their respective groups, surpassing 80%.

Construction material processing lifecycles encompass four stages or components: (1) Design and documentation (D), (2) Material procurement (P), (3) Material handling, storage, and transportation (HST), and (4) On-site management (M). *Design and documentation:* Modifications to the design may result in various forms of waste at different stages of the project. Should the change occur during construction, it may necessitate a demolition, leading to considerable material waste. This waste may result in a project COR as new materials are supplied. In addition, previous research reported that design changes are a major contributor to COR, potentially leading to costs exceeding the original budget by 5% to 40% of the overall project cost⁷⁷. *Material procurement:* Surplus materials may remain unused and potentially become waste; materials failing to meet project specifications may be discarded or substituted; early deliveries may linger on-site, increasing the risk of damage or theft; poor supplier selection could result in inferior materials; and delayed deliveries may necessitate hasty usage or improper storage. This will result in material waste and subsequently elevate project costs.

Material handling, storage, and transportation: Improper handling may lead to damage to materials during loading, unloading, or movement; inadequate storage may result in deterioration or loss due to weather exposure or insufficient security; and substandard transportation may cause damage during transit due to vibration or improper securing. *On-site management:* Poor site supervision can lead to material misuse and worker errors; insufficient waste monitoring may result in unnoticed and uncontrolled excess waste; and ineffective communication may prompt workers to utilize incorrect materials, necessitating replacement. All of this may lead to substantial waste and, thus, to COR.

Other (O) factors include unfavorable weather conditions, such as temperature fluctuations, which can damage construction materials, requiring expensive replacements or repairs, hence contributing to project cost overruns. Additionally, they encompass accidents and hazards that might lead to work delays, both directly and indirectly, resulting in economic repercussions and budget overruns.

SEM model results

The SEM model consists of two components: measurement and structural models. The measurement model evaluates the correlation between the indicators or CMWFs and their latent constructs or groups/stages

of material processes based on the computed outer loadings. The structural model assesses the relationship among the five latent constructs or material processing phases and the COR using the path coefficient values. The preliminary development of the SEM model followed the conceptual framework depicted in Fig. 4. Each construct comprises indicators or CMWFs, as illustrated in Table 2; Fig. 4, while the construct of COR consists of a single indicator (i.e., COR01). The COR01 indicator represents the percentage of cost overrun, calculated as follows: $[(\text{actual cost} - \text{budgeted cost}) / \text{budgeted cost}] \times 100\%$. Utilizing one indicator to represent a construct may result in inaccurate evaluation of the construct's validity. Nevertheless, singular indicators are frequently employed in prior research when the constructs are unidimensional²³, or when constructs are objectively measured and unambiguously quantified, as exemplified by the construct of project COR.

The initial SEM model findings indicated that all indicators had significant outer loadings over 0.7, as specified in⁷⁸, except for the indicator D04, which was then eliminated to improve model efficiency. The final SEM model was subsequently developed using the remaining 19 CMWFs.

Assessment of measurement model

The performance of the measurement model was assessed in two stages: (1) consistency, reliability, and convergent validity, and (2) discriminant validity.

Consistency, reliability, and convergent validity

Cronbach's Alpha and reliability (Rho_a) were examined to ensure that the indicators consistently measure the same underlying latent variable or construct. Table 3 shows that the Cronbach's Alpha values exceed 0.7, affirming

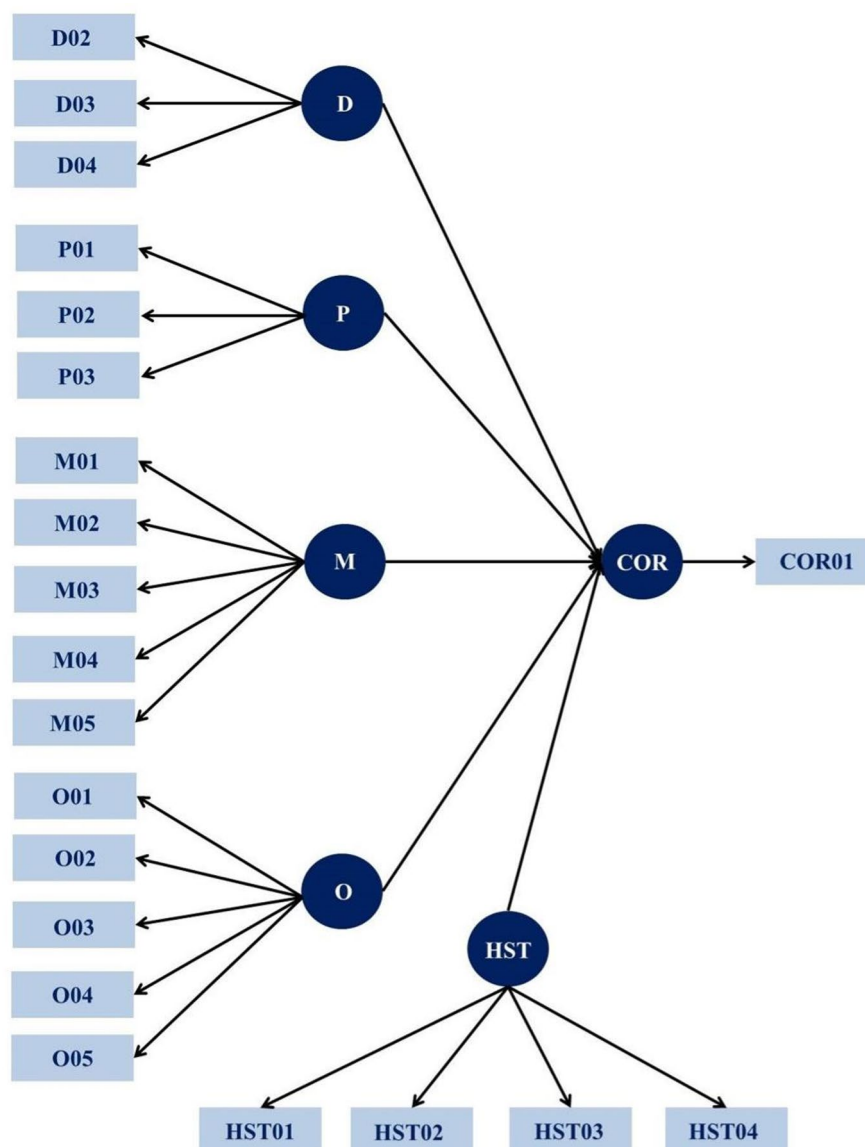


Fig. 4. Conceptual framework of SEM model.

Constructs	Cronbach alpha	Reliability		AVE
		Rho_a	Rho_c	
D	0.751	1.142	0.874	0.778
O	0.828	0.831	0.879	0.593
HST	0.839	0.845	0.893	0.676
M	0.844	0.852	0.889	0.618
P	0.819	1.030	0.880	0.710

Table 3. Consistency, reliability, and convergent validity of SEM model.

	COR	D	O	HST	M	P
COR	1.000					
D	0.095	0.882				
O	0.515	0.058	0.770			
HST	0.689	0.097	0.393	0.822		
M	0.633	0.061	0.449	0.546	0.786	
P	0.119	−0.011	0.023	0.045	0.037	0.843

Table 4. Square root of AVE and correlations among constructs.

satisfactory internal consistency in the established PLS-SEM model⁷⁹. Rho_a values exceeding 0.8 signify good internal consistency reliability of constructs or material processing phases; however, the Rho_a values for phases D and P slightly surpass 0.95, suggesting potential redundancy among the indicators measuring these two constructs, rather than reflecting distinct facets. All composite reliability (Rho_c) values are greater than 0.8 and less than 0.95, reaffirming the internal consistent reliability of all constructs and indicating that their measurement indicators are significantly different. Consequently, future research may investigate the potential similarities among select indicators of the constructs P and D.

The convergent validity of the constructs was assessed by computing the Average Variance Extracted (AVE). Table 3 presents the calculated AVE values for the five constructs, all above 0.5. This implies that the constructs accurately account for a substantial percentage of the variance in the indicators and reliably represent all the indicators they embody⁸⁰.

Discriminant validity

This validity test ensures that each construct is empirically different from the others. Discriminant validity can be assessed using three metrics: the Fornell-Larcker criterion, cross-loadings, and the Heterotrait-Monotrait (HTMT) ratio of correlations. The Fornell-Larcker criterion stipulates that the square root of the AVE for each construct (on-diagonal values in Table 4) should be greater than its correlations with other constructs (off-diagonal elements)⁸¹. Table 4 indicates that this criterion was fulfilled. The cross-loading criterion guarantees that the loading or correlation of any indicator with its construct exceeds that with other constructs. Table 5 shows that this requirement is likewise satisfied. The HTMT ratio for each construct in relation to other constructs was calculated and presented in Table 6. All values are below the threshold of 0.85. The results of the three discriminant validity assessments confirm that all constructs are empirically distinct, with each indicator linked to a single construct, hence removing redundancy among the indicators or constructs of the SEM model.

Assessment of structural model

The performance of the structural model was evaluated using four methodologies: collinearity, effect size, PLSpredict, and path analysis.

Collinearity

The Variable Inflation Factor (VIF) was computed to assess collinearity among the constructs and indicators, as well as test for the common method bias. All calculated VIF values are below 3.3, indicating reduced collinearity, hence affirming consistent path coefficients and diminished standard errors. The VIF values suggest that the established SEM model is free of common method bias⁸², indicating that the computed correlations among all variables are unlikely to be skewed or inflated by the data collection method.

Effect size

The effect size statistic (f^2) measures the impact of an independent variable on a dependent variable. It calculates the variations in the R^2 of a target construct when a certain independent or exogenous variable is omitted from the structural model, signifying whether that variable has a substantial impact⁸³. The established thresholds for f^2 are 0.35 for a large effect, 0.15 for a medium effect, and 0.02 for a small effect⁸⁴. The f^2 values of the constructs of HST, M, and O exceed 0.15, suggesting a moderate influence on COR. On the other hand, the f^2 values of the constructs P and D are below 0.02, indicating their minimal effect on COR.

	COR	D	O	HST	M	P
COR01	1.000	0.095	0.515	0.689	0.633	0.119
D02	0.045	0.792	0.050	0.037	0.021	−0.061
D03	0.105	0.964	0.054	0.111	0.071	0.012
O01	0.337	0.018	0.776	0.274	0.330	0.005
O02	0.412	0.052	0.789	0.315	0.321	0.027
O03	0.373	0.002	0.732	0.303	0.304	−0.009
O04	0.433	0.064	0.749	0.343	0.430	0.083
O05	0.410	0.076	0.800	0.270	0.332	−0.024
HST01	0.517	0.084	0.314	0.751	0.465	0.013
HST02	0.550	0.105	0.231	0.825	0.330	0.049
HST03	0.620	0.069	0.384	0.872	0.574	0.003
HST04	0.575	0.064	0.356	0.836	0.416	0.083
M01	0.487	−0.026	0.311	0.412	0.766	0.029
M02	0.424	−0.001	0.316	0.347	0.750	0.087
M03	0.452	0.052	0.344	0.402	0.787	−0.023
M04	0.569	0.046	0.460	0.516	0.875	0.055
M05	0.532	0.156	0.317	0.443	0.745	−0.001
P01	0.048	−0.021	−0.058	−0.026	−0.019	0.769
P02	0.077	−0.052	−0.028	0.025	−0.026	0.834
P03	0.137	0.018	0.075	0.069	0.082	0.918

Table 5. Cross-loadings of indicators on constructs.

	COR	D	O	HST	M	P
COR	--					
D	0.097	--				
O	0.561	0.076	--			
HST	0.751	0.106	0.466	--		
M	0.683	0.093	0.528	0.639	--	
P	0.113	0.072	0.085	0.082	0.071	--

Table 6. Heterotrait-Monotrait (HTMT) ratio.

	PLS-SEM	LM	IA
RMSE	0.477	0.498	0.738
MAE	0.375	0.391	0.534

Table 7. Prediction errors across PLS-SEM, LM, and IA.

PLSpredict

PLSpredict evaluates the out-of-sample predictions and stability of the PLS-SEM model. It generates predictions for items or constructs utilizing unseen data⁷⁶. This analysis employs three performance metrics: cross-validated redundancy (Q^2), root mean squared error (RMSE) and mean absolute error (MAE). The Q^2 metric assesses the predictive relevance of the inner model. Q^2 was computed utilizing a blindfolded procedure⁸⁵ and found to be 0.583, so validating the predictive relevance of the established SEM model. The performance of the developed PLS-SEM model was further compared with two benchmark models: the linear regression model (LM) and the indicator average (IA) model⁷⁹. Table 7 displays the RMSE and MAE values for PLS-SEM, LM, and IA. The RMSE and MAE of the PLS-SEM are lower than those of the LM and IA, hence reaffirming the stability and robust predictive power of the SEM model.

Path analysis

The bootstrapping method was employed to evaluate the pathway strength and the statistical significance of path coefficients between the constructs and the dependent variable (COR). The bootstrapping approach was designed to resample the dataset by randomly drawing 5,000 cases with replacement. Table 8 shows the findings of the bootstrapping analysis. All path coefficients exhibit p-values below 0.05 at a 95% confidence level, except

	Relationship	Original sample	Sample mean	Standard deviation	T statistics	p-value
H1	D → COR	0.023	0.027	0.042	0.548	0.584
H2	O → COR	0.206	0.202	0.058	3.524	0.000
H3	HST → COR	0.441	0.441	0.054	8.166	0.000
H4	M → COR	0.295	0.293	0.061	4.821	0.000
H5	P → COR	0.084	0.085	0.042	1.989	0.047

Table 8. Bootstrapping analysis results.

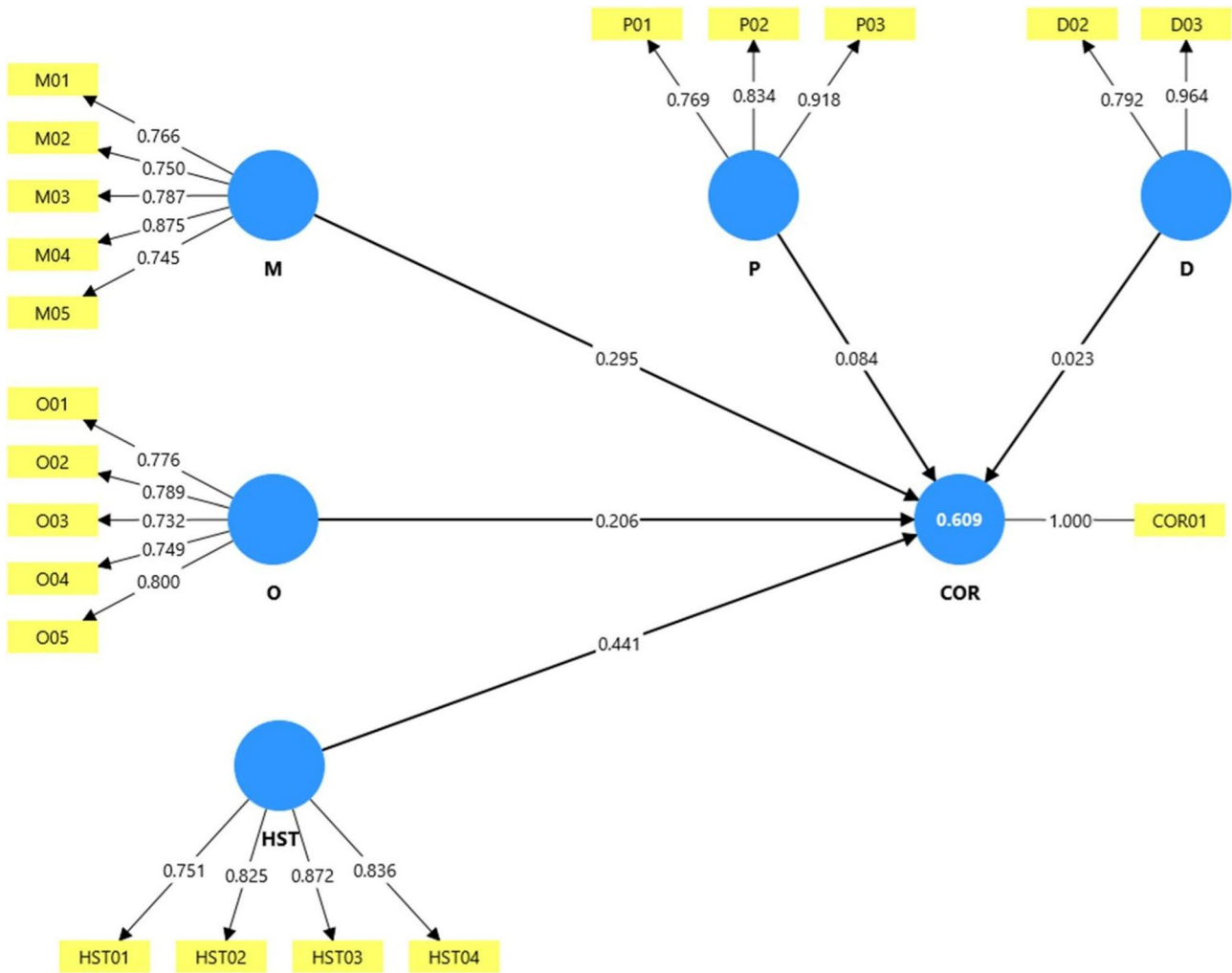


Fig. 5. SEM model: measurement and structural results.

for the pathway connecting the D phase to COR, signifying statistically significant correlations between most material processing phases and project COR.

Final SEM model

Figure 5 illustrates the results of the final SEM model. All outer loadings are greater than 0.7, indicating that these indicators accurately represent their corresponding constructs. The path coefficient values suggest that the constructs HST and M have a strong to moderate effect on project COR, whereas the constructs O, P and D have minimal to negligible influence on project COR. The model exhibits an R^2 of 0.609, indicating moderate to high explanatory power according to the established PLS-SEM guidelines⁷⁹. This suggests that the predictors or CMWFs explain approximately 61% of the variance in project COR.

The findings demonstrate that construction material waste across material processing phases has a varying impact on project COR, with the D phase exhibiting limited to negligible influence. The results reveal that material waste during the HST phase significantly affects project COR, demonstrating a correlation of 0.441. This research signifies a robust relationship between the ineffective management of the HST phase and COR

in construction projects. This aligns with prior studies, including⁸⁶, which reported that the capacity of on-site storage has a moderate impact on project COR. Another research indicated that the insufficient storage facilities contribute to the escalation of project expenses⁸⁷. Furthermore, this result is consistent with a study conducted in Egypt demonstrating that improper storage practices contribute to COR⁸⁸. The waste of construction material during the M phase has a moderate impact on project COR, with a correlation coefficient of 0.295. This finding aligns with previous research that identifies inadequate site management and poor site supervision as primary factors influencing COR in construction projects^{89–91}.

The waste of construction material during the P phase has a minimal effect on COR, with a correlation of 0.084. This finding coincides with the study by⁹², which recognized late material supply as a contributing factor to COR in Egyptian construction projects, albeit with a relatively minor impact. Furthermore, the D phase exhibits a statistically insignificant effect on COR, evidenced by a correlation of 0.023 and a p-value greater than 0.05. This may be due to the early detection and correction of design and documentation deficiencies prior to material quantification and procurement. The material waste generated during the design and documentation stage may incur costs that are very minor compared to the overall project costs. This finding corresponds with the study by⁹³, which indicated that design and documents do not have a significant impact on the evaluation of project cost or COR. Another study revealed that factors associated with design and documentation have a minimal impact on COR²³.

The group of other factors (O), including weather conditions and off-site accidents unrelated to a particular phase of material processing, has a moderate influence on project COR, with a correlation coefficient of 0.206. These results align with the conclusions of a study conducted in Sri Lanka⁸⁷, which determined that weather conditions significantly contribute to material waste, hence leading to COR in construction projects.

Conclusions

The excessive generation of construction material waste increases the overall costs of construction projects. Construction professionals encounter numerous challenges in identifying the main drivers of material waste and developing necessary effective mitigation strategies. Therefore, it is imperative to thoroughly investigate the underlying factors contributing to material waste and their correlation with project cost overruns.

CMWFs were identified from past research studies. A total of 195 factors were found and further examined in a pilot study to shortlist them based on their relative importance. The top 20% of factors were chosen according to the 80/20 Pareto principle, resulting in 39 factors. A questionnaire was subsequently prepared, tested, and distributed to subject matter experts to collect the required data. Critical CMWFs were classified into distinct categories using the EFA, reflecting material processing phases. The groups include M, HST, D, P, and O. Finally, an SEM model was developed to unearth the correlation between CMWFs, material processing stages, and project cost overruns.

The results demonstrate that the CMWFs associated with the HST stage have the most significant impact on the financial outcomes of construction projects. The M and P phases have the least impact on project cost overruns. The research findings offer valuable insights for stakeholders in the Egyptian construction sector and similar practices in other countries. These insights can assist in formulating strategies to effectively mitigate waste factors, manage construction material waste, and minimize project overruns.

Limitations and future research

Despite the contributions of this research study, some limitations still exist. The SEM model was developed using data obtained through a questionnaire survey, resulting in subjective perspectives rather than actual data. Future research is recommended to validate the created model employing empirical data on factors affecting material waste and cost overruns when accessible. The findings of this study may be limited to the Egyptian construction projects. However, the results may prove advantageous for nations with similar construction industries and practices. Countries with different practices are recommended to validate the model's applicability to their construction industries.

Data availability

The data used in this study were collected through a questionnaire survey and are available from the corresponding author upon reasonable request.

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Author contributions

L.K. contributed to data collection, formal analysis, methodology development, and manuscript drafting. M.S.Y. contributed to conceptualization, methodology, supervision, validation, interpretation of results, and manuscript review and editing. H. E. H. contributed to data analysis, validation, visualization, supervision, and critical revision of the manuscript. All authors reviewed and approved the final version of the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to M.S.Y.

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