Optimal Strategies for Construction Waste Mitigation: A Structural Equation Modelling Approach

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Abstract. Notwithstanding the significant number of studies and other interventions, such as government policies and fiscal measures to address its waste intensiveness, the construction industry remains the largest contributor of wastes to landfill across many nations, while also consuming a significant proportion of energy and mineral resources. Consequently, this study aims at establishing the most effective strategies for mitigating waste during construction processes. The study adopts an exploratory sequential mixed-method approach, using the findings from thematically analysed focus group discussion and systematic literature review, from the exploratory stage to inform a questionnaire design. A Structural Equation Model (SEM) approach for Confirmatory Factor Analysis (CFA) was developed at the second stage of the study. The study suggests that while policy and legislative provisions should provide great motivation for construction waste mitigation, six key measures are requisite for effective waste mitigation. Most importantly, the use of prefabrication construction method instead of cast-in-situ could reduce construction waste significantly. Other key strategies include contractual provisions for waste minimization, maximization of materials reuse, contractors' dedication and competencies, waste effective site planning, and enhanced collaborative culture in project delivery. The findings of this study would assist in understanding the major measures and requisite practices for engendering waste minimization during the construction stage of project delivery processes.

BACKGROUND TO THE STUDY

Several studies and sources have confirmed the construction industry to be the largest contributor of waste to landfills across various nations [1][2]. For instance, the UK's statistics suggest that while Commercial and Industrial waste, Household waste and waste from other activities contributed 19%, 12% and 7% of the UK's waste respectively, the construction industry generated 62% of total waste in 2018 [3], implying that the industry generated more than five times the household waste. In the US, the volume of construction waste generated in 2018 at 600 million tons was more than twice the volume of Municipal Solid Waste, with the waste from construction sources increasing by 342% between 1990 and 2018.

Consequently, the construction industry has become a major target for reducing environmental degradation and the impacts of global warming. Studies argued that the industry is essential to achieving the global sustainability agenda due to its impacts on materials usage, energy consumption, waste generation and other forms of environmental impacts [4]. To mitigate the waste generated by the construction industry, various measures are being put in place in different nations. Examples of such measures include landfill tax being charged on waste deposited in landfills and the aggregate tax that are is aimed at encouraging materials reuse in the UK [5].

Studies into construction waste management have sought to understand its causes [6], estimate its proportion [5][7], or propose solutions for addressing the waste intensiveness of the industry [8]. To achieve waste mitigation, researchers have also investigated the measures for enhancing waste effectiveness of the construction industry using the different stages of project delivery processes. For instance, Osmani et al. [9], Wang et al. [10] and Ajayi et al. [11] explored the measures for designing out waste ahead of the actual construction processes. These sets of studies argued that designing out waste should be prioritized over other measures, as it aligns with the tenet of "reduce", which is on the highest hierarchy of the waste management pyramid [11]. Consequently, designers' competencies for driving the waste mitigation agenda have also been explored [5].

Waste minimization has also been studied from a construction project and material procurement processes perspective to investigate the waste-reducing measures that could be adopted in the processes. For instance, Ajayi and Oyedele [12] developed a structural equation model to determine the waste-efficient materials procurement process. Daoud et al. [13] similarly investigated the relationship between construction waste generation and approaches to materials procurement. The studies confirmed that several measures, such as a take-back scheme with suppliers, reduced materials packaging, and enhanced quantity estimation, among others, are essential for construction waste minimization.

With the actual waste not generated until the construction stage of project delivery processes, the largest set of studies on waste management focus on the measures for mitigating waste during the construction stage. Examples of such studies include Ajayi et al.[14], de Magalhães et al. [15] and Bao et al. [16], which investigated the onsite measures for mitigating construction waste from both technical and management perspectives. This category of studies has produced a significant number of measures that could be put in place to reduce waste generated during the construction processes.

Notwithstanding the number of waste-mitigating measures that have been identified by the various studies focusing on the construction stages of project delivery processes, the industry remains the largest contributor of waste across nations. Consequently, using the existing measures identified in the literature, as well as engagement with industry practitioners, this study aims at confirming the most effective strategies for mitigating waste during construction processes. The study fulfils its aim through the following objectives:

1. To explore the site-based measures for mitigating construction waste
2. To confirm the most efficient on-site strategies for driving construction waste minimization

Using a sequential exploratory mixed-method approach, the study employs the findings from literature review and focus group discussion as an input into a questionnaire, which was later used for confirmatory factor analysis, using structural equation modelling. The subsequent sections of the paper include an explanation and justification of the methodological approach and a culmination of the study through a discussion and conclusion section.

METHODOLOGY

This study adopts a sequential exploratory mixed method approach as espoused by Creswell [17]. The study commenced with a systematic review of measures for reducing waste during actual construction processes, using two major citation indexing platforms which are Engineering Village and Web of Knowledge. In addition, the top "waste management and disposal" journals were identified using SCImago and the two top journals – waste management and resources conservation and recycling – were also searched. In addition, four focus group discussions involving 30 experts from the UK construction industry was carried out to explore the current strategies being employed to address waste generation on construction sites. Table 1 shows the demography of the participants in the focus group discussion. Using Atlas-ti for thematic analysis, the transcript from the focus group discussions were analysed to determine the waste management strategies. Overall, the review of the literature and the findings from the qualitative studies generated 93 measures for driving construction waste mitigation, which are further categorised into 12 groups of measures. The 12 measures are (i) Contractors' readiness for low waste projects, (ii) Contractual provisions for waste-efficient projects, (iii) Deconstruct- ability and reusability enhanced technique, (iv) Waste-efficient Formworks and falseworks, (v) Prefabrication and offsite techniques, (vi) Site Planning for Low Waste Projects, (vii) Waste segregation, (viii) Logistic Management, (ix) Materials reuse, (x) Cultural changes for driving low waste projects, (xi) Legislative and policy drivers of low waste projects, and (xii) Human resources coordination for the waste-efficient project.

TABLE 1. Overview of the focus group discussions and the participants

Focus Groups	Categories of the Participants	No of experts	Experience (Years)	Duration
1	• 2 architects and design managers • 2 structural/civil engineers • 1 site waste manager • 2 project managers • 1 Other**	8	7 – 26	111

2	• 2 architects and design managers • 1 structural/civil engineer • 1 site waste manager • 2 project managers • 1 Other**	7	11 – 23	102
3	• 2 architects and design managers • 1 structural/civil engineer • 2 site waste managers • 2 project managers • 1 Other**	8	10 – 27	119
4	• 2 architects and design managers • 1 structural/civil engineer • 1 site waste manager • 2 project managers • 1 Other**	7	9 – 25	120

*** "Others" refers to sustainability experts, supply chain managers and lean practitioners in construction.*

To determine the most efficient measures for driving construction waste mitigation, the second stage of the study involved a Confirmatory Factor Analysis (CFA), using Structural Equation Modelling (SEM). The 93 factors and the 12 measures identified were used to develop an initial SEM, as shown in Figure 1 which was later refined into the final structural model as shown in Figure 2

In order to rest the initial structural model of the measures for mitigating construction waste and establish the major approaches, a questionnaire incorporating the 93 factors was developed using a five-point Likert scale. Following a pilot test with seven experts, the questionnaire was administered using Google Form. The participants were selected through a random sampling approach. The sampling frame used includes the list of top 100 UK construction firms and databases of different professional bodies, including the CIOB, CIAT, ICE and APM. In all, 302 responses were received out of 622 invitations made, with 17 of the responses removed from further analysis due to significant missing data. Table 2 shows the distribution of the 285 participants whose responses were used for the study.

TABLE 2. Overview of the research respondents

Item/Variables	Groups/Labels	Frequency	Percentage (%)
Job roles/titles	Architects	72	25.3
	Civil engineers	56	19.6
	Project managers	96	33.7
	Site waste managers	16	5.6
	Others	45	15.8
Years of experience (years)	1-5	31	10.9
	6-10	54	18.9
	11-15	104	36.5
	16-20	64	22.5
	21-25	16	5.6
	Above 25	16	5.6

As recommended by Kline [18], Nunnally and Bernstein [17] and others, initial analysis, including missing value analysis, Mahalanobis distance (D) test and Cronbach Alpha test, were carried out. This resulted in the removal of six of the 93 factors, with an overall Cronbach alpha coefficient of 0.95 consequently achieved. The Cronbach Alpha coefficients for the 12 groups of factors also range from 0.729 to 0.993, which suggests an excellent and reliable outcome [17].

Using AMOS 22 for SEM, the Maximum Likelihood (ML) approach was used for model estimation as recommended by Kline (2010). The initial model shows poor fit statistics as well as insignificant loading of some of the first-order factors and their indicators. As such, the model was re-specified and modified to improve fit statistics and reliability of the constructs. This led to the deletion of four latent factors, which are waste-efficient formwork (WEForm), Human resources management measures (HRMan), Waste segregation (WSeg) and Logistic Management

(LogMan). Although two of the latent factors (WSeg and LogMan) have good Composite Reliability (CR ≥ 0.87) and Average Variance Extracted (AVE ≥ 0.61), they show low factor loading to the second-order variable at 0.18 and 0.21 respectively. What this suggests is that although the two factors have impacts on construction waste, they are of less significance. The other two latent factors (WEForm and HRMan) have poor CR and AVE, with insignificant impacts on the second-order factor (Waste-efficient Construction). The final model with good fit statistics, reliability and validity, are presented in Table 3.

Consequently, the results of the SEM suggest that eight key factors determine the waste effectiveness of the construction process. These include waste effective site planning, materials reuse, prefabrication and offsite technique, contractual provisions, contractors' commitment and competencies, cultural change as well as legislative provisions. 40 measured variables were established as the main indicators of underlying measures for waste effectiveness of the building construction process. The mean and overall percentage of variance extracted by the model shows that the measures on the model are fit and significant enough to account for the waste effectiveness of construction projects.

TABLE 3. Thresholds for model fit indices and achieved values.

First-order CFA			
Relationship	***Estimate***	***AVE***	***CR***
CF17<--- SPlan	0.50		
CF29<--- SPlan	0.62		
CF30<--- SPlan	0.84	0.57	0.84
CF31<--- SPlan	0.64		
CF32<--- SPlan	0.74		
CF34<--- SPlan	0.69		
CF6<--- MatReuse	0.64		
CF9<--- MatReuse	0.77		
CF10<--- MatReuse	0.65		
CF13<--- MatReuse	0.93	0.63	0.85
CF23<--- MatReuse	0.70		
CF24<--- MatReuse	0.72		
CF26<--- MatReuse	0.65		
CF36<--- MatReuse	0.69		
CF7<--- Deconstuct	0.46		
CF38<--- Deconstuct	0.80		
CF44<--- Deconstuct	0.62	0.62	0.77
CF45<--- Deconstuct	0.57		
CF47<--- Deconstuct	0.67		
CF55<--- Deconstuct	0.54		
CF40<---PreFab	0.81		
CF49<---PreFab	0.52	0.67	0.89
CF50<---PreFab	0.70		
CF51<---PreFab	0.57		
CF57<---Contract	0.73		
CF61<---Contract	0.80		
CF65<---Contract	0.66	0.70	0.86
CF70<---Contract	0.51		
CF77<---Contract	0.56		
CF1<---Contractor	0.70		
CF52<---Contractor	0.60	0.59	0.82
CF62<---Contractor	0.59		
CF68<---Contractor	0.74		
CF74<---Culture	0.67		
CF75<---Culture	0.87	0.51	0.72
CF76<---Culture	0.58		
CF85<---L&PProv	0.89		
CF86<---L&PProv	0.59	0.63	0.79
CF87<---L&PProv	0.56		

Second-order CFA			
Relationship	***Est***	***AV***	***CR***
SPlan <--- CONSTRUCTION	0.94		
MatReuse <--- CONSTRUCTION	0.95		
Deconstuct<--- CONSTRUCTION	0.81		
PreFab <--- CONSTRUCTION	0.89	0.73	0.86
Contract<--- CONSTRUCTION	0.86		
Contractor<--- CONSTRUCTION	0.88		
Culture<--- CONSTRUCTION	*0.61*		
CONSTRUCTION <--- L&PProv	0.63		

MODEL FIT INDICES		
Indices	***Initial Model***	***Final model***
X^2/degree of freedom	1.582	1.299
RMSEA	0.032	0.027
GFI	0.855	0.961
AGFI	0.839	0.952
CFI	0.682	0.948
NFI	0.469	0.906
TLI	0.556	0.953
PGFI	0.766	0.953
PNFI	0.554	0.957
IFI	0.616	0.971
Cronbach's Alpha	0.949	

CF89<---L&PProv	0.72

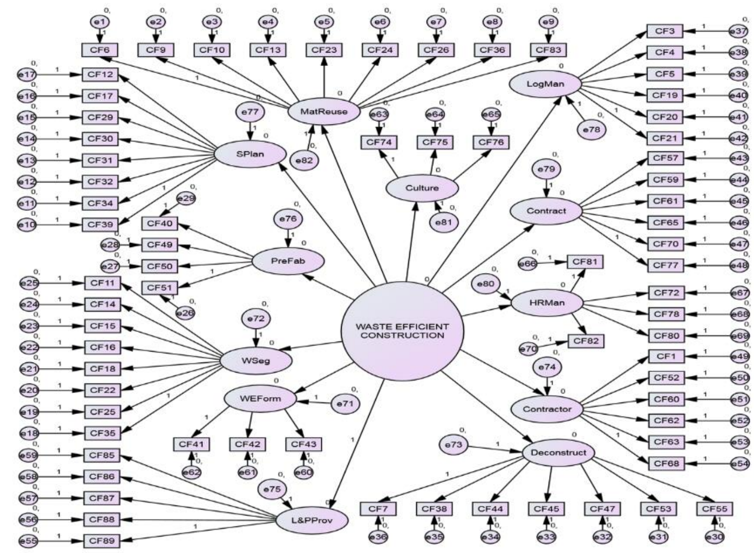

FIGURE 1. Initial model of waste-efficient construction indices

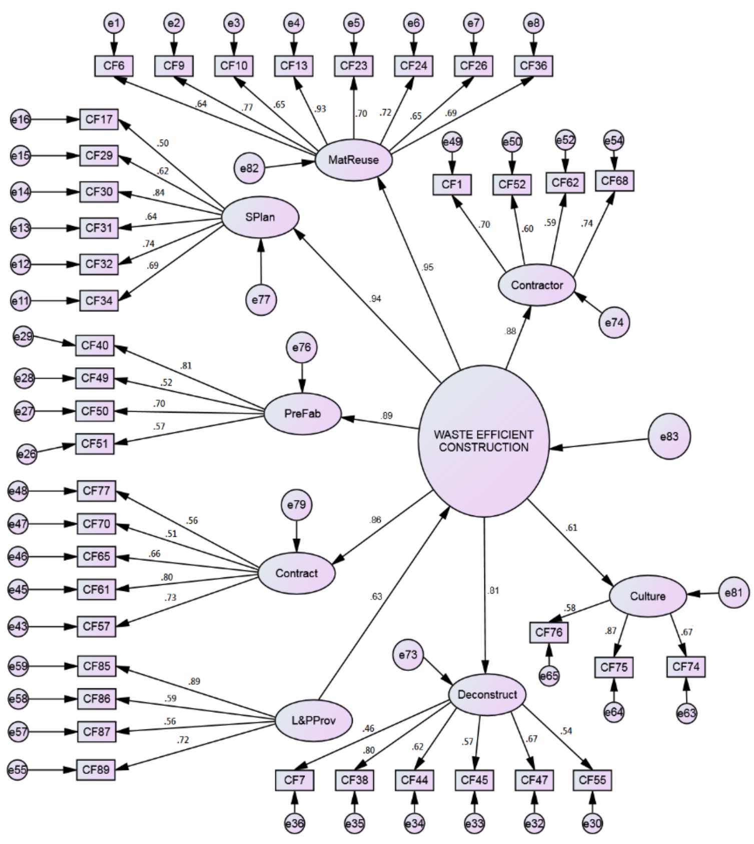

Figure 2. Final Model of waste-efficient construction indices

DISCUSSION AND CONCLUSION

Prefabrication and offsite technology are confirmed as the key underlying measure for preventing waste generated by the construction industry. The key dimension of waste-efficient construction has a β value of 0.97 and 94% of its variance is explained by the latent factor. This makes the construction technique the underlying strategy with the highest factor loading to the waste-efficient construction process. This strategy is in line with the propositions of lean construction principles, and it involves the use of precast components and modules, modular construction technique and other offsite technologies. Through this measure, waste due to wet trades, offcuts, materials breakage and reworks could be prevented [19][20]. This approach requires that building elements are manufactured offsite, assembled onsite, while several factors that cause waste such as materials handling, poor storage as well as design changes have been entirely prevented. This would not only reduce construction waste due to in-situ and finishes [21], it would also support the reusability of the components at the end of the building lifecycle.

Similarly, the finding confirmed that a waste-efficient project is characterized by maximization of materials reuse during the construction activities. This requires adequate segregation of different materials, by providing skips for specific materials and through adequate communication of materials reuse strategies [22]. It also ensures maximization of on-site reuse of materials, with reuse of such materials as off-cut, the soil remains, as well as excavation and demolition materials. To achieve this, effective planning of the site activities becomes a requisite [14]. Consequently, site layout planning, site waste management plan, communication strategies, review of project specification are part of site planning measures for driving waste minimization.

Contractors' competencies and dedication is also confirmed as another underlying strategy for driving waste minimization in construction projects. The study suggests that without committed and dedicated contractors, other waste management strategies could not be effective. This is especially as a poor work sequence could result in breakage of previously completed work, thereby resulting in reworks and subsequent waste generation. In addition, it is when contractors are committed to waste minimization that materials reuse or secondary materials could be considered [5]. Nonetheless, such commitment could be engendered by contractual and legislative provisions that penalize and reward waste generation and minimization respectively [17]. Usually, waste minimization is of secondary importance in many construction projects, as project performance is measured through such key performance indicators as cost, time and quality. The study, therefore, suggests that by making waste minimization a part of key performance indicators, a substantial volume of waste would be diverted from landfills.

Apart from strategies for minimization waste in construction projects, an overarching approach to preventing waste is improved collaboration within the construction industry. Currently, the construction industry is characterized by fragmentation and poor collaboration among project stakeholders. This results in information loss, poor communication and blame-shifting rather than ensuring a collaborative working environment [23]. This is despite that each profession has its unique input, which could be valuable throughout the process of project delivery. In concurrence with this, the study confirmed collaborative culture as a key driving force for engendering waste minimization in construction projects.

This study has been carried out within the UK's context and it has specifically focused on the key measures for reducing waste during the construction stage of project delivery processes. Further study could confirm the applicability of its findings to other nations. The key measures for driving waste-efficient projects through activities at the design and procurement stages of project delivery processes could also be confirmed by other studies.

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