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Building Information Modeling (BIM) Application in Construction Waste Quantification—A Review †

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Abstract: The construction industry is known for poor performance, low productivity, high waste generation, and for lagging in the adoption of new technology. A high rate of material wastage in construction projects has economic and environmental implications for concerned stakeholders. Construction waste quantification is an essential requirement for formulating waste management strategies. Technological advancements like building information modeling (BIM) and artificial intelligence (AI) provide effective solutions to the construction industry to deal with these prevalent issues. This literature review-based study observes the scarcity of research on the application of BIM in construction waste quantification. The limited number of studies found in the literature confirm the ability of BIM-aided waste quantification models to forecast waste generation. Moreover, the application of these models can also assist in reducing waste to a considerable extent. This study recommends that further studies should be conducted on technology-assisted waste quantification in building and infrastructure projects to evaluate their effectiveness for subsequent implementation in the industry.

Keywords: construction waste; waste quantification; waste estimation; Building Information Modeling; technology application

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1. Introduction

The construction industry continues to endure challenges like poor performance, low productivity, a high rate of consumption of materials, and a susceptibility to large volumes of waste [1,2]. However, it has not been able to use technology optimally to tackle these issues because of its poor prowess in digitization and automation as compared to other industries [3]. Construction waste (CW) has serious economic and environmental implications [4]. Construction projects around the globe produce millions of tons of waste; in Australia, CW accounts for 40% of the entire waste produced in the country [5]. It is believed that 10–15% of the overall material procured for construction projects is wasted, resulting in huge financial losses [6]. The use of digital technologies like artificial intelligence (AI), building information modeling (BIM), global information system (GIS), the Internet of things (IoT), blockchain technology, and big data analytics is being applied in various areas of CW management to improve the performance and productivity of existing systems and processes [7], although the adoption of these solutions by the industry will take a considerable amount of time and resources due to the current capacity of the construction industry [8].

The application of BIM on a wide range of topics falling in the realm of construction management has drawn a lot of attention from researchers in the last two decades. However, BIM-aided waste management solutions have been evaluated by researchers only in recent years [9]. Studies in the literature confirm that the adoption of BIM-aided waste management solutions can decrease conflicts, reduce rework, assist in clash detection, enhance communication, test design options, and improve decision making [10]. Quantification of CW is considered an essential requirement for formulating constriction waste management (CWM) frameworks. A limited number of studies have examined the efficacy of BIM-aided waste quantification models on building construction projects; therefore, this knowledge area demands more attention from researchers.

This literature review-based study aims to highlight the status of BIM-assisted waste quantification studies and their outcomes. Google Scholar, Web of Science, and Scopus databases were utilized to search all relevant studies. The keywords used for searching were "construction waste", "quantification", "prediction", "estimation", "BIM", and "Building Information Model".

2. Literature Review

2.1. Construction Waste (CW)

CW is solid waste generated from numerous construction activities including the execution of construction and demolition works [11]. It has been defined as the difference between the quantity of materials transported to the project site and the materials consumed [12]. The waste at construction sites has been categorized into physical and non-physical waste. Physical waste comprises materials lost and damaged while non-physical waste comprises cost and time overrun [13]. CWM strategies are formulated based on the 3R (reduce, reuse, and recycle) waste hierarchy [9] wherein reduction is considered the most cost-effective approach to minimize waste as it prevents much of the waste before it becomes generated in projects [14].

2.2. Construction Waste Quantification

The CW quantification helps in benchmarking material waste percentages and facilitates accurate forecasting/estimation of future project costs. CW quantification is considered a prerequisite for formulating waste management frameworks for construction projects and is regarded as an essential requirement for the planning and contract administration of construction projects [15]. Moreover, CW quantification has also been described as a key decision-making tool for management [16,17]. Waste generation rates assessed through the process of quantification assist in evaluating project performance and in identifying sources of inefficiencies [18]. Figure 1 shows various functions of CW quantification in construction management reported in the literature. It is important to note that incorrect estimation in construction projects can result in an increase in material waste generation, the flawed ordering of materials, and consequently project cost overrun [19].

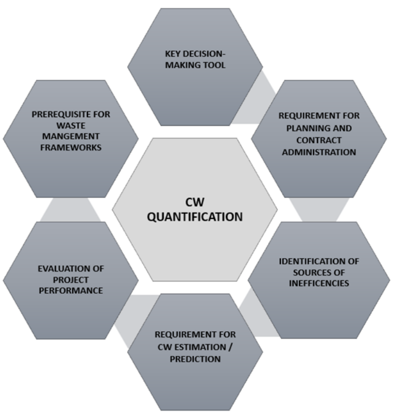

Figure 1. Functions of CW quantification in construction management.

Quantification of CW has been evaluated in studies based on parameters such as the percentage of materials used in a project, the weight/volume of waste generated in a project, and on the scope of waste estimation, e.g., regional-level or project-level [20]. Table 1 shows evaluation models used for CW quantification: waste generation rates, waste generation areas, waste percentage, and wastivity. All waste quantification studies are based on the application of either a single model or a combination of these models. These models are applied to either project-level and regional-level quantification of waste generation. It is important to note that waste quantification can be impacted by a wide range of factors including the nature of the construction project, the location of the project site, attributes of construction materials used, quantification method used, etc.

Table 1. Construction waste quantification models.

Source	Quantification Evaluation Models	Unit
[17]	Waste generation rates (WGR) are based on the volume of waste per unit area.	m^3/m^2
[21,22]	Waste generation areas (WGA) are based on the weight of waste per unit area.	kg/m^2
[23–25]	Percentage of waste is based on the total material wasted out of all the material delivered to the site.	Percentage
[26]	Wastivity is based on the ratio of wasted material to consumed material.	Ratio

Most of the waste quantification studies have been conducted on building projects. The salient points of conventional CW studies selected in this review are summarized in Table 2. The analysis of the values of wastage of various construction materials quantified in several studies shows significant variation [27]. Waste generation in buildings computed in a study conducted in New Zealand was 32.2 kg/m^2, whereas it was evaluated as more than double that value (69 kg/m^2) in another study in the US [21,22]. Likewise, wastage evaluated in building projects in Brazil and Hong Kong was reported as 0.21 m^3/m^2 and 0.6 m^3/m^2, respectively [15,17]. These variations and inaccuracies need to be examined thoroughly using digital technology to acquire correct/reliable results. Research has confirmed the ability of BIM and AI technologies to quantify/estimate waste percentages [4].

Table 2. Important studies on CW quantification.

Source	Country		Waste Generation
[21]	New Zealand	Buildings	32.2 kg/m^2
[23]	Pakistan		Wood (36.2%), Sand (28.8%)
[17]	Brazil		0.21 m^3/m^2
[22]	US		69 kg/m^2
[24]	Pakistan		Bricks 5.99–9%, Plaster 6.58–7.33%
[15]	Hong Kong		0.54–0.6 m^3/m^2
[28]	Egypt		Timber (8.96%), Sand (5.70%), Bricks (4.45%)
[26]	India		Concrete (4.14%), Steel (1.62%)
[18]	Indonesia	Road	Aggregate (26%), Concrete (5.3%)
[25]	US		29.4%
[29]	UK		Concrete (10.9%), Tarmac (22.0%), Cement (79.7%)

Waste generation rates (WGR) assessed through the process of quantification assist in evaluating project performance and in identifying sources of inefficiencies [18]. The salient points of CW studies are summarized in Table 2. It has been observed that incorrect estimation can result in enormous quantities of material waste, the faulty ordering of materials, and consequently cost overrun [19]. The analysis of waste percentages of various construction materials quantified in numerous studies shows significant variation in values [27]. The use of automated quantification/estimation of waste percentages in construction projects results in improved accuracy [4].

2.3. Application of BIM in Construction Management

BIM is considered to be one of the most inspiring evolutions in the construction industry [30]. It is an innovative approach to virtual design, project management, and performance management [31]. BIM adoption in construction projects assists in better cost estimation, better design comprehension, reduced construction cost, improved construction planning and monitoring, and project quality enhancement [32]. BIM addresses issues of cost/time performance and low productivity prevalent in the construction industry through technological innovation, automation, and computerization [33]. BIM adoption in construction projects accrues benefits in efficient project management, better risk mitigation, onsite progress monitoring, precise measurements, and accurate calculations [34]. The benefits of BIM adoption in numerous fields of construction management have been established in the literature. Figure 2 explains the BIM-integrated platform and shows the relationship of BIM dimensions (3 D, 4 D, 5 D, 6 D, and 7 D) with CW management and project management fields [35]. Here, the automated CW quantification modeling stage can be seen as the beginning of the CW management process distributed over subsequent stages of project management.

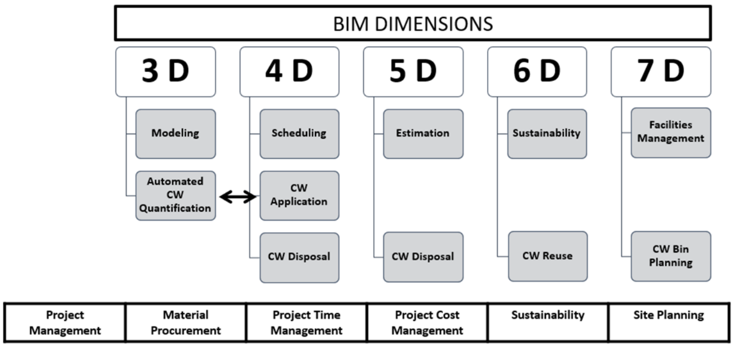

Figure 2. Application of BIM in integrated CW management (source [35]).

2.4. BIM-Aided Quantification of CW

The advantages of BIM adoption in various fields of construction management have been well-established in the literature. The use of BIM in CW reduction is a less researched area, especially in the sphere of CW quantification. Various BIM-aided CW quantification models have been formulated and their accuracy was compared with waste computed through conventional methods. Table 3 shows the outcome of important studies conducted on BIM-aided waste quantification models.

CWM has also been assisted by technological advancements like AI and machine learning (ML) [3]. While most AI-based studies in the field of CWM are focused on the detection of several types of construction materials, only a few studies provide waste quantification solutions [36,37].

Table 3. BIM and AI-aided construction waste quantification studies.

Source	Journal	Scope	Project	Outcome
[38]	*Waste Management*	BIM-based CW quantification model.	A 47-floor building in Hong Kong.	CW Variation 15.8%
[35]	*Resources, Conservation and Recycling*	BIM-based CW quantification for concrete.	Institutional academic building in the US.	CW Variation 5.3%
[4]	*Computing in Civil Engineering*	BIM-based CW estimation of wood wastage.	Institutional building project in the US.	CW Variation 21.8%
[39]	*Waste Management*	BIM-based CW quantification for drywall.	Institutional building project in the US.	CW Variation 11%

Table 3. *Cont.*

Source	Journal	Scope	Project	Outcome
[40]	*Waste Management*	BIM-based design validation.	In 2 residential buildings in South Korea.	CW Reduction 4.3–15.2%
[41]	*Recycling*	BIM-based quantification of CW in early design stages.	A 4-story residential building in Spain.	CW Reduction 56%
[36]	*Waste Management*	AI/ML-based estimation of CW at the regional level.	In 11 cities in China.	CW produced in 11 cities was 364 million m^3.
[42]	*Journal of Cleaner Production*	AI/ML-based prediction models for CW.	Predictive models in South Korea.	Accuracy 95%
[37]	*Asian Journal of Civil Engineering*	AI/ML-based prediction models for CW.	In 134 construction sites in India.	Accuracy 88%

Accuracy is calculated from the difference between actual and predicted CW values.

2.5. Limitations of Existing Studies on BIM-Aided CW Quantification

BIM-aided CW quantification models are mostly developed on the Autodesk Revit platform. A brief explanation of the studies and their corresponding limitations is summarized in Table 4. All selected studies were conducted in specific geographical contexts and they each address specific waste streams. The results have been validated by comparing them with onsite measurement of wastage (through conventional means) or by CW computed through other models. Almost all studies lack generalizability for broader applications due to their limited scopes. Limitations of BIM estimation methods include lack of generalizability, specific geometric and parametric definitions, etc. [4].

Table 4. Limitations of BIM-aided CW quantification studies.

Source	Explanation	Limitation	Source	Explanation	Limitation
[38]	Applied on a multistory building.	Applicable in the context of Hong Kong.	[4]	Applied on a building project for quantification of wood formwork waste.	Only applicable for estimating CW generated by wood formwork. Validated by and assessed for construction practices of the US.
[40]	Applied to 2 building projects. Estimates CW attributable to design errors.	CW was generated for formwork; packaging was not considered.	[39]	Used for estimating CW generated by concrete and drywall.	Only applicable for CW by concrete and drywall.
[35]	The seven-dimensional framework incorporates scheduling, estimation, sustainability, and site planning for concrete in buildings	Only considered a single material concrete.	[41]	CW quantification at the early design stage for concrete and steel structure building.	Developed in the EU context. Applicable for the design stage of CW.

3. Findings

A. Variation and inaccuracies in the quantification of waste carried out through conventional methods necessitate the use of automation/digital technologies like BIM for correct/reliable results [4,17].

B. Sufficient studies are available in the literature on the application of BIM technology in construction management [10,34]; however, only a few studies are available on BIM and AI-assisted CW quantification (See Table 3). Almost all available studies on

CW quantification have been conducted on building construction projects, ignoring infrastructure projects.

C. The results of BIM-aided CW quantification, reported in the literature, lack generalizability for broader application due to their limitations [4].

D. BIM-aided CW quantification assists in the considerable reduction of waste generation in building construction projects in various countries [40,41]. A study in South Korea validated a BIM-based quantification model on two residential buildings and a sports complex. BIM implementation at the design validation stage was able to reduce waste between an observed 4.3% and 15.2% [40]. In another study conducted in Spain, the implementation of a BIM-based quantification model was able to reduce waste by 56% [41].

E. Considerable variation has been observed between the values of waste percentage quantified by BIM-based models and wastage computed through other means. A study conducted on 47 residential buildings in Hong Kong reported a difference of 15% between the BIM-based model and the actual values of CW [38], whereas a study in the US reported a variation of 5.3% between BIM-computed and conventionally computed wastage [35]. Two different studies in the US observed 19.7–21.8% variation in the wastage of wood and an 11% variation in the values of drywall concrete wastage [4,39].

F. AI-based waste quantification models have been able to predict wastage with a high degree of accuracy. Recent studies in India and South Korea predicted waste through various AI-based models with an accuracy of 88% and 95%, respectively [37,42]. A study conducted in China quantified wastage for 11 cities using ML-based models [36].

4. Conclusions and Recommendations

BIM serves as a multidisciplinary collaboration platform that provides effective solutions for construction waste management (CWM) to project stakeholders for financial and environmental benefits. This study reinforces the benefits of BIM-aided CWM as well as BIM-aided construction waste (CW) quantification. BIM-based CW quantification models have shown their ability to predict wastage. Moreover, they have assisted in a substantial reduction in material waste. It is recommended that the construction industry should embrace the latest technological advancements in all fields of construction management, especially CWM and CW quantification, to improve its overall productivity and performance [43]. Further studies on technology-aided waste quantifications should be conducted to validate the findings of the available studies. Future research should also be conducted on infrastructure projects in addition to building projects. This study contributes to the existing literature by highlighting the immense importance of the application of technologies like BIM in important areas like CW quantification and estimation.

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