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A BIM-Based Risk Management Model for Construction Waste Reduction and Control

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The construction industry has long been criticized for being responsible for a significant portion of waste generation worldwide. Although different approaches have been developed over the years for waste reduction and control, they are not sufficiently implemented in practice, and waste generation in the construction industry still shows an increasing trend. As a digital technology platform, Building Information Modelling (BIM) offers promising solutions for the broader adoption of waste management practices. It has the potential to be utilized as a supporting technology to manage the risk factors affecting waste generation. It can also serve as a knowledge management platform to facilitate decision-making processes in waste management. Using BIM in this way may help reduce uncertainties about waste prediction and management in construction projects. From this point of view, this research aims to develop a novel model that benefits from BIM to manage risks and knowledge related to construction waste. Accordingly, a process model was proposed, which integrates the steps of estimating material waste, performing risk assessment, analyzing the impact of waste, developing waste reduction strategies, and monitoring & controlling the waste management plan.

Keywords: Risk, BIM, waste, knowledge, digitalization, construction management.

1. Introduction

The construction industry has been at the center of criticism for a long time because of its detrimental impacts on the environment, including water and air pollution, soil degradation, and overconsumption of natural resources. It is responsible for consuming up to 50% of natural mineral resources, generating up to 35% of waste in landfills, and producing more than 33% of global CO_2 (Ajayi et al., 2015). In the European Union, 25-30% of the total waste is generated by the construction industry (Quiñones et al., 2021). Considering the end-of-life activities such as demolition, waste from construction works reaches 50% worldwide (Akanbi et al., 2018). Apart from its environmental effects, waste also places an economic burden on construction projects. For instance, the yearly landfill tax paid by construction companies in the UK is over £200 million (Osmani, 2012). As such, sustainable waste management practices that contribute to the circular economy have received increasing attention from the scientific community. Over the years, researchers have developed various methods, techniques, and tools to manage construction and demolition waste more effectively (Jin et al., 2019). Despite these efforts, waste generation in the construction industry still shows an increasing trend (Pellegrini et al., 2021). This discrepancy may be due to a lack of awareness among construction practitioners toward the value of waste management practices. One of the main barriers to implementing waste management is the common perception that it delays project activities and has a lower priority compared to other project management issues (Bakchan et al., 2019). Since waste generation is considered inevitable, waste management is often neglected, or reactive strategies are implemented instead of preventive measures (Ajayi et al., 2015). In order to overcome this problem, novel approaches need to be developed, which can help construction practitioners understand the tangible benefits of waste management practices and take proactive measures at the planning stage.

As a digital technology platform, Building Information Modeling (BIM) offers promising solutions not only for more efficient waste reduction and control but also for the broader adoption of waste management practices within the construction industry (Ajayi et al., 2015; Lu et al., 2017; Sepasgozar et al., 2021). BIM uses that have a positive impact on construction and demolition waste management include "design review," "3D coordination," "quantity take-off," "phase planning," "site utilization planning," "digital prefabrication," "3D control and planning," and "construction system design." (Won and Cheng, 2017). For example, according to the findings of two case studies in South Korea, BIM-based design validation could reduce the amount of construction waste by 4.3% to 15.2% (Won et al., 2016). Furthermore, it may be possible to gain more benefits by developing BIM-integrated waste management models and tools. For this purpose, Cheng and Ma (2013) developed a BIM application programming interface in Revit to estimate demolition and renovation waste, pick-up truck requirements, and waste disposal fees. Akinade et al. (2015) utilized a mathematical modeling approach to develop a BIM-based deconstructability assessment score (BIM-DAS), which determines the potential deconstructability of a building in the design stage. Lu et al. (2017) proposed a computational BIM framework to estimate the waste generated during the design and construction phases based on the waste generation rates of building materials. Kim et al. (2017) introduced a BIM-based framework that calculates the demolition waste in the early design stages using material quantities and their rate of volume change. Bakchan et al. (2019) presented a framework incorporating all BIM dimensions for waste quantification and management. Guerra et al. (2019) estimated the construction waste generation of concrete and drywall based on the difference between the total amount of materials purchased and the actual amount of materials quantified by the BIM model. Akinade and Oyedele (2019) developed an Adaptive Neuro-Fuzzy Inference System (ANFIS)-based waste analytics system (A-WAS) and integrated it into Revit for waste prediction in the construction supply chain. Xu et al. (2019) built a BIM-based construction and demolition waste information management system for quantifying and reducing greenhouse gas emissions. Jayasinghe and Waldmann (2020) developed a web tool that can quantify the waste amount for disposal, reuse, and recycling by extracting material volumes from the BIM model. Finally, Jalaei et al. (2021) designed a BIM-integrated tool that estimates the amount of waste during the whole life of a facility for use in life-cycle assessment (LCA).

Although the studies mentioned above have made significant contributions to the waste management literature, they have some shortcomings in utilizing the full potential of BIM. Most of them use BIM mainly for automating the quantity take-off process. The quantities are multiplied by the waste generation rates defined for each building material to calculate the amount of waste generated during construction or demolition. Then, waste management plans are developed by determining the rates of reuse, recycling, and disposal based on the assumptions made according to the type of waste. The effectiveness of this deterministic approach considerably depends on the accuracy of the data used. However, the reliability of the waste generation rates is questionable as most of them are determined without considering the multidimensional nature of waste-causing factors (Gupta et al., 2022). There are many risk sources that may contribute to the variability of waste generation (Bakchan et al., 2019). Besides, the rates used in waste management plans cannot be generalized as they differ from region to region. For instance, the recycling rate is 65% in Australia, while it is only 5% in China (Nikmehr et al., 2021). Hence, practitioners need to evaluate all possibilities related to waste generation together with its impacts to make more accurate decisions about waste management. In this respect, BIM can be used as a supporting technology for risk management activities (Hartmann et al., 2012). It can also serve as a knowledge management platform for more informed decision-making (Oti et al., 2018). Since waste management performance depends on the accuracy of the data used and the assumptions made, relevant information should be captured and stored (Mirshekarlou et al., 2021). Incorporating lessons learned into BIM during the course of the project could allow decision-makers to use more accurate data and make more realistic assumptions in the following stages. Using BIM in this way could also support the Integrated Project Delivery (IPD) approach by promoting effective communication and collaboration and bridging the knowledge gap between the project teams (Akinade et al., 2015). Recording information obtained from past projects in a database system may help reduce uncertainties about waste prediction and management in subsequent projects. From this point of view, the aim of this research is to develop an innovative waste management model that uses BIM as a risk and knowledge management platform.

2. Risk Factors Related to Construction Waste Generation

Although waste is a broad concept that includes "transportation," "inventory," "motion," "waiting," "over-processing," "overproduction," and "defects" from the lean production perspective (Koskela et al., 2013), the scope of this research consists of material waste. Material waste is one of the most important sources of waste generation and cost overruns in construction projects (Mirshekarlou et al., 2021). Moreover, the approach proposed in this research mainly focuses on the waste generated during the construction phase though it can be adapted to cover the entire life cycle of a building, including the design, construction, operation, maintenance, and demolition phases. Accordingly, based on the definition of Skoyles and Skoyles (1987), this study considers waste as any material "which needed to be transported elsewhere from the construction site or used on the site itself other than the intended specific purpose of the project due to damage, excess or non-use, or which cannot be used due to non-compliance with the specifications, or which is a by-product of the construction process."

The amount of material wasted during construction may vary depending on many factors. Table 1 compiles a general list of risk factors affecting waste generation with examples from the literature.

Table 1. Risk Factors Affecting Waste Generation

Risk Factor	Reference
Design mistakes	Luangcharoenrat et al. (2019)
Design complexity	Domingo (2015)
Design changes	Wan et al. (2009)
Supplier & material order mistakes	Fadiya et al. (2014)
Material damages during transportation	Wang et al. (2008)
Low-quality/defective materials	Formoso et al. (2002)
Improper material storage & handling	Gavilan and Bernold (1994)
Improper construction method	Khanh and Kim (2014)
Lack of construction experience	Bekr (2014)
Lack of training and supervision	Adewuyi and Otali (2013)
Low-quality/wrong information & documentation	Poon et al. (2004)
Poor workmanship	Faniran and Caban (1998)
Rework	Nagapan et al. (2012)
Equipment breakdown	Tam et al. (2007)
Accidents at the construction site	Ekanayake and Ofori (2004)
Unfavorable weather conditions	Urio and Brent (2006)
Theft and vandalism at the construction site	Osmani et al. (2008)
Lack of waste awareness	Yuan (2013)
Lack of waste management plan	John and Itodo (2013)
Lack of legal obligations on waste management	Al-Hajj and Hamani (2011)

It is evident that a systematic approach is needed to assist practitioners in managing the factors in Table 1. The next section describes the model proposed for this purpose.

3. Proposed Model

Fig. 1 depicts the process model that provides a basis for the BIM-based risk management model for construction waste reduction and control.

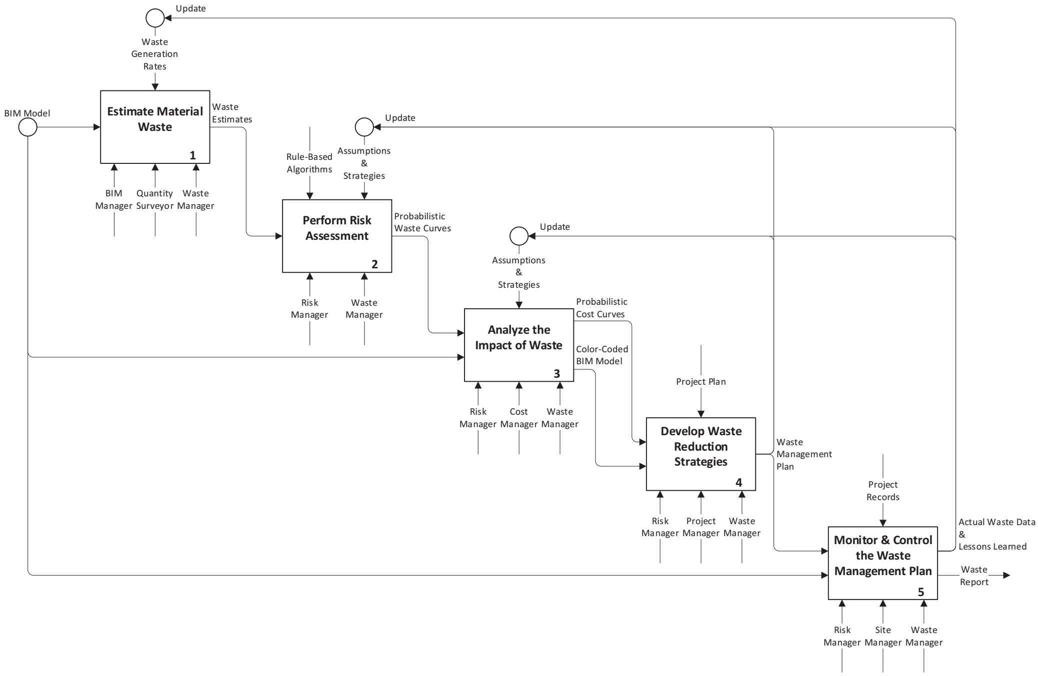

Fig. 1. Process Model

The first step of the process model is to estimate material waste. The BIM model provides the quantities for each building component group having different materials. These quantities are converted into waste estimates using the waste generation rates database. The process should be carried out under the supervision of the BIM manager, quantity surveyor, and waste manager.

In the second step, risk assessment is performed to turn deterministic waste estimates into probabilistic waste curves, which inform decision-makers about all possible outcomes of waste generation. A rule-based expert system can be utilized to this end. The system should assist the risk manager and waste manager in evaluating all risk sources affecting the amount of waste (Table 1). The algorithms in the system can determine the probability interval of waste curves by considering the risk ratings. However, since the assigned risk ratings depend on various assumptions and strategies, they also need to be recorded.

The third step is to analyze the impact of waste. Since the main priority of project managers is often to keep the cost under control, they need to realize the practical benefits of waste management. For example, Begum et al. (2006) estimated that the net benefit of reusing and recycling construction waste is 2.5% of the total project budget. Thus, this step can encourage decision-makers to adopt waste management practices by enabling them to analyze the economic consequences of different reuse, recycling, and disposal rates. It involves generating probabilistic cost curves over the probabilistic waste quantities. Moreover, the initial BIM model is used to create a color-coded BIM model that helps compare the waste impact of different building components. Embedding waste analytics functionalities into BIM through interactive visualization is an effective way of achieving sound waste management decisions (Akinade et al., 2018). This step requires the active participation of the risk manager, cost manager, and waste manager since its outputs depend on various assumptions related to rates and prices.

Then, these outputs are utilized to develop waste reduction strategies in the next step. As “minimization at source” is the most effective strategy for waste management (Jalaei et al., 2021), different alternatives should be evaluated to reduce the total amount of waste. The risk manager, project manager, and waste manager should develop a waste management plan by considering the requirements of the project plan as well. Possible strategies in the plan may include just-in-time delivery (JIT), off-site construction, and training of workers. It should be noted that the waste management plan can affect the assumptions and strategies related to risk ratings and waste impact analysis. Therefore, there are feedback loops to update the control parameters in the second and third steps.

The final step is to monitor and control the waste management plan during construction. Accordingly, the planned and actual performance comparison should be made using project records. For example, the actual waste amount of the completed building components can be determined by subtracting the material quantities in the BIM model from the difference between the quantities purchased and waiting in the stockyard. The actual waste rates specified in this way can provide feedback to the initial process to provide more realistic estimates for the remaining parts of the project. Similarly, lessons learned from waste management activities and actual data on reuse, recycling, and disposal rates can update the assumptions in the second and third processes, resulting in a better waste management plan. Furthermore, the knowledge recorded in the waste report by the risk manager, site manager, and waste manager can be utilized in future projects for more effective waste reduction and control strategies.

4. Conclusions

The construction industry needs to revolutionize its current practices urgently for a more sustainable future. In this direction, this research proposes a novel approach for more efficient construction waste reduction and control, contributing to achieving sustainable development goals (SDGs) for 2030 (United Nations, 2015). Additionally, Europe is now on the verge of a paradigm shift towards Industry 5.0 that endorses a human-centric technology approach. According to the transformative vision report for Europe, Industry 5.0 places emphasis on "people-planet-prosperity" by promoting sustainable, circular, and regenerative economic value creation as well as digitalization for the purpose of sustainability and climate action (European Commission, 2022). Hence, the BIM-based waste management model proposed in this research can contribute to the societal and planetary requirements of Industry 5.0. It is believed that this research also has significant potential in terms of scientific impact. Although knowledge-based approaches have been developed for waste management, risk integration has not yet been achieved at the desired level. This research could be the first attempt to bring these concepts together through BIM.

Nevertheless, the fact that the conceptual model has not been tested in practice limits the validity of the reported benefits. Its performance with respect to usability, functionality, and comprehensiveness needs to be assessed through site investigations. It should be noted that the presented work constitutes the initial phase of an ongoing research project. The forthcoming study of the authors is to test the proposed model in a real project environment. Based on the findings of the field tests, a computer tool is aimed to be developed. Since the proposed model requires keeping the BIM model up to date during construction, the tool can be used in conjunction with digital survey techniques, such as laser scanning and photogrammetry. Radio-frequency identification (RFID) technology can support tracking material flows during construction. The tool can also be integrated with enterprise resource planning (ERP) and other reporting systems to facilitate data transfer. When it is implemented in a sufficient number of projects, waste prediction models can be developed with machine learning techniques. Last but not least, the proposed waste management approach can also pave the way for developing risk-based models and tools for environmental impact assessment and energy analysis.

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