Journal of Construction in Developing Countries, 30(Supp. 1), 97–119, 2025

Integrating Economic, Social, Governance and Construction 4.0 in Construction Waste Management: A Comprehensive Framework

Mohd Reza Esa, *Noor Sahidah Samsudin and Azizan Abdul Aziz

Published: 31 July 2025

To cite this article: Mohd Reza Esa, Noor Sahidah Samsudin and Azizan Abdul Aziz (2025). Integrating economic, social, governance and Construction 4.0 in construction waste management: A comprehensive framework. *Journal of Construction in Developing Countries*, 30(Supp. 1): 97–199. https://doi.org/10.21315/jcdc.2025.30.s1.5

To link to this article: https://doi.org/10.21315/jcdc.2025.30.s1.5

Abstract: The robust growth of the construction industry in Malaysia has increased the amount of construction waste significantly, causing environmental degradation and resource depletion. Integrating the economic, social and governance (ESG) principles with advanced technologies from Construction 4.0 can revamp the inefficient management of construction waste. This study aimed to identify the potential barriers to the implementation of a comprehensive construction waste management framework. A framework was developed based on the circular economy concept. The Delphi method was then utilised to gather expert consensus. Expert opinions of contractors, consultants, developers and government agencies were compiled to derive the framework. The study results revealed that the developed framework can succeed if the identified barriers are overcome. This comprehensive framework will lay a platform for better construction waste management.

Keywords: ESG, Construction 4.0, Circular economy, Barriers, Comprehensive framework

INTRODUCTION

Global megatrends are causing rapid change in organisations worldwide, including in the construction industry. For example, Construction 4.0 which refers to the fourth industrial revolution within the construction industry, changes the design, construction, operation, and maintenance of infrastructure, real estate, and other built assets. The Construction 4.0 Strategic Plan (2021–2025) was introduced in Malaysia recently. The plan identifies 12 new technologies as the principal driving force, namely (1) prefabrication and modular construction, (2) three-dimensional (3D) printing and additive manufacturing, (3) autonomous construction, (4) augmented reality and virtualisation, (5) cloud and real-time collaboration, (6) 3D scanning and photogrammetry, (7) artificial intelligence (AI), (8) blockchain, (9) big data and predictive analytics, (10) advanced building materials, (11) Internet of Things (IoT) and (12) building information modelling (BIM) (CIDB [Construction Industry Development Board], 2020). As a result, businesses and governments need to understand, identify, examine, fix, and opt for appropriate emerging

School of Construction and Quantity Surveying, Faculty of Built Environment, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, MALAYSIA
*Corresponding author: noorsahidah@uitm.edu.my

technologies, as they may influence Malaysian construction companies to become more technologically adept and advance the industry, transgressing technological waves.

The growing amount of waste produced locally and globally poses environmental and social challenges, which waste management helps address. Sustainable development, resource conservation and environmental protection are all aided by effective waste management. Note that the dramatic growth of the construction industry has made it one of the largest waste generators. In Malaysia, the contribution of the construction industry to the country's gross domestic product increased from MYR14.1 billion in 2018 to MYR34.1 billion in 2023 (Department of Statistics, 2023). The amount of waste generated during construction is anticipated to rise significantly (Department of Statistics, 2022). Waste reduction through reuse, recycling and proper disposal is essential to construction waste management. By maximising design, construction techniques and material selection, waste reduction strategies prioritise reducing waste generation at its source. Moreover, initiatives for reuse concentrate on recovering and reusing materials, parts and buildings that increase their lifespan and decrease the need for new resources.

Managing construction waste is crucial in moving towards the sustainability objective. In Malaysia, sustainable construction has been integrated into the national agenda to protect the environment. Excessive waste generation strains available landfill areas, drains natural resources and creates further problems with illegal dumping. If no significant effort is made to mitigate it, it is predicted that the greenhouse gas effects brought on by carbon dioxide emissions will rise to 40 billion tonnes by 2030 (Bao, 2023). Accordingly, the pressure to reduce waste has significantly changed construction players' mindsets, especially in ignoring the use of linear-based practices. The environmental, social and governance (ESG) terminology should be utilised and prioritised in managing construction waste. In addition, waste generation must be controlled to regulate construction costs and time and enhance the quality and productivity of end products.

Many previous studies on construction waste management have explored specific barriers to the integration of ESG; however, a holistic understanding of the integration across micro-, meso- and macro-levels remains underexplored. As such, this study aimed to identify the barriers that could prevent the integration of ESG with Construction 4.0 and provide solutions to manage construction waste in Malaysia effectively. Theoretically, this study would contribute to expanding a three-layered framework that integrates micro-, meso- and macro-levels, offering a novel perspective on integrating ESG with waste management in the construction industry. Practically, the study serves as a catalyst and offers a guide for construction industry stakeholders to detail strategies to overcome resistance to change and foster sustainable waste management practices through targeted interventions. By bridging theoretical gaps and offering practical guidance, this research is a critical step toward enhancing construction waste management, ultimately contributing to environmental sustainability and industry efficiency.

LITERATURE REVIEW

Construction Waste Management

Waste should be treated properly and differently. A waste management hierarchy helps construction players to manage waste efficiently. The most recognised waste management hierarchy is known as the 3Rs (reduce, reuse and recycle) principles. Wastes should be managed in accordance with their suitability for reduction, reuse and recycling prior to being subjected to the final mechanism, which is landfill disposal (Peng, Scorpio and Kitbert, 1997). In addition, some studies support the application of the reduction strategy. This includes implementing a charging system that changes the attitudes of the top management and employees toward better waste management (Botchway et al., 2023; Ma et al., 2023; Tu et al., 2023). Therefore, the 3Rs principle is a cornerstone of sustainable waste management techniques since it encourages resource efficiency and reduces environmental impact. They can be utilised in several industries, including construction, to manage waste and promote a more environmentally friendly way of doing things. Correspondingly, Wolsink (2010) improves the hierarchy by including an additional step, namely, avoiding waste production. Figure 1 depicts the waste management hierarchy evolving from Peng, Scorpio and Kitbert (1997) and Wolsink (2010).

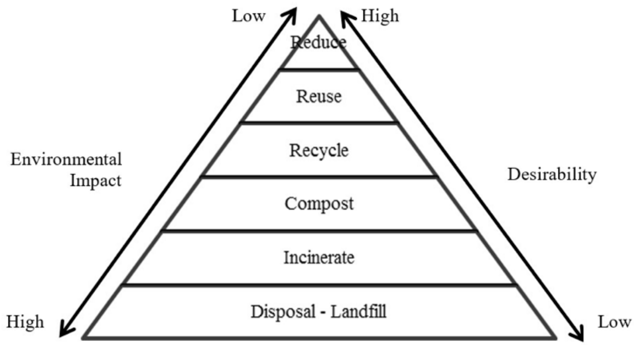

Figure 1. Waste management hierarchy

Source: Peng, Scorpio and Kitbert (1997) and Wolsink (2010)

However, according to Esty and Winston (2006), the 3Rs principle is a traditional priority in environmental thinking. According to Amudjie et al. (2023), the 3Rs principle is a common waste minimisation strategy. Some authors have noted the economic viability of construction waste management, particularly if much attention is paid to raising the rate of reuse and recycling strategies (Daoud et al., 2023; Ryłko-Polak, Komala and Białowiec, 2022). Several authors even coined the reuse and recycling strategies as the most widely used waste minimisation methods (Amudjie et al., 2023; Ma et al., 2023; Nawaz, Chen and Su, 2023). To ensure that the waste management process and design are more innovative, redesigning and reimagining should be conducted prior to considering the reduction element. Figure 2 displays the hierarchy of waste management, which places a strong emphasis on redesigning and reimagining.

Figure 2. Strategic hierarchy of environmental management

Source: Esty and Winston (2006)

Circular Economy

A circular economy (CE) is a viable solution for addressing the increasing amount of construction waste, notably in terms of resource depletion and environmental degradation (Saidani et al., 2019). The current study utilised CE to develop a comprehensive framework for construction waste management that integrates ESG with Construction 4.0. The framework helped manage waste generation throughout the construction cycle. The framework consisted of three primary phases: the planning and design phase, the procurement phase and the building and demolition phase.

The CE concept was implemented at all levels: micro, meso and macro (Geng and Doberstein, 2008; Yuan, Bi and Moriguichi, 2006; Zhu and Huang, 2005). Geng and Doberstein (2008) state that the CE concept would be successfully implemented through a three-circle approach, while Yuan, Bi and Moriguichi

(2006) named it a three-layer approach. The approach consisted of micro, meso and macro. The micro level necessitates the implementation of a cleaner production process and a more environmentally sustainable design in the production area. The meso level necessitates an environmentally sustainable design that promotes implementing a waste trading system. Meanwhile, the macro level necessitates an enhanced industry collaboration network through promoting the 3Rs principles. The approach was integrated into the study's theoretical framework. Besides that, the main element of the framework is to manage waste by employing Construction 4.0. Hence, the employment of Construction 4.0 must influence the minimisation of waste generation.

Barriers to Construction Waste Management

According to de Jesus and Mendonça (2018), the classification of potential barriers can be grouped into hard (technical and economic) and soft (institutional and social) barriers. Guldmann and Huulgaard (2020) further classify the barriers into four levels: market and institutional, value chain, organisational and employee. At the same time, Kirchherr et al. (2018) urge that those classifications of barriers are interrelated. Based on this evidence, the barriers were categorised into economic, informational, institutional, political and technological. Table 1 contains a summary of potential barriers.

Table 1. Summary of potential barriers

Categories	Description
Economic	Lack of financial support or subsidies.
Informational	Lack of necessary information such as the amount of waste, type of waste, source of waste and composition of waste. That information is vital in ensuring the effectiveness of construction waste management.
Institutional	Support from top management is vital for implementing effective construction waste management. Currently, priorities are given towards managing construction cost and time, with construction waste management becoming a secondary consideration. At the same time, there is a lack of knowledge, integration and cooperation between stakeholders.
Political	To accelerate the development of construction waste management, better regulations must be implemented. The role of government is critical in executing construction waste management, such as implementing a charging scheme to control waste going to landfills.
Technological	Inadequate technology and infrastructure.

Theoretical Framework

At this stage, the 3Rs principles were integrated and the potential barriers to implementing the proposed solutions were explored. An effective construction waste management system is necessary in Malaysia. First, it is crucial to recognise the potential barriers (as shown in Table 1) to improve construction waste management in the Malaysian construction industry. Hence, a theoretical framework based on a systematic literature review was developed (as shown in Figure 3). This framework utilised the CE concept as its foundation. This is because the construction industry has been urged to revamp linear-based practices towards a more circular approach that could stimulate the operation of the construction industry by maximising resources while minimising waste (Purchase et al., 2022). As such, the CE concept could help the construction industry to produce a more sustainable and regenerative system (Geng and Doberstein, 2008). In the study's theoretical framework of construction waste management, Construction 4.0 strategies were integrated at each level by focusing on the stages involved throughout the construction cycle using this three-layer approach.

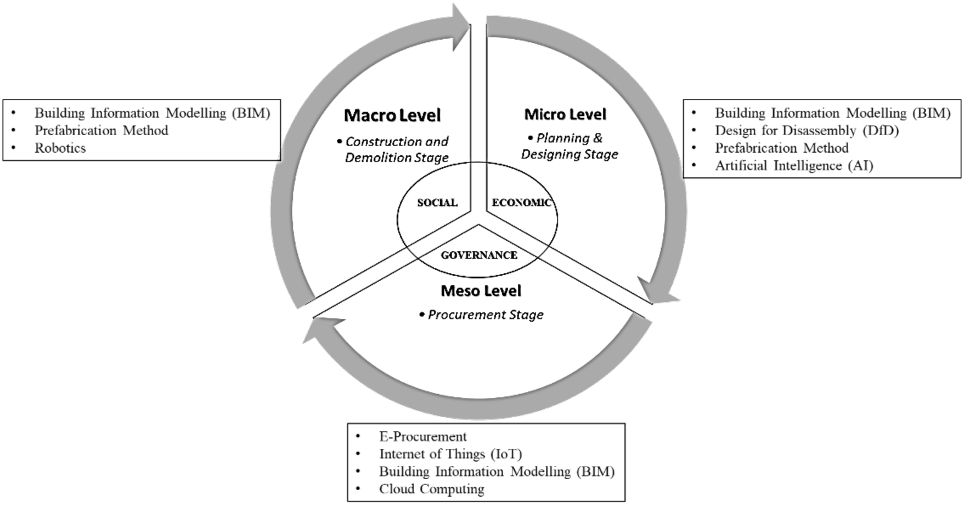

Figure 3. A theoretical framework of construction waste management

Construction 4.0 for Construction Waste Management

Waste management is a serious problem with many implications for professionals in the field and society at large. Nonetheless, in the construction industry, activities that apply a labour-intensive approach generate more waste. The opportunity to use more waste-reducing, environmentally friendly construction techniques can be provided by leveraging digitalisation. This is because Construction 4.0 requires deviation from the established construction industry norms in response to the urgent issue of managing construction waste.

Most developing nations, including Malaysia, regularly dispose of their waste in landfills. Dumping construction waste in landfills will undoubtedly negatively impact the environment, society and economy. The 3Rs principle, which aligns with the concept of CE, has been identified by Amudjie et al. (2023) as the common practice used to minimise waste. In the construction industry, waste minimisation should begin at the planning stage, such as when choosing materials, as it is crucial to manage waste in a circular fashion. Instead of dumping waste into landfills, early planning and selecting the most appropriate materials would aid in promoting the recycling mechanism. Furthermore, the concept of "turning waste into wealth" should be implemented as early as the construction project's planning stage. Table 2 summarises the potential strategies of Construction 4.0 that could be integrated into the framework of construction waste management examined in previous studies.

Table 2. Summary of waste minimisation strategies

Sources	Technology
Costa and Grilo (2015); Akinade et al. (2016); Cheng et al. (2022); Liu et al. (2015); Saxena et al. (2022)	BIM
Ghazilla et al. (2015); Jaillon and Poon (2014); Rios, Chong and Grau (2015); Won, Cheng and Lee (2016)	Design for disassembly (Dfd)
Cheng et al. (2022); Jaillon and Poon (2014); Lu and Yuan (2013); Mostafa et al. (2020); Tam and Hao (2014)	Prefabrication method
Abdallah et al. (2020); Jude et al. (2022)	AI
Anagnostopoulos, Zaslavsky and Medvedev (2015); Zhao, Liu and Mbachu (2019)	IoT
Bello et al. (2021); Chong, Wong and Wang (2014)	Cloud computing
Costa and Grilo (2015); Alite et al. (2023); Debnath, Roychoudhuri and Ghosh (2016); Hashim, Said and Idris (2013); Zunk et al. (2014)	E-procurement
Pan et al. (2018); Pradhananga ElZomor and Santi Kasabdji (2021); Wang, Li and Yang (2020)	Robotics

The developed theoretical framework was enhanced by integrating the suitable 3Rs principles and examining the potential barriers to its implementation. CE concept was employed as it was perceived as an emerging green growth method for controlling construction waste. As such, the concept ensures that waste generated by the construction industry is efficiently managed. However, Malaysia lacks a specific policy, framework or guideline focusing on overseeing construction waste. Therefore, Malaysia must set a precedent and learn from other Asian countries, such as China and Japan, regarding sustainable construction. Therefore, extensive efforts should be made to ensure that construction waste in Malaysia is managed efficiently. This includes integrating digitalisation, such as AI, IoT and prefabrication methods, to generate more sustainable and greener construction practices. At the end of this study, a circular framework for construction waste management that emphasises the aspects of ESG and Construction 4.0 was developed and made practicable in Malaysia.

METHODOLOGY

In this study, a comprehensive framework was developed and used as a guide to enhance the integration of potential barriers that might thwart its implementation. The Delphi method was employed, and experts were allowed to alter their choices until they agreed with the outcomes. Various definitions of the Delphi method can be derived from the literature. "Delphi" was obtained from the ancient Greek temple where prophecy could be found (Grisham, 2009). Early in the 1950s, the Delphi method was first applied to technological prediction. Since then, it has become more common as a research instrument. The Delphi method has been employed in various fields, including tourism management (e.g., Yoopetch, Kongarchapatara and Nimsai, 2022), education (e.g., Tangalakis et al., 2023), healthcare (e.g., Bajwa et al., 2023), and business models (e.g., Aghayari, Valmohammadi and Alborzi, 2022). Notably, the construction industry has been one of the industries that utilise the Delphi method regularly (e.g., Pamidimukkala and Kermanshachi, 2022). Table 3 provides a summary of the Delphi method and its various applications.

Table 3. Research on the construction industry using the Delphi method

Sources	No. of Experts	No. of Rounds	Area of Study
Naji et al. (2024)	13	2	The readiness of the construction industry towards digitisation in Qatar.
Kermanshachi, Rouhanizadeh and Dao (2020)	10	3	Finalising the indicators of complexity for construction projects.

(*Continued on next page*)

Table 3. *Continued*

Sources	No. of Experts	No. of Rounds	Area of Study
Pamidimukkala and Kermanshachi (2023)	12	2	Establishing strategies to overcome occupational challenges for female workers in the construction industry.
Yeung et al. (2007)	31	4	Key performance indicators used in evaluating the success of collaborative construction projects in Hong Kong.

The Delphi technique is commonly employed to conduct repeated rounds of surveys among a panel of experts, with the results then evaluated until consensus is achieved (Hallowell and Gambatese, 2009; Kermanshachi, Rouhanizadeh and Dao, 2020; Tseng et al., 2023). Accordingly, three essential characteristics of the Delphi method make it a special process (Dalkey, 1969; Manoliadis, 2008; Wang and Reio, 2017). The characteristics are anonymity, iteration and statistical analysis. Anonymity refers to how the chosen experts remain unidentified to each other to prevent bias and to facilitate the candid expression of their views. Iteration refers to several rounds that allow the chosen experts to modify their opinions until the necessary level of consensus is reached. Meanwhile, statistical analysis is a straightforward and understandable method that allows for a straightforward and understandable analysis without misunderstandings among experts.

There is disagreement regarding the number of rounds and experts needed to execute the Delphi method. According to Wang and Reio (2017), the total number of rounds selected is to increase precision and reach consensus among experts. Often, studies were conducted using the Delphi method in two to four rounds, as indicated in Table 3. According to Wang and Reio (2017), the Delphi method may require up to six rounds of surveying before a decision is made. However, using the three rounds of the Delphi method is the most effective at illustrating the experts' opinions. In essence, reaching a level of consensus is prioritised over arguing meaningless points of view in the third round (Hallowell and Gambatese, 2009). Nonetheless, the current study proceeded with two rounds of the Delphi method. Even though it was mentioned in the literature that the number of experts can range from three to eighty, it is challenging to pinpoint the exact number that is pertinent (Hallowell and Gambatese, 2009; Rowe and Wright, 1999; Wang and Reio, 2017). The crucial factor is the consistency of the chosen experts who participate until the end of the Delphi method. Accordingly, eight experts participated in the current study to share their perspectives in order to develop a comprehensive framework for construction waste management in Malaysia.

Development Process

The current study utilised two rounds of an online survey as part of the Delphi method. It was intended to present a comprehensive framework for construction waste management that could be used in Malaysia's construction industry. Experts from various fields, including contractors, developers, consultants and governmental organisations, participated in this study. This is because their contributions were crucial to creating a circular model for managing construction waste. The expert panels had shared criteria, namely, (1) they had at least ten years' worth of experience working in the construction industry and (2) they possessed knowledge of construction waste management components.

The survey was divided into three parts: the planning and designing stage (micro), procurement stage (meso) and construction stage (macro). In the beginning, the experts were required to answer questions concerning 3Rs principles. Consequently, the experts were asked about the potential barriers preventing effective construction waste management. Finally, the experts had to decide on the best waste minimisation strategies that could be adopted in each stage of the construction process. All the questions were solicited in an open-ended manner. The multiple response frequency analysis function in the Statistical Package for Social Science was employed to examine the data from the first round of surveys. The results were presented in a table ranking format and made available to experts in the survey's second round. Correspondingly, the experts were requested to evaluate the ranking and respond with a new ranking if they disagreed with the original ranking or deemed it should be reconsidered. An overall level of agreement among the experts was required to finalise the results. Table 4 summarises the implementation of the Delphi method.

Table 4. Process of the Delphi method

	Round 1	**Round 2**
Database for questionnaire	Literature review	Results from Round 1
Duration	10th July 2023 to 20th July 2023	25th July 2023 to 5th August 2023
Number of experts responded	Eight were selected from the 20 responses based on the specified criteria	8

First Stage: Selection of Experts

The first step of the Delphi method is the selection of expert panels (Okoli and Pawlowski, 2004). A total of 10 to 18 expert panels are considered adequate to conduct this method. This study included contractors, consultants, developers and government organisations as key players in the construction industry. To obtain an objective result regarding the study's goal, 20 prospective expert panels were identified, as indicated in Table 5.

Table 5. Expert breakdown

Organisations	Quantity
Contractors	5
Consultants	5
Developers	5
Government agencies	5
Total	20

Second Stage: Format of First Round

The Delphi method was conducted using an online survey, with invitations to experts sent via email. The email explained the structure of the survey. The survey consisted of two rounds, following the Delphi method. The experts were also informed that survey questions were separated into two parts: Part A examined the experts' backgrounds and Part B addressed construction waste management. Part B required information at three management stages: planning and design, procurement and construction. The survey asked the experts which of the 3Rs principles best suited each stage of the construction process. In addition, the experts had to evaluate the potential barriers to implementing effective construction waste management. Finally, they were required to rank the most suitable strategy for waste minimisation. A list of potential barriers and waste minimisation strategies culled from earlier research and published material was also provided for their reference. Each potential barrier and strategy was coded to ease the analysis process. Table 6 provides the list given to the experts.

Table 6. List of potential barriers and waste minimisation strategy

Construction Cycle	Potential Barriers	Strategies
Planning and designing		1S1. BIM 1S2. Dfd 1S3. Prefabrication method 1S4. AI
Procurement	PB1. Economic PB2. Informational PB3. Institutional PB4. Political PB5. Technological	2S1. E-procurement 2S2. IoT 2S3. BIM 2S4. Cloud computing
Construction		3S1. BIM 3S2. Prefabrication method 3S3. Robotics

Third Stage: Format of Second Round

The results from the first round were presented to the experts. The simple format for the final round required the experts to re-evaluate the results or reach a consensus prior to finalising the results. The results were presented in a ranking table format. In this final round, the experts were asked to evaluate the ranking and indicate whether they agreed with it or would reconsider it and offer a new ranking. To reach a consensus among the experts, each ranking provided in this round must have a percentage value of more than 60% (Rayens and Hahn, 2000; Wang and Reio, 2017).

The Development of a Comprehensive Framework for Construction Waste

The rising volume of construction waste necessitates a better management system. However, the awareness of the environmental and financial effects of waste generation needs to be enhanced to shift the mindset of the construction players in Malaysia. Based on the groundbreaking idea of the CE concept, a theoretical framework for controlling construction waste throughout the construction cycle was created in the current study (as shown in Figure 3). The Delphi method was then applied to validate the theoretical framework. There were two rounds of the Delphi method. This study aimed to create a refined framework that might apply to the context of the Malaysian construction industry. Even though Malaysia was utilised as a case study to gather pertinent data, the results are still useful to relevant businesses throughout the construction process in terms of how they may improve their methods for managing construction waste. The comprehensive framework was developed with experts' opinions on Malaysian construction actors in mind. The current study required experts, including contractors, consultants, developers and government organisations, to evaluate crucial elements such as 3Rs principles, potential obstacles and waste minimisation measures. Note that the use of the Delphi method allows experts to change their preferences until the necessary level of consensus is reached.

Background of the Expert Panels

A snowball sampling technique was adopted in this study to randomly approach potential experts who fit this study's requirements. From this technique, 20 potential experts were identified. The potential experts were invited through email and the Delphi method was explained. After all potential experts submitted responses and their qualifications were assessed, a total of eight experts were selected. The experts embodied a broad range of parties involved, with two experts each from consultants, contractors, governments and developers. The variety offered a diverse perspective for this study. Table 7 lists the experts and their positions in the organisations.

Table 7. List of the experts

Organisations	Position	Experience (Years)	Quantity
Contractor	Director Project manager	20 15	2
Consultant	Site engineer Senior quantity surveyor	12 10	2
Developer	Project executive Clerk of works	12 11	2
Government agency	Civil engineer Quantity surveyor	10 15	2
Total			8

RESULTS AND DISCUSSION

Results of Round 1

First, the experts had to decide which 3Rs strategies would be most effective for each stage of the construction process. The potential barriers to creating an efficient construction waste management system were referred to the experts. Both questions allowed the experts to select from a variety of options. The outcome was analysed using the multiple-response frequencies analysis. According to Table 8, the most appropriate principles to use during the planning and design stages were reduce and reuse, with frequencies of 75% and 63%, respectively. In terms of potential barriers that could prevent the implementation of construction waste management during the planning and design stages, institutional (PB3) and technological (PB5) were ranked highest, with 75% and 63% frequencies, respectively. At the procurement stage, all experts agreed that the 3Rs principles should be considered, with a frequency of 63%. Political (PB4) was the most common potential barrier at the procurement stage, with an 88% frequency. Meanwhile, experts identified recycling and reusing as the best principles to be implemented at the construction stage. The most common potential barriers were economic (PB1) and technological (PB5), each with a frequency of 75%. This finding is consistent with Amudjie et al. (2023), who described the importance of employing the 3Rs principles throughout the construction cycle. In addition, previous studies have also demonstrated that all the barriers are interrelated and crucial to be identified to provide an effective solution for better construction waste management (Kirchherr et al., 2018).

Table 8. Results of the 3Rs principles and potential barriers

Stages	3Rs Principles			Barriers				
	Reduce (%)	Reuse (%)	Recycle (%)	PB1 (%)	PB2 (%)	PB3 (%)	PB4 (%)	PB5 (%)
Planning and designing	75	63	25	25	38	75	50	63
Procurement	63	63	63	63	75	75	88	13
Construction	50	75	88	75	50	63	63	75

Furthermore, to determine the best strategies to be employed at each stage of the construction process, the experts' suggestions were also carefully analysed to identify the two most important. Table 9 reports the selection frequencies.

Table 9. Summary of waste minimisation strategies

Stages	Strategies	Frequencies (%)	Rank
Planning and designing	1S1. BIM	88	2
	1S2. Dfd	63	3
	1S3. Prefabrication method	100	1
	1S4. AI	25	4
Procurement	2S1. E-procurement	88	1
	2S2. IoT	63	3
	2S3. BIM	88	2
	2S4. Cloud computing	50	4
Construction	3S1. BIM	88	2
	3S2. Prefabrication method	100	1
	3S3. Robotics	75	3

The current study concluded appropriate waste minimisation strategies by selecting the top two frequencies recommended by experts. Notably, prefabrication and BIM were the most suitable waste minimisation strategies to consider during the planning and design stages. This result corroborates the findings of Saxena et al. (2022) and Cheng et al. (2022) on the capability of prefabrication methods to reduce waste generation. Furthermore, most experts agreed that e-procurement is essential for developing a construction waste management system at the procurement stage. Before commencing the construction work, all stakeholders must be aware of and know how to implement construction waste management. Furthermore, BIM must be regulated to ensure that construction waste management is prioritised in construction projects. These results align with previous studies (Alite et al., 2023; Debnath, Roychoudhuri and Ghosh, 2016). Finally, the experts selected the prefabrication method and BIM as the top two suggestions at the construction stage. Again, the involved parties at this stage should be responsible for employing a prefabrication method as the primary construction method in their projects. In addition, the experts agreed that BIM must be utilised throughout the construction cycle. The application of BIM in construction projects will impact the reduction in waste generation (Saxena et al., 2022).

Result of Round 2

Table 10 lists the conclusions reached during the consensus stage of the second round of the Delphi method for the 3Rs principles, possible barriers and waste minimisation strategies. The findings indicated that every element met the required level of consensus, which was 60%.

Table 10. Level of consensus

Stage	Elements		Rank	Level of Consensus (%)
Planning and designing	3Rs	Reduce	1	85.4
		Reuse	2	85.4
	Barriers	Institutional	1	74.8
		Technological	2	65.6
	Strategies	Prefabrication method	1	68.2
		BIM	2	65.3
Procurement	3Rs	Reduce	1	79.6
		Recycle	2	75.3
	Barriers	Political	1	90.6
		Informational	2	77.5
	Strategies	E-procurement	1	74.5
		BIM	2	70.8
Construction	3Rs	Recycle	1	84.6
		Reuse	2	77.5
	Barriers	Economic	1	76.7
		Technological	2	75.8
	Strategies	Prefabrication method	1	85.4
		BIM	2	78.4

Comprehensive Framework for Construction Waste Management

This study used rounds of the Delphi method. Waste management strategies and appropriate principles for consideration were identified. There was also consensus on the potential barriers to improved construction waste management. Accordingly, the comprehensive framework for construction waste management was developed using the results of two rounds of the Delphi method, as illustrated in Figure 4.

The identified waste minimisation strategies of the prefabrication method and BIM could reduce waste generation during the planning and designing stages. The implementation of successful waste reduction and sustainability initiatives within a construction project or organisation depends on having top management support for the management of construction waste. Thus, it is essential to get support from the top management due to the need for resource allocation, policy implementation, change of mindset and stakeholder perceptions. Moreover, it can be challenging to implement sustainable waste reduction practices in construction projects due to a lack of technology for effective construction waste management. While overcoming a lack of technology can be complex, it is critical to remember that development is ongoing and the construction industry is increasingly emphasising sustainable practices. Therefore, the framework can create a more sustainable future and effective construction waste management by actively looking for and implementing available technologies.

The principles of reduction and recycling should be incorporated at the procurement stage to limit waste generation. In order to ensure the application of suggested strategies like e-procurement and BIM, it is necessary to emphasise the identified barriers. Moreover, better regulations must be implemented to advance the growth of construction waste management. Local government intervention is required to ensure that waste generation is managed correctly. Additionally, the government's role in implementing construction waste management is crucial. Furthermore, additional information is needed, including the waste's source, composition, type and quantity, to implement construction waste management. This data is necessary to guarantee the viability of waste minimisation strategies. However, since it may vary depending on the nature and scope of the projects, it is particularly challenging to produce the related information.

Finally, the prefabrication method and BIM were the finalised waste minimisation strategies during construction. At this stage, recycling and reuse principles were used to manage the generated waste appropriately. However, the economic aspects of integrating the prefabrication method and BIM were perceived as challenging by the study experts. Implementing the prefabrication method involves a high cost, which is difficult for most construction players with limited financial resources. Thus, financial support, such as subsidies and levy exemptions, is required to ensure the construction players can employ prefabrication methods in the construction projects.

Due to time constraints, only eight experts were involved in the Delphi method. A reminder was sent to ensure the selected experts completed the task given and the deadline had to be extended to provide extra time for the experts. Since the Delphi approach demanded a significant level of commitment from each expert, simple yet adequate questions were created for each round to make sure the experts participated all the way through. Note that it was crucial to keep all experts involved until the level of agreement was achieved. The phrasing used in developing the questionnaires was thoroughly selected and user-friendly online survey software was employed.

It might be challenging to create a framework for construction waste management that is applicable throughout the construction process, considering the waste management approach differs based on the projects' popularity, geographic location and type. The context of the Malaysian construction industry served as the basis for this study and this background also shaped the expert judgements. The experts' dedication is crucial to the Delphi process. This approach had helped define relevant components for the growth of construction waste management. Furthermore, the outcomes of the study revealed that the consistency of the construction waste management components significantly improved over several Delphi rounds. As a result, a comprehensive framework that could be helpful in further research is created.

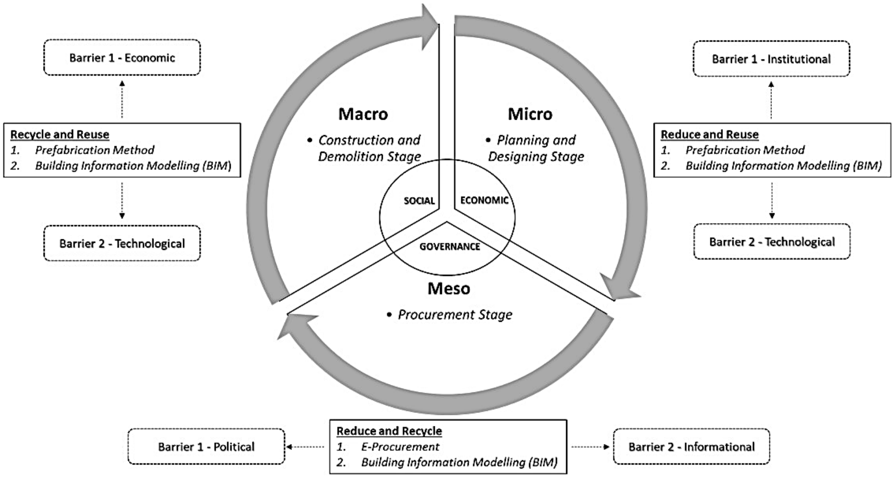

Figure 4. A comprehensive framework for construction waste

CONCLUSIONS

In conclusion, it takes a combination of communication, education, leadership support and a people-centred approach to address resistance to change and foster adaptability to new technology and mindsets. It can be achieved by facilitating a smoother transition to an efficient construction waste management system by involving employees, addressing concerns and highlighting the advantages of change. A comprehensive strategy is required to attain success in construction waste management. Notably, a total commitment and long-term dedication from all the construction players will pave the way for better construction waste management that could create a more sustainable environment.

The current study proposed a comprehensive framework to serve as a reminder of the importance of waste management for construction actors that suits each nation's construction performance. This is in addition to supporting initiatives to increase construction productivity through technologies. In line with the conclusion of the current study, it is suggested that future studies look into how cultural and behavioural factors impact the acceptance and effectiveness of waste management strategies in construction. A cross-cultural study may examine how it could affect the adoption and success of waste management systems in the construction industry. In addition, specific Construction 4.0 technologies should also be explored further to determine their influence on waste management practices in the construction industry.

ACKNOWLEDGEMENTS

The authors express gratitude to the School of Construction and Quantity Surveying, Faculty of Built Environment, Universiti Teknologi MARA, for organising the 4th International Conference on Built Environment and Engineering (IConBEE) 2024, which provided a platform for exposure, facilitating continuous growth and experience gain.

REFERENCES

Abdallah, M., Talib, M. A., Feroz, S., Nasir, Q., Abdalla, H. and Mahfood, B. (2020). Artificial intelligence applications in solid waste management: A systematic research review. *Waste Management*, 109: 231–246. https://doi.org/10.1016/j.wasman.2020.04.057

Aghayari, J., Valmohammadi, C. and Alborzi, M. (2022). Explaining the effective factors on digital transformation strategies in the telecom industry of Iran using the Delphi method. *Discrete Dynamics in Nature and Society*, 1: 9562936. https://doi.org/10.1155/2022/9562936

Akinade, O.O., Oyedele, L.O., Munir, K., Bilal, M., Ajayi, S.O., Owolabi, H.A., Alaka, H.A. and Bello, S.A. (2016). Evaluation criteria for construction waste management tools: towards a holistic BIM framework. *International Journal of Sustainable Building Technology and Urban Development*, 7(1): 3–21. https://doi.org/10.1080/2093761x.2016.1152203

Alite, M., Abu-Omar, H., Agurcia, M.T., Jácome, M., Kenney, J., Tapia, A. and Siebel, M. (2023). Construction and demolition waste management in Kosovo: a survey of challenges and opportunities on the road to circular economy. *Journal of Material Cycles and Waste Management*, 25(2): 1191–1203. https://doi.org/10.1007/s10163-022-01577-5

Amudjie, J., Agyekum, K., Adinyira, E., Amos-Abanyie, S. and Kumah, V.M.A. (2023). Awareness and practice of the principles of circular economy among built environment professionals. *Built Environment Project and Asset Management*, 13(1): 140–156. https://doi.org/10.1108/bepam-11-2021-0135

Anagnostopoulos, T., Zaslavsky, A. and Medvedev, A. (2015). Robust waste collection exploiting cost efficiency of IoT potentiality in smart cities. In *2015 International Conference on Recent Advances in Internet of Things (RIoT)*. Singapore: Institute of Electrical and Electronics Engineers (IEEE), 1–6. https://doi.org/10.1109/riot.2015.7104901

Bajwa, M., Ahmed, R., Lababidi, H., Morris, M., Morton, A., Mosher, C., Wawersik, D., Herx-Weaver, A., Gross, I.T. and Palaganas, J.C. (2023). Development of distance simulation educator guidelines in healthcare: a Delphi method application. *Simulation in Healthcare*, 19(1): 1–10. https://doi.org/10.1097/sih.0000000000000707

Bao, Z. (2023). Developing circularity of construction waste for a sustainable built environment in emerging economies: New insights from China. *Developments in the Built Environment*, 13: 100107. https://doi.org/10.1016/j.dibe.2022.100107

Bello, S.A., Oyedele, L.O., Akinade, O.O., Bilal, M., Delgado, J.M.D., Akanbi, L.A., Ajayi, A.O. and Owolabi, H.A. (2021). Cloud computing in construction industry: Use cases, benefits and challenges. *Automation in Construction*, 122: 103441. https://doi.org/10.1016/j.autcon.2020.103441

Botchway, E.A., Asare, S.S., Agyekum, K., Salgin, B., Pittri, H., Kumah, V.M.A. and Dompey, A.M.A. (2023). Competencies driving waste minimization during the construction phase of buildings. *Buildings*, 13(4): 971. https://doi.org/10.3390/buildings13040971

Cheng, B., Huang, J., Lu, K., Li, J., Gao, G., Wang, T. and Chen, H. (2022). BIM-enabled life cycle assessment of concrete formwork waste reduction through prefabrication. *Sustainable Energy Technologies and Assessments*, 53: 102449. https://doi.org/10.1016/j.seta.2022.102449

Chong, H.-Y., Wong, J. S. and Wang, X. (2014). An explanatory case study on cloud computing applications in the built environment. *Automation in Construction*, 44: 152–162. https://doi.org/10.1016/j.autcon.2014.04.010

CIDB (Construction Industry Development Board) (2020). *Construction 4.0 Strategic Plan (2021–2025): Next Revolution of the Malaysian Construction Industry*. Kuala Lumpur: CIDB.

Costa, A.A. and Grilo, A. (2015). BIM-based e-procurement: An innovative approach to construction e-procurement. *The Scientific World Journal*, 1: 905390. https://doi.org/10.1155/2015/905390

Dalkey, N.C. (1969). *The Delphi Method: An Experimental Study of Group Opinion*. Vol. 3. Santa Monica: Rand Corporation. https://doi.org/10.7249/rm5888

Daoud, A.O., Omar, H., Othman, A.A.E. and Ebohon, O.J. (2023). Integrated framework towards construction waste reduction: The case of Egypt. *International Journal of Civil Engineering*, 21(5): 695–709. https://doi.org/10.1007/s40999-022-00793-2

De Jesus, A. and Mendonça, S. (2018). Lost in transition? Drivers and barriers in the eco-innovation road to the circular economy. *Economics*, 145: 75–89. https://doi.org/10.1016/j.ecolecon.2017.08.001

Debnath, B., Roychoudhuri, R. and Ghosh, S.K. (2016). E-waste management: A potential route to green computing. *Procedia Environmental Sciences*, 35: 669–675. https://doi.org/10.1016/j.proenv.2016.07.063

Department of Statistics (2023). *Construction Statistics: Fourth Quarter 2023*. Putrajaya: Department of Statistics Malaysia. Available at: https://www.dosm.gov.my/portal-main/release-content/construction-statistics-fourth-quarter-2023

______. (2022). *Quarterly Construction Statistics: First Quarter 2022*. Putrajaya: Department of Statistics Malaysia. Available at: https://www.dosm.gov.my/site/downloadrelease?id=quarterly-construction-statistics-first-quarter-2022&lang=English

Esty, D.C. and Winston, A.S. (2006). *Green to Gold: How Smart Companies Use Environmental Strategy to Innovate, Create Value and Build Competitive Advantage*. New Haven: Yale University Press.

Geng, Y. and Doberstein, B. (2008). Developing the circular economy in China: Challenges and opportunities for achieving "leapfrog development". *International Journal of Sustainable Development and World Ecology*, 15(3): 231–239. https://doi.org/10.3843/SusDev.15.3:6

Ghazilla, R.A.R., Sakundarini, N., Taha, Z., Abdul-Rashid, S.H. and Yusoff, S. (2015). Design for environment and design for disassembly practices in Malaysia: A practitioner's perspectives. *Journal of Cleaner Production*, 108: 331–342. https://doi.org/10.1016/j.jclepro.2015.06.033

Grisham, T. (2009). The Delphi technique: A method for testing complex and multifaceted topics. *International Journal of Managing Projects in Business*, 2(1): 112–130. https://doi.org/10.1108/17538370910930545

Guldmann, E. and Huulgaard, R.D. (2020). Barriers to circular business model innovation: A multiple-case study. *Journal of Cleaner Production*, 243: 118160. https://doi.org/10.1016/j.jclepro.2019.118160

Hallowell, M.R. and Gambatese, J.A. (2009). Qualitative research: Application of the Delphi method to CEM research. *Journal of Construction Engineering and Management*, 136(1): 99–107. https://doi.org/10.1061/(asce)co.1943-7862.0000137

Hashim, N., Said, I. and Idris, N.H. (2013). Exploring e-procurement value for construction companies in Malaysia. *Procedia Technology*, 9: 836–845. https://doi.org/10.1016/j.protcy.2013.12.093

Jaillon, L. and Poon, C.S. (2014). Life cycle design and prefabrication in buildings: A review and case studies in Hong Kong. *Automation in Construction*, 39: 195–202. https://doi.org/10.1016/j.autcon.2013.09.006

Jude, A.B., Singh, D., Islam, S., Jameel, M., Srivastava, S., Prabha, B. and Kshirsagar, P.R. (2022). Retracted article: An artificial intelligence based predictive approach for smart waste management. *Wireless Personal Communications*, 127(1): 15–16. https://doi.org/10.1007/s11277-021-08803-7

Kermanshachi, S., Rouhanizadeh, B. and Dao, B. (2020). Application of Delphi method in identifying, ranking and weighting project complexity indicators for construction projects. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, 12(1): 04519033. https://doi.org/10.1061/(asce)la.1943-4170.0000338

Kirchherr, J., Piscicelli, L., Bour, R., Kostense-Smit, E., Muller, J., Huibrechtse-Truijens, A. and Hekkert, M. (2018). Barriers to the circular economy: Evidence from the European Union (EU). *Ecological Economics*, 150: 264–272. https://doi.org/10.1016/j.ecolecon.2018.04.028

Liu, Z., Osmani, M., Demian, P. and Baldwin, A. (2015). A BIM-aided construction waste minimisation framework. *Automation in Construction*, 59: 1–23. https://doi.org/10.1016/j.autcon.2015.07.020

Lu, W. and Yuan, H. (2013). Investigating waste reduction potential in the upstream processes of offshore prefabrication construction. *Renewable and Sustainable Energy Reviews*, 28: 804–811. https://doi.org/10.1016/j.rser.2013.08.048

Ma, W., de Jong, M., Zisopoulos, F. and Hoppe, T. (2023). Introducing a classification framework to urban waste policy: Analysis of sixteen zero-waste cities in China. *Waste Management*, 165: 94–107. https://doi.org/10.1016/j.wasman.2023.04.012

Manoliadis, O.G. (2008). The role of adaptive environmental management in sustainable development case study assessing the economical benefits of sustainable construction in Greece. In E.B.O. Gungor (ed.), *Environmental Technologies*. London: INTECH Open Access Publisher, 85–96.

Mostafa, S., Kim, K.P., Tam, V.W. and Rahnamayiezekavat, P. (2020). Exploring the status, benefits, barriers and opportunities of using BIM for advancing prefabrication practice. *International Journal of Construction Management*, 20(2): 146–156. https://doi.org/10.1080/15623599.2018.1484555

Naji, K.K., Gunduz, M., Alhenzab, F., Al-Hababi, H. and Al-Qahtani, A. (2024). Assessing the digital transformation readiness of the construction industry utilizing the Delphi method. *Buildings*, 14(3): 601. https://doi.org/10.3390/buildings14030601

Nawaz, A., Chen, J. and Su, X. (2023). Exploring the trends in construction and demolition waste (CandDW) research: A scientometric analysis approach. *Sustainable Energy Technologies and Assessments*, 55: 102953. https://doi.org/10.1016/j.seta.2022.102953

Okoli, C. and Pawlowski, S.D. (2004). The Delphi method as a research tool: an example, design considerations and applications. *Information and Management*, 42(1): 15–29. https://doi.org/10.1016/j.im.2003.11.002

Pamidimukkala, A. and Kermanshachi, S. (2023). Occupational challenges of women in construction industry: Development of overcoming strategies using Delphi technique. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, 15(1): 04522028. https://doi.org/10.1061/(asce)la.1943-4170.0000571

_______. (2022). Development of strategies to improve health and safety of women in construction industry: A Delphi method. In F. Jazizadeh, T. Shealy and M.J. Garvin (eds.), *Construction Research Congress 2022*. Reston, VA: American Society of Civil Engineers, 314–323. https://doi.org/10.1061/9780784483985.032

Pan, M., Linner, T., Pan, W., Cheng, H. and Bock, T. (2018). A framework of indicators for assessing construction automation and robotics in the sustainability context. *Journal of Cleaner Production*, 182: 82–95. https://doi.org/10.1016/j.jclepro.2018.02.053

Peng, C.L., Scorpio, D.E. and Kitbert, C.J. (1997). Strategies for successful construction and demolition waste recycling operations. *Construction Management and Economics*, 15(1): 49–58. https://doi.org/10.1080/014461997373105

Pradhananga, P., ElZomor, M. and Santi Kasabdji, G. (2021). Identifying the challenges to adopting robotics in the US construction industry. *Journal of Construction Engineering and Management*, 147(5): 05021003. https://doi.org/10.1061/(asce)co.1943-7862.0002007

Purchase, C.K., Al Zulayq, D.M., O'Brien, B.T., Kowalewski, M.J., Berenjian, A., Tarighaleslami, A.H. and Seifan, M. (2022). Circular economy of construction and demolition waste: A literature review on lessons, challenges and benefits. *Materials*, 15(1): 76. https://doi.org/10.3390/ma1501007

Rayens, M.K. and Hahn, E.J. (2000). Building consensus using the policy Delphi method. *Policy, Politics, and Nursing Practice*, 1(4): 308–315. https://doi.org/10.1177/152715440000100409

Rios, F.C., Chong, W.K. and Grau, D. (2015). Design for disassembly and deconstruction-Challenges and opportunities. *Procedia Engineering*, 118: 1296–1304. https://doi.org/10.1016/j.proeng.2015.08.485.

Rowe, G. and Wright, G. (1999). The Delphi technique as a forecasting tool: issues and analysis. *International Journal of Forecasting*, 15(4): 353–375. https://doi.org/10.1016/s0169-2070(99)00018-7

Ryłko-Polak, I., Komala, W. and Białowiec, A. (2022). The reuse of biomass and industrial waste in biocomposite construction materials for decreasing natural resource use and mitigating the environmental impact of the construction industry: a review. *Materials*, *15*(12), 4078. https://doi.org/10.3390/ma15124078

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F. and Kendall, A. (2019). A taxonomy of circular economy indicators. *Journal of Cleaner Production*, 207: 542–559. https://doi.org/10.1016/j.jclepro.2018.10.014

Saxena, A., Singh, R., Gehlot, A., Akram, S.V., Twala, B., Singh, A., Montero, E.C. and Priyadarshi, N. (2022). Technologies empowered environmental, social and governance (ESG): An industry 4.0 landscape. *Sustainability*, 15(1): 309. https://doi.org/10.3390/su15010309

Tam, V.W. and Hao, J.J. (2014). Prefabrication as a mean of minimizing construction waste on site. *International Journal of Construction Management*, 14(2): 113–121. https://doi.org/10.1080/15623599.2014.899129

Tangalakis, K., Lexis, L., Hryciw, D.H., Towstoless, M., Bakker, A.J., Beckett, E., Brown, D., Cameron, M., Choate, J. and Chopin, L. (2023). Establishing consensus for the core concepts of physiology in the Australian higher education context using the Delphi method. *Advances in Physiology Education*, 47(3): 419–426. https://doi.org/10.1152/advan.00140.2022

Tseng, M.-L., Li, S.-X., Lin, C.-W.R. and Chiu, A.S. (2023). Validating green building social sustainability indicators in China using the fuzzy Delphi method. *Journal of Industrial and Production Engineering*, 40(1): 35–53. https://doi.org/10.1080/21681015.2022.2070934

Tu, B., Pan, M., Zuo, J., Chang, R.-D., Webber, R.J., Zou, Z. and Dong, N. (2023). Cost-benefit analysis of construction waste source reduction: a system dynamics approach. *Environmental Science and Pollution Research*, 30(1): 557–577. https://doi.org/10.1007/s11356-022-22148-z

Wang, V.C. and Reio Jr, T.G. (2017). *Handbook of Research on Innovative Techniques, Trends and Analysis for Optimized Research Methods*. Hershey: IGI Global. https://doi.org/10.4018/978-1-5225-5164-5

Wang, Z., Li, H. and Yang, X. (2020). Vision-based robotic system for on-site construction and demolition waste sorting and recycling. *Journal of Building Engineering*, 32: 101769. https://doi.org/10.1016/j.jobe.2020.101769

Wolsink, M. (2010). Contested environmental policy infrastructure: Socio-political acceptance of renewable energy, water and waste facilities. *Environmental Impact Assessment Review*, 30(5): 302–311. https://doi.org/http://dx.doi.org/10.1016/j.eiar.2010.01.001

Won, J., Cheng, J.C. and Lee, G. (2016). Quantification of construction waste prevented by BIM-based design validation: Case studies in South Korea. *Waste management*, 49: 170–180. https://doi.org/10.1016/j.wasman.2015.12.026

Yeung, J.F., Chan, A.P., Chan, D.W. and Li, L.K. (2007). Development of a partnering performance index (PPI) for construction projects in Hong Kong: a Delphi study. *Construction Management and Economics*, 25(12): 1219–1237. https://doi.org/10.1080/01446190701598673

Yoopetch, C., Kongarchapatara, B. and Nimsai, S. (2022). Tourism forecasting using the Delphi method and implications for sustainable tourism development. *Sustainability*, 15(1): 126. https://doi.org/10.3390/su15010126

Yuan, Z., Bi, J. and Moriguichi, Y. (2006). The circular economy: A new development strategy in China. *Journal of Industrial Ecology*, 10(1–2): 4–8. https://doi.org/10.1162/108819806775545321

Zhao, L., Liu, Z. and Mbachu, J. (2019). Development of intelligent prefabs using IoT technology to improve the performance of prefabricated construction projects. *Sensors*, 19(19): 4131. https://doi.org/10.3390/s19194131

Zhu, D.J. and Huang, X.F. (2005). Building up a model for circular economy based on object, main body and policy. *Naikai Academic Journal*, 4: 86–93.

Zunk, B., Marchner, M., Uitz, I., Lerch, C. and Schiele, H. (2014). The role of E-procurement in the Austrian construction industry: Adoption rate, benefits and barriers. *International Journal of Industrial Engineering and Management*, 5(1): 13–21. https://doi.org/10.24867/ijiem-2014-1-102