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Developing a model for the implementation of designing out waste in construction

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ABSTRACT

Waste mitigation is recognised as the most effective strategy for managing construction and demolition waste. Designing out Waste (DoW) is an approach aimed at reducing waste during construction and demolition by improving project planning and design. Despite its recognition, limited research has been conducted on the factors influencing the implementation of DoW in construction. A questionnaire survey was conducted to collect data on DoW practices, barriers, and enablers from 76 construction practitioners in New South Wales, Australia. A model was developed and analysed using partial least squares structural equation modelling (PLS-SEM). The results indicate a significant relationship between DoW practices and two key barriers: Design-related Barriers and Lack of Experience and Skills. The results also show a significant relationship between Enablers and DoW. Three significant enabling variables identified in this study, which are good communication and coordination, Building Information Modelling (BIM), and utilisation of prefabrication, precast and 3D printing. However, no moderating influence of the enablers was identified in the relationship between the barriers and DoW practices. Through the developed model, this research provides insights into implementing DoW in construction by addressing multifaceted barriers and implementing interventions for effective waste reduction.

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Construction waste management; designing out waste (DoW); PLS-SEM; Australia; waste mitigation

Introduction

Waste is a global concern, with the East Asia and Pacific region responsible for about 23% of worldwide waste (The Worold Bank, 2018). High-income nations, including Australia, significantly contribute to this issue (Doust, Battista, & Rundle, 2021). In 2018–2019, Australia generated 76 million tonnes of waste, a 10% increase from 2016 to 2017, with over half recycled and 27% sent to landfills (Australian Bureau of Statistics, 2020). The construction sector in Australia plays a substantial role in waste production. Per capita construction waste rose by 32% in 13 years (Pickin, Wardle, O'Farrell, Nyunt, & Donovan, 2020). In 2016–2017, this sector generated 12.7 million tonnes of waste, about 17% of all waste produced, costing over 2 billion AUD in waste services (Australian Bureau of Statistics, 2020). Construction waste volume increased by 22% from 2016–2017 to 2018–2019 (Australian Bureau of Statistics, 2020), with this upward trend expected to continue due to expanded construction activities in Australia.

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Waste reduction is a key measure to mitigate the adverse environmental impact and alleviate the economic burden associated with waste management (NSW EPA, 2022). Waste mitigation, which entails adopting strategies and procedures aimed at preventing and reducing waste at its source (Keys, Baldwin, & Austin, 2000), has gained widespread acceptance as the most effective strategy. While several studies have examined construction waste mitigation in the design phase (Ajayi & Oyedele, 2018; Akinade et al., 2018; Laovisutthichai, Lu, & Bao, 2020; Olanrewaju & Ogunmakinde, 2020; Xu & Lu, 2019), basic waste reduction strategies and tools remain largely unexplored (Ajayi et al., 2017). Designing out Waste (DoW) has specifically emerged as an efficient strategy for waste minimisation by enhancing decision-making and improving the design process. Although DoW is recognised as the most efficient and cost-effective method of waste management (Yang, Xia, Thompson, & Flower, 2017), its application in the construction industry has yet to reach its full potential. The limited progress within the Australian construction sector regarding the adoption of waste mitigation strategies over the past two decades can be attributed to government policies that primarily prioritise waste recycling over waste minimisation (Doust et al., 2021).

While several studies focus on the barriers of waste management in construction in general (e.g. Udawatta et al., 2018), limited research can be found on the factors influencing DoW specifically. Therefore, the objective of this study is to identify the barriers and enablers of DoW practices, using Australia as a case study. Identifying such factors is crucial for understanding how DoW can be applied in practice more widely. The following section provides further details about DoW in construction, followed by a section on the barriers and enablers of waste mitigation drawn from the existing literature.

Designing out waste practice in construction

DoW is defined as an approach that controls resources effectively during the design phase of a project to reduce waste generated during the construction and demolition phases (Othman & Elsawaf, 2021). Keys et al.'s (2000) study is one of the pioneering works that played a pivotal role in advocating the implementation of DoW in the construction sector. DoW practices in construction can be divided into three levels: strategies, guidelines, and tools.

Commitment from top management in construction firms is vital for successful waste mitigation (Camilleri, 2022). The adoption of ISO 14000 environmental management standards within the firm is an indicator of such commitment. However, according to Osmani et al. (2008b), some UK architectural firms displayed limited ISO 14001 adoption, reflecting inadequate knowledge of waste issues. Another pertinent standard is the British Standard BS 8895, titled 'Designing for Material Efficiency in Building Projects'. This standard offers recommendations for optimising material efficiency in design and construction, promoting virgin material reduction and waste prevention (Osmani, 2013).

In terms of guidelines, the Waste and Resource Action Programme (WRAP) can be implemented in construction projects (Laovisutthichai et al., 2020). Originating in the UK, WRAP offers five principles, which are design for material optimisation, design for recovery and reuse, design for waste-efficient procurement, design for off-site construction, and design for deconstruction and flexibility (Langdon, 2009). Although, the Better Practice Guidelines for Waste Management by the Environment Protection Authority (EPA) in New South Wales (NSW) encourage sustainable waste management in design and operation (NSW EPA, 2012), they lack specific design-related waste mitigation strategies. In addition, EPA's toolkit aids project managers in handling construction and demolition waste but lacks detailed waste reduction strategies during design and procurement (NSW EPA, 2020).

DoW tools like design reviews and meetings can identify waste mitigation opportunities in the project's early stages (Ajayi & Oyedele, 2018). Waste reduction meetings can be conducted periodically or on an ad-hoc basis and may involve the client as necessary (Baldwin, Poon, Shen, Austin, & Wong, 2009). However, these meetings are not commonly practised due to the perception that waste is inevitable and can be dealt with at another phase of the project (Akinade et al., 2018). Building Information Modelling (BIM) is another tool that supports waste mitigation by enhancing project performance through detailed modelling, visualisation, simulation, clash detection, enhanced coordination, and streamlined communication for better understanding and quicker decision-making (Ajayi et al., 2017; Akinade et al., 2018; Liu, Osmani, Demian, & Baldwin, 2015).

Designing out waste barriers and enablers

As mentioned earlier, there is a dearth of studies focusing on the barriers and enablers of DoW in the construction industry. However, existing studies have indicated several factors influencing waste minimisation in construction more broadly. An in-depth literature review has uncovered 15 barriers to waste minimisation as summarised in Table 1. The barriers can broadly be categorised into design-related, project-related, and designer-related barriers. For example, design changes can contribute to construction waste through several mechanisms such as re-work, demolition of existing structures or components, disposal of unused materials, reordering and repackaging, and material overordering.

On the other hand, enablers are actions or conditions that facilitate DoW implementation. Enablers empower designers, contractors, and clients to effectively reduce construction and demolition waste (Batoul & Amna, 2019; Davis, Sher, Tang, & Newaz, 2018; Kabirifar, Mojtahedi, Wang, & Tam, 2020; Newaz, Davis, Sher, & Simon, 2020; Udawatta, Zuo, Chiveralls, & Zillante, 2015). For example, using incentives led to a substantial 23% waste reduction in a Hong Kong hotel redevelopment project (Seneviratne, Rameezdeen, & Amaratunga, 2015). Eight potential enablers have been identified through the literature review as shown in Table 1. For instance, the utilisation of prefabrication, precast and 3D printing can mitigate waste at its source by several means such as reducing site work, allowing for more recyclable materials to be used, promoting customisation and optimisation of design and structures, creating on-demand production and reducing the need for large inventories, and producing components with high precision thereby reducing the need for on-site adjustments and cutting waste. In addition, good communication and coordination among designers and professionals help to ensure efficient planning, accurate project specifications, optimum construction processes, and design for efficiency in terms of material use. The empirical research will validate the identified barriers and enablers of waste minimisation and evaluate their relevance and influence on DoW practices, as detailed in the next sections.

Research method

Method of data collection

A questionnaire survey was conducted to gather data from professionals in the construction sector in NSW, Australia. The survey is used to validate the factors of DoW and test the relationship between the barriers, enablers and DoW practices. The survey consisted of four sections. The first section collected background information about the respondents, including their education, job title, years of experience in the construction industry, and project types. The second section focused on DoW practices in construction. The third and fourth sections covered DoW barriers and enablers. Respondents rated these DoW factors on a five-point Likert scale, ranging from 'strongly disagree' to 'strongly agree' with each statement.

A probability random sampling method was employed to target construction industry professionals in NSW, including designers, architects, construction project managers, engineering managers, and sustainability managers. NSW was chosen for its status as the most economically vibrant Australian state with the highest construction activity levels. The population size of relevant professionals was estimated using data from the Labour Market Information Portal (LMIP, 2021), indicating around 340,000 professionals employed in the construction industry in NSW at the time of conducting this study. Given this population size, a sample of approximately 196 respondents was determined using relevant sample size equations by considering a 95% confidence level and 0.07 confidence interval (Moinester & Gottfried, 2014; Riley et al., 2020).

Table 1. Barriers and enablers of waste minimisation in construction.

Category	Variable	Reference
Barriers	Design changes	(Ajayi et al., 2016; Doust et al., 2021; Ekanayake & Ofori, 2004; Laovisutthichai et al., 2020; Liu et al., 2015; Llatas & Osmani, 2016; Olanrewaju & Ogunmakinde, 2020; Osmani et al., 2008a; Salgin, Cosgun, Ipekci, & Karadayi, 2020; Wang, Li, & Tam, 2014)
	Change in processes and practices of design	(Ajayi & Oyedele, 2018; Osmani et al., 2008a; Osmani, Price, & Glass, 2005; Xu & Lu, 2019)
	Poor design	(Liu et al., 2015; Llatas & Osmani, 2016; Osmani et al., 2008a; Osmani et al., 2008b)
	Design complexity	(Ajayi & Oyedele, 2018; Ajayi et al., 2017; Laovisutthichai et al., 2020; Liu et al., 2015; Llatas & Osmani, 2016; Osmani, 2013; Osmani et al., 2008a; Osmani et al., 2008b; Osmani et al., 2005; Wang et al., 2014)
	Contract does not specify reducing waste during the design phase	(Akinade et al., 2018; Doust et al., 2021; Llatas & Osmani, 2016; Osmani, 2013; Osmani et al., 2005)
	Lack of interest of the client in reducing waste	(Olanrewaju & Ogunmakinde, 2020; Osmani, 2013; Osmani et al., 2008a; Osmani et al., 2008b; Wang, Yu, Tam, Li, & Xu, 2019)
	Project constraints (e.g. no sufficient time or resources to review the design)	(Olanrewaju & Ogunmakinde, 2020; Osmani, 2013; Osmani et al., 2008a; Osmani et al., 2008b; Salgin et al., 2020)
	Lack of information, documentation, and drawings	(Ajayi & Oyedele, 2018; Akinade et al., 2018; Jaques, 2000; Osmani, 2013; Salgin et al., 2020; Wang et al., 2014); (Olanrewaju & Ogunmakinde, 2020)
	Lack of collaboration among professionals from different disciplines	(Ajayi et al., 2016); Ajayi & Oyedele, 2018; Ipsen, Pizzol, Birkved, & Amor, 2021; Laovisutthichai et al., 2020; Liu et al., 2015; Osmani, 2013; Ajayi et al., 2017; Mohammed et al., 2022)
	Lack of DoW tools such as ICT tools	(Akinade et al., 2018; Li et al., 2015; Llatas & Osmani, 2016; Wang et al., 2014; Wong, Wu, & Chi-Sun, 2021)
	Designers' negative perception (behaviour and attitude) towards DoW	(Ajayi et al., 2016; Liu et al., 2015; Wang et al., 2014; Wang et al., 2019)
	Lack of experience and skills in implementing DoW	(Ajayi et al., 2016; Osmani et al., 2008a; Salgin et al., 2020; Wang et al., 2014)
	Lack of awareness	(Ajayi et al., 2016; Liu et al., 2015; Llatas & Osmani, 2016; Olanrewaju & Ogunmakinde, 2020; Osmani, 2013)
	Lack of knowledge about standardisation (e.g. material size in the market)	(Ajayi & Oyedele, 2018; Ajayi et al., 2017; Ajayi et al., 2016; Alshboul & Abu Ghazaleh, 2014; Banihashemi, Tabadkani, & Hosseini, 2018; Ekanayake & Ofori, 2004; Jaques, 2000; Liu et al., 2015; Llatas & Osmani, 2016; Olanrewaju & Ogunmakinde, 2020; Osmani, 2013; Osmani et al., 2008a; Osmani et al., 2005; Salgin et al., 2020; Wang et al., 2014, 2015; Xu & Lu, 2019)
	Designers' limited knowledge of construction processes	(Ajayi et al., 2016; Ipsen et al., 2021; Olanrewaju & Ogunmakinde, 2020)
Enablers	Prefabrication, precast and 3D printing	(Ajayi & Oyedele, 2018; Ajayi et al., 2017; Ajayi et al., 2016; Doust et al., 2021; Jaques, 2000; Laovisutthichai et al., 2020; Llatas & Osmani, 2016; Osmani et al., 2008a; Osmani et al., 2008b; Wang et al., 2014)
	Education or training	(Ajayi et al., 2016; Jaques, 2000; Olanrewaju & Ogunmakinde, 2020; Osmani et al., 2008a; Wang et al., 2014)
	Good communication and coordination	(Ajayi & Oyedele, 2018; Ajayi et al., 2016; Akinade et al., 2018; Jaques, 2000; Liu et al., 2015; Llatas & Osmani, 2016; Osmani, 2013; Osmani et al., 2008a; Salgin et al., 2020)
	Material selection or alternative products	(Ajayi et al., 2016; Ajayi & Oyedele, 2018; Akinade et al., 2018; Doust et al., 2021; Ekanayake & Ofori, 2004; Jaques, 2000; Laovisutthichai et al., 2020; Li et al., 2015; Llatas & Osmani, 2016; Olanrewaju & Ogunmakinde, 2020; Osmani, 2013; Osmani et al., 2005; Salgin et al., 2020; Wang, Li, & Tam, 2015)
	Legislation, regulations, government requirements	(Doust et al., 2021; Laovisutthichai et al., 2020; Li et al., 2015; Olanrewaju & Ogunmakinde, 2020; Osmani, 2013; Osmani et al., 2008a; Osmani et al., 2008b; Osmani et al., 2005; Wang et al., 2014; Wang et al., 2019; Wong et al., 2021)
	Financial incentive or cost-saving	(Ajayi et al., 2016; Ajayi et al., 2017; Ajayi & Oyedele, 2018; Akinade et al., 2018; Jaques, 2000; Laovisutthichai et al., 2020; Olanrewaju & Ogunmakinde, 2020; Osmani, 2013; Wang et al., 2014, 2015; Wong et al., 2021)
	Using Building Information Modelling (BIM)	(Akinade et al., 2018; Liu et al., 2015; Llatas & Osmani, 2016; Mohammed et al., 2022)

(*Continued*)

Table 1. Continued.

Category	Variable	Reference
	Modular construction	(Ajayi et al., 2017; Ajayi & Oyedele, 2018; Akinade et al., 2018; Banihashemi et al., 2018; Wang et al., 2015; Wang et al., 2019; Wong et al., 2021)

The survey was created using the Qualtrics online survey tool, a well-established platform renowned for its real-time interaction and user-friendly interface (Molnar, 2019). After obtaining research ethics approval (approval number H14793), the survey was primarily distributed through direct email outreach to individuals and construction companies. It was also shared across various professional and social networks, with a particular emphasis on the LinkedIn platform. LinkedIn, a leading online platform for professional networking and job searching, is widely recognised as one of the largest professional networks on the internet (Ponte, Méndez-Zorrilla, & Ruiz, 2022; Rapanta & Cantoni, 2017).

Response rate and respondents information

One week following the initial survey distribution, a reminder was sent to prompt respondents to complete the survey, followed by two additional reminders at two and three weeks post-initial distribution. A total of 112 responses were received. After screening, it was identified that 18 respondents had not completed the entire survey, and another 18 were not part of the intended population (i.e. not working in NSW nor in the construction industry). Consequently, 76 valid responses were eligible for analysis, resulting in a response rate of approximately 39%. This response rate is considered acceptable, especially in the construction field, which can attract 25-35% or lower (Fellows & Liu, 2021). The demographic information of the respondents is shown in Table 2.

Table 2. Background information of respondents.

Category	Item	Percentage
Occupation	Construction Project Manager	22.37
	Engineering Manager	18.42
	Civil Engineer	15.79
	Sustainability Manager	10.53
	Builder / Contractor	6.58
	Architect	6.58
	Mechanical Engineer	3.95
	Others (electrical engineers, graphic designers, interior designers)	15.79
Qualification	Project or Construction Management	28.26
	Civil Engineering	27.17
	Engineering Management	19.57
	Architecture	7.61
	Mechanical Engineering	7.61
	Others (building design, electrical engineering, interior design)	9.78
Years of Experience	Over 15 years	32.89
	Between 10–14 years	25.00
	Between 5–9 years	21.05
	Between 1–4 years	19.74
	Less than 1 year of experience	1.32
Project type	Infrastructure (Roads, Bridges, Airports, …)	32.63
	Residential Building	16.84
	Mixed Development	25.26
	Energy Facilities (Oil and Gas, Solar Energy, …)	14.74
	Intuitional and Office Buildings	6.32
	Others (e.g. places of worship, transportation, and aged care facilities)	4.21

Method of data analysis

Factor analysis and partial least squares-structural equation modelling (PLS-SEM) are used to analyse the collected data. Initially, factor analysis was performed to reduce the numerous items or variables into a smaller set of components (Hair, Black, Babin, & Anderson, 2018). Subsequently, PLS-SEM was employed to validate the outcomes of the factor analysis and to develop a DoW in construction model. According to Henseler et al. (2014), PLS-SEM serves as a valuable tool for reducing the dimensionality of data and modelling latent variables as well as composites. It is particularly useful when research objectives involve balancing prediction and theory testing, or when the model is complex, involving constructs with only one measurement item, which is the case in this study.

Prior to the analysis, the analysis of variance (ANOVA) test was carried out to evaluate the data homogeneity and determine if there were any significant differences in opinions among the respondents from various occupational backgrounds. As shown in Table 3, the results indicate no significant differences in the opinions of respondents, confirming the homogeneity of the dataset. Table 3 also shows the variables used in the survey, including their respective codes used in the model.

Results

Factor analysis results

As presented in the literature review section, this study initially identified fifteen barriers, which can be reduced further into a smaller number of components using factor analysis. This test was not applied to the enablers as only eight enabling factors were identified from the literature. To confirm the data's suitability for factor analysis, the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy (Wiesen, 2019) and Bartlett's test of sphericity (Denis, 2018) were conducted first. The result of KMO was 0.746 while Bartlett's test of sphericity resulted in Chi-square value of 410.914 with degree of freedom equal 105 and a significance level of less than 0.001 indicating the suitability of the data for this test. Subsequently, Principal Component Analysis extraction method was used with Varimax rotation to enhance variable distribution within the components. As shown in Table 4, the analysis resulted in five components of barriers that collectively explained more than 69% of the total variance.

As shown in the result, the items distribution within constructs is generally good. However, 'Lack of knowledge about standardisation' exhibits cross-loading with Component 1 and Component 2. This variable can be more appropriately assigned to Component 2, as it appears more relevant to the other items of this component compared to Component 1.

Based on the items representing each component, the extracted components can be named as follows:

- Component 1: Lack of Experience and Skills
- Component 2: Knowledge-related Barriers
- Component 3: Design-related Barriers
- Component 4: Project-related Barriers
- Component 5: Client-related Barriers

Further analysis using PLS-SEM serves to validate the extracted components and explore the impact of the identified barriers and enablers on DoW practices, as elaborated in the subsequent section.

PLS-SEM results and full model configuration

The full model of the relationships between barriers, enablers, and DoW was created using SmartPLS version 4. Measurement items were reflectively assigned to their corresponding latent variables (i.e.

Table 3. Result of ANOVA of DoW factors.

Construct	Code	Factor	Sum of squares	Mean square	*F*	Sig.
DoW Practice	Q13_1	My company has a strategy or policy to support DoW practice for all construction projects	8.159	1.166	0.790	0.598
	Q13_2	In my company, we conduct waste meetings to discuss ways to optimise the design and reduce waste	19.397	2.771	1.976	0.071
	Q13_3	My company adopts the following local standards of waste management; 'Better Practice Guidelines for Waste Management and Recycling in Commercial and Industrial Facilities'	7.209	1.030	0.937	0.484
	Q13_4	My company adopts the following local standards of waste management; 'Standards for managing construction waste in NSW'	8.561	1.223	1.195	0.318
	Q13_5	My company practices international standers, such as ISO 14001	6.763	0.966	0.776	0.609
	Q13_6	My company practices international standers, such as BS 8895: Designing for material efficiency in building projects	13.179	1.883	1.493	0.185
	Q13_7	My company practices the following guidelines: 'Design for material optimisation'	4.449	0.636	0.565	0.781
	Q13_8	My company practices the following guidelines: 'Design for recovery and reuse'	4.551	0.650	0.582	0.768
	Q13_9	My company practices the following guidelines: 'Design for waste-efficient procurement'	6.303	0.900	0.820	0.574
	Q13_10	My company practices the following guidelines: 'Design for off-site construction'	8.922	1.275	0.910	0.504
	Q13_11	My company practices the following guidelines: 'Design for deconstruction and flexibility'	4.856	0.694	0.535	0.805
DoW Barriers	Q10_1	Design changes	5.502	0.786	1.235	0.296
	Q10_2	Poor design	9.805	1.401	2.089	0.056
	Q10_3	Complex design	4.498	0.643	0.697	0.674
	Q10_4	Change in processes and practices of design	5.936	0.848	1.100	0.373
	Q10_5	Contract does not specify reducing waste during the design phase	2.027	0.290	0.274	0.962
	Q10_6	Lack of interest of the client in reducing waste	7.031	1.004	1.073	0.390
	Q10_7	Project constraints (e.g. no time to change design)	6.069	0.867	1.121	0.361
	Q10_8	Designers' negative perception towards DoW	3.016	0.431	0.628	0.731
	Q10_9	Lack of ICT tools	7.446	1.064	0.962	0.466
	Q10_10	Lack of experience and skills in implementing DoW	4.407	0.630	0.824	0.571
	Q10_11	Lack of awareness of DoW	6.374	0.911	0.905	0.508
	Q10_12	Lack of knowledge about standardisation (e.g. material size in the market)	2.881	0.412	0.569	0.779
	Q10_13	Lack of information, documentation, and drawings from the design stage	3.907	0.558	0.657	0.707
	Q10_14	Designers' limited knowledge about construction processes	3.618	0.517	0.496	0.834
	Q10_15	Lack of collaboration among professionals from different disciplines	7.296	1.042	1.263	0.282
DoW Enablers	Q11_1	Utilisation of prefabrication, precast and 3D printing	2.926	0.418	0.779	0.607
	Q11_2	Utilisation of modular construction	2.178	0.311	0.454	0.864
	Q11_3	Education and training in DoW	4.646	0.664	1.038	0.413
	Q11_4	Good communication and coordination	8.362	1.195	1.736	0.115
	Q11_5	Appropriate material selection or alternative products	0.882	0.126	0.293	0.954
	Q11_6	Government legislation and regulations	2.571	0.367	0.710	0.663
	Q11_7	Financial incentives (i.e. cost-saving)	3.444	0.492	0.948	0.476
	Q11_8	Using Building Information Modelling (BIM)	6.646	0.949	1.756	0.111

constructs) to establish the model (Sarstedt & Cheah, 2019). Several algorithm iterations were carried out within SmartPLS to refine the model and ensure it met established quality criteria. During the model configuration, certain items were removed from latent variables to enhance construct validity and reliability (Hair, Risher, Sarstedt, & Ringle, 2019).

The construct 'Client-related Barriers' retained only one measurement item, as the second item, 'lack of interest of the client,' was excluded due to its limited indicator loading. Constructs with single item have no reliability and validity generated because reliability and validity are measured

Table 4. Result of the rotated component matrix of DoW barriers.

Variable[a]	Component[b] 1	2	3	4	5
Lack of experiences and skills in implementing DoW	0.783				
Lack of ICT tools	0.762				
Lack of awareness of DoW	0.752				
Lack of knowledge about standardisation (e.g. material size in the market)	0.570	0.548			
Designers' negative perception towards DoW	0.566				
Lack of information, documentations, and drawings from the design stage		0.820			
Designers' limited knowledge about construction processes		0.773			
Lack of collaboration among professionals from different disciplines		0.762			
Change in processes and practices of design			0.835		
Design changes			0.723		
Complex design			0.642		
Poor design				0.761	
Project constraints (e.g. no time to review the design)				0.709	
Lack of interest of the client in reducing waste					0.798
Contract does not specify reducing waste during the design phase					0.723

[a]Extraction Method: Principal Component Analysis.
[b]Rotation Method: Varimax with Kaiser Normalisation.

as the interaction among the items constituting the construct (Hair et al., 2019). Thus, reliability and validity result for 'Client-related Barriers' construct is not included here. Figure 1 presents the final model of DoW in construction.

The PLS-SEM model is structured into two levels of linear equations: the measurement model (or outer model) and the structural model (or inner model). The measurement model defines the relationship between a construct and its measurement items, such as 'Knowledge-based Barriers' and its set of measurement items. In contrast, the structural model outlines the relationships among the constructs, like the connection between 'Knowledge-based Barriers' and 'DoW.' The enablers are configured to have a moderating effect on the relationship between the barriers and DoW. The evaluation of the model's quality involves assessing both the measurement and structural models.

The evaluation of the measurement models was carried out using various methods. First, construct reliability was assessed using both Cronbach's alpha and composite reliability. As displayed in Table 5, the constructs' reliability ranged from acceptable to good, with values between 0.6 and 0.9, except for 'Project-related Barriers,' which scored slightly below the threshold (Hair et al., 2019). This is considered acceptable considering that this is a new construct (i.e. not being tested in previous research) and it has a few measurement items which can reduce the reliability score. Second, construct convergent validity was evaluated using the Average Variance Extracted (AVE), which should be 0.5 or above to explain at least 50% of the variance of its items (Hair et al., 2019). All constructs in this study exceeded this threshold. Last, discriminant validity was assessed using the heterotrait-monotrait (HTMT) ratio of correlations (Henseler, Ringle, & Sarstedt, 2015), and all constructs exceeded the threshold, as illustrated in Table 5.

After establishing the quality of the measurement models, further analysis was conducted to assess the structural model's quality and to test the significance of the relationships between the constructs. Various measures were employed for this assessment, including collinearity assessment, explanatory power via the coefficient of determination (R-square), predictive model power, and examination of the significance and relevance of the model using path coefficients (Hair et al., 2019). First, collinearity was assessed to examine the regression result of the relationships between the constructs using VIF, which should be close to 3 or lower (see Table 7). Second, R-square was used to determine the extent of change in the endogenous construct affected by the exogenous constructs in the model. The results indicate that the R-square is 0.447 (adjusted R-square is 0.351), indicating moderate explanatory power. In other words, approximately 45% of the variation in DoW practices is explained by the barriers and enablers, which is good, emphasising

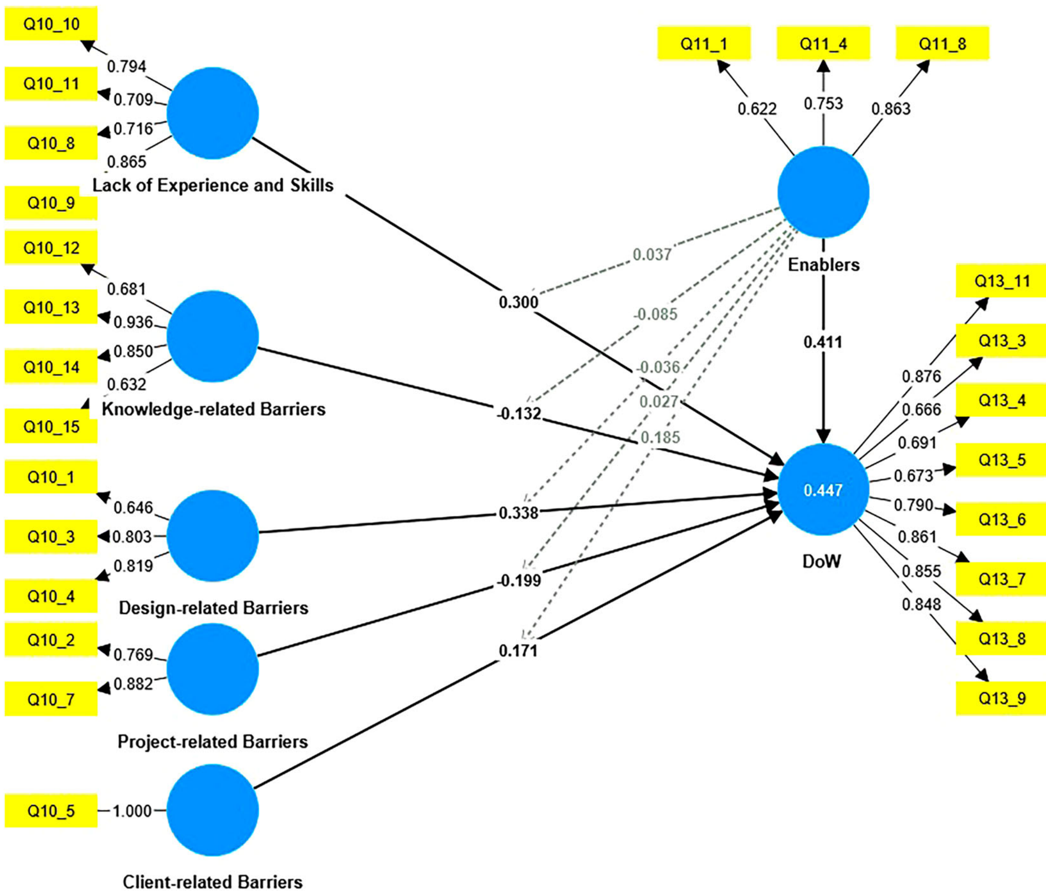

Figure 1. Full model of DoW in construction (algorithm result).

the importance of addressing these constructs when implementing DoW in practice. Third, the Q^2 was calculated to assess the predictive accuracy of the model using PLSpredict with the default settings of the number of folds and repetitions set to 10 (Shmueli et al., 2019). The result of Q^2 for the endogenous construct and its indicators is above zero, indicating the predictive accuracy of the structural model for DoW. As shown in Table 6, all indicators in the PLS-SEM analysis have lower RMSE (root mean squared error) values compared to the naïve LM (linear regression model) benchmark, indicating high predictive power of the model (Shmueli et al., 2019). RMSE was chosen for comparison instead of MAE (mean absolute error) as the prediction error of the indicators does not exhibit a highly non-symmetric distribution. Overall, the Q^2 predict for the DoW construct is 0.149, indicating a small predictive relevance of the PLS-path model (Hair et al., 2019). Last, the significance and relevance of the path coefficients were evaluated using the bootstrapping procedure in SmartPLS, as elaborated in the following section.

Path coefficient procedure and results

The bootstrapping analysis was conducted in SmartPLS to determine the significance of the relationships between the constructs. As illustrated in Figure 2 and Table 7, 'Lack of Experience and Skills', 'Design-related Barriers', and 'Enablers' exhibit a significant relationship with 'DoW', with *p*-values equal to 0.043, 0.024, and 0.001, respectively. However, the other constructs within the model did

Table 5. Construct reliability, convergent validity, and discriminant validity.

	Reliability and convergent validity				Discriminant validity (HTMT)					
Construct	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)	Client-related Barriers	Design-related Barriers	DoW	Enablers	Knowledge-related Barriers	Lack of Experience and Skills
Client-related Barriers										
Design-related Barriers	0.651	0.685	0.803	0.578	0.210					
DoW	0.911	0.922	0.928	0.620	0.233	0.554				
Enablers	0.645	0.723	0.794	0.566	0.201	0.506	0.569			
Knowledge-related Barriers	0.826	0.898	0.862	0.616	0.220	0.349	0.233	0.487		
Lack of Experience and Skills	0.785	0.838	0.856	0.599	0.454	0.282	0.329	0.352	0.693	
Project-related Barriers	0.549	0.582	0.812	0.685	0.301	0.498	0.133	0.464	0.492	0.589

Table 6. Predictive power result (PLSpredict).

Item	Q^2predict	PLS-SEM_RMSE	LM_RMSE
Q13_11	0.170	1.019	1.159
Q13_3	0.020	1.045	1.243
Q13_4	0.068	0.992	1.139
Q13_5	0.084	1.062	1.083
Q13_6	0.115	1.085	1.219
Q13_7	0.070	1.009	1.071
Q13_8	0.115	0.985	1.130
Q13_9	0.048	1.023	1.066

Q^2 predict (DoW) = 0.149.
RMSE (DoW) = 0.953.
MAE (DoW) = 0.721.

not demonstrate strong or statistically significant relationship with 'DoW'. The effect size (f-square), which measures the impact of removing an exogenous construct on the R-square value (Hair et al., 2019), is medium for both 'Enablers' and 'Design-related Barriers', and small for the remaining constructs (see Table 7). Furthermore, it is worth noting that 'Enablers' did not show a moderating effect on the relationship between the barriers and DoW.

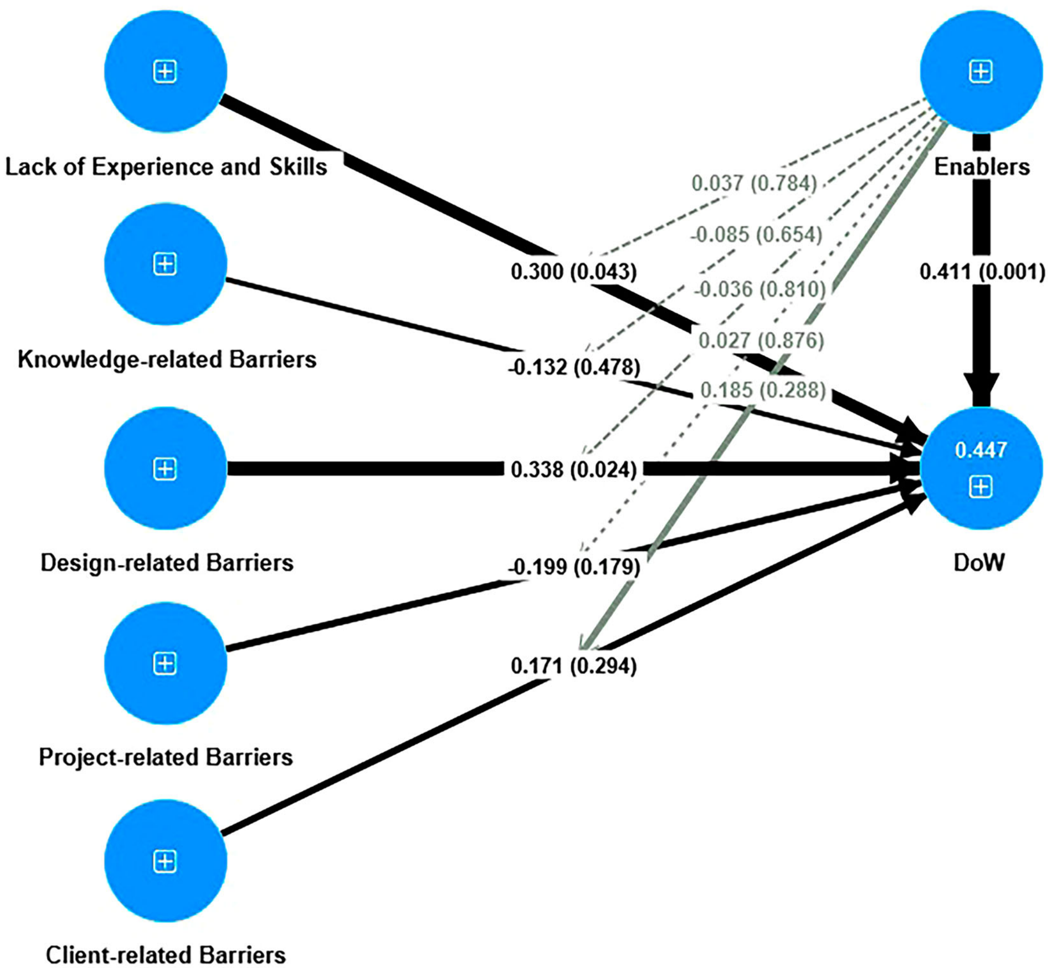

Figure 2. Path coefficients results (bootstrapping results).

Table 7. Path coefficients, F-square, and collinearity (VIF) results.

Relationships	Original sample	Sample mean	Standard deviation	*T* statistics	*p*-values	f-square	VIF
Client-related Barriers -> DoW	0.171	0.155	0.163	1.049	0.294	0.039	1.367
Design-related Barriers -> DoW	0.338	0.307	0.149	2.264	**0.024**	**0.151**	1.368
Enablers -> DoW	0.411	0.376	0.125	3.283	**0.001**	**0.210**	1.448
Knowledge-related Barriers -> DoW	−0.132	−0.082	0.186	0.709	0.478	0.019	1.680
Lack of Experience and Skills -> DoW	0.300	0.301	0.148	2.026	**0.043**	0.075	2.171
Project-related Barriers -> DoW	−0.199	−0.118	0.148	1.344	0.179	0.049	1.464
Enablers x Project-related Barriers -> DoW	0.027	0.091	0.176	0.156	0.876	0.001	1.938
Enablers x Design-related Barriers -> DoW	−0.036	−0.087	0.149	0.241	0.810	0.001	1.825
Enablers x Client-related Barriers -> DoW	0.185	0.169	0.174	1.063	0.288	0.029	3.034
Enablers x Knowledge-related Barriers -> DoW	−0.085	−0.054	0.19	0.448	0.654	0.005	2.150
Enablers x Lack of Experience and Skills -> DoW	0.037	−0.028	0.136	0.274	0.784	0.002	2.600

Importance performance map results

The Importance Performance Map (IPMA) analysis (Hair et al., 2019; Ringle & Sarstedt, 2016) provided deeper insights into the findings. Unlike traditional ranking methods such as mean values, IPMA assesses the overall impact of the model on DoW and compares it to the average scores of the preceding constructs. Figure 3 shows the performance and importance matrix of the exogenous constructs on DoW. For example, 'Enablers' has an importance value of 0.411 (total effects) with approximately 67% performance on DoW. This implies that a one-unit increase in 'Enablers' performance can lead to a corresponding increase in DoW performance, independent of other constructs in the model. The performance of all items of the exogenous constructs on DoW is summarised in Table 8. Notably, Q11_4 exhibits the highest performance for DoW with about 78%, and a total effect of 0.179. This is followed by Q10_5, Q10_4, Q10_7, Q10_2, Q10_3, Q10_8, Q11_8, and Q10_9.

Discussion of results

Barriers of designing out waste in construction

The study confirmed the significant influence of Design-related Barriers and Lack of Experience and Skills on the practice of Designing out Waste (DoW) in construction. The Importance Performance

Table 8. IPMA results of indicators' total effects and performance.

Item code	Item name	Performance	Importance
Q11_4	Good communication and coordination	77.632	0.179
Q10_5	Contract does not specify reducing waste during the design phase	75	0.171
Q10_10	Lack of experience and skills in implementing DoW	72.697	0.08
Q10_4	Change in processes and practices of design	72.697	0.173
Q10_7	Project constraints (e.g. no time to change design)	71.711	−0.137
Q10_15	Lack of collaboration among professionals from different disciplines	71.382	0.002
Q10_2	Poor design	71.382	−0.101
Q10_12	Lack of knowledge about standardisation (e.g. material size in the market)	71.053	−0.029
Q10_1	Design changes	70.724	0.085
Q10_11	Lack of awareness of DoW	70.724	0.063
Q10_3	Complex design	68.092	0.176
Q10_14	Designers' limited knowledge about construction processes	67.105	−0.052
Q10_13	Lack of information, documentation and drawings from the design stage	65.789	−0.074
Q10_8	Designers' negative perception towards DoW	65.789	0.102
Q11_1	Utilisation of prefabrication, precast and 3D printing	61.842	0.091
Q11_8	Using Building Information Modelling (BIM)	61.842	0.254
Q10_9	Lack of ICT tools	60.855	0.138

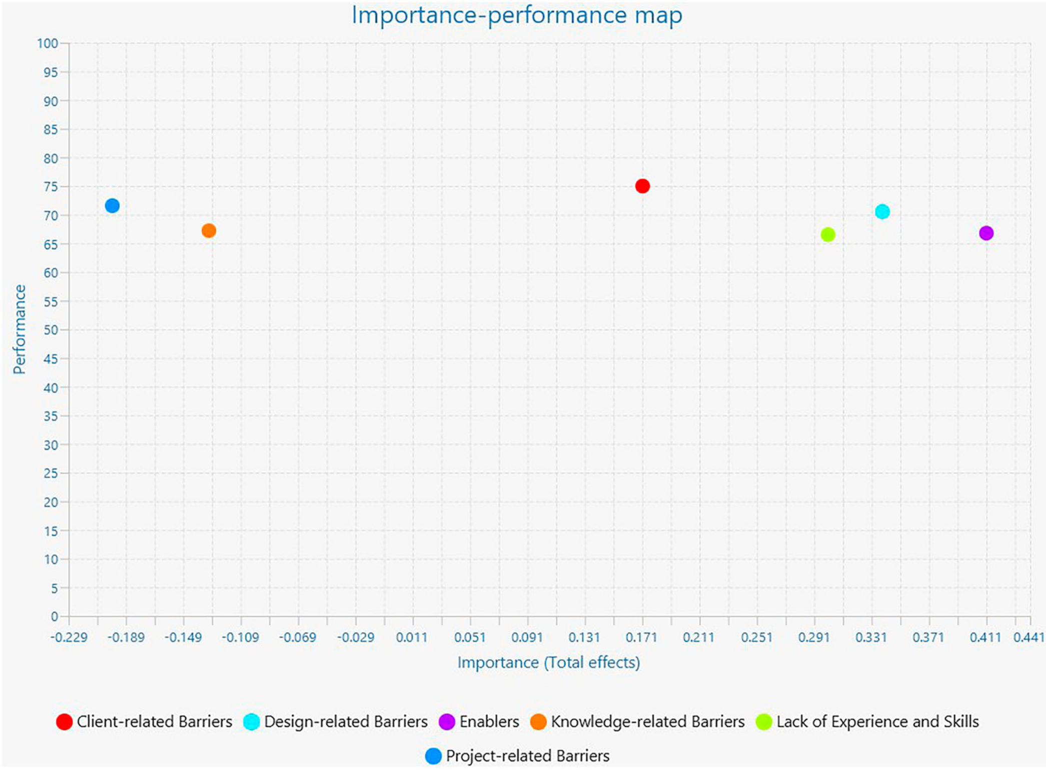

Figure 3. IPMA results of exogenous constructs.

Map Analysis (IPMA) highlighted specific barriers that have a significant impact on DoW. These include the following: contract does not specify reducing waste during the design phase, changes in processes and practices of design, project constraints, poor design, complex design, designers' negative perceptions towards DoW, and a lack of information and communication technology (ICT) tools. These findings underline the complexity of barriers in the construction industry, emphasising the need for targeted interventions to effectively overcome them.

The first construct with a significant influence on DoW is Design-related Barriers, encompassing the following variables: complex design, changes in design processes, and design changes. This result aligns with previous research emphasising the importance of addressing design-related barriers for effective waste reduction (Ajayi et al., 2017; Ajayi & Oyedele, 2018).

Complex design can lead to errors, ambiguities, and re-work, requiring additional time, specialised skills, and resources. Thorough planning, design review, and effective communication among project teams are essential to address these barriers. Furthermore, ensuring adequate detailing of complex designs can enhance design quality and reduce waste, as mentioned by Ajayi and Oyedele (2018). Besides, changes in design processes and practices can result in construction waste due to communication issues and material ordering errors. Furthermore, design changes may cause substantial waste during the construction stage. In the study of Olanrewaju and Ogunmakinde (2020), 'design changes' was ranked second among other major variables contributing to construction material waste. It can increase material costs and re-work leading to more waste (Doust et al., 2021). In addition, design changes can lead to acquiring additional materials, duplicating previously purchased items, creating excess inventory. To minimise waste resulted from design changes, it is crucial to implement a well-structured change management process. This process should involve effective communication among main project stakeholders, clear documentation of changes, and a comprehensive evaluation of the impact of change on existing materials and work. Proactive planning and decision-making are essential for waste reduction and enhancing construction project efficiency.

The second construct, Lack of Experience and Skills, includes four barriers: lack of experience and skills in implementing DoW, designers' negative perception towards DoW, lack of ICT tools, and lack of awareness of DoW. When designers lack experience in DoW principles, they may inadvertently create designs that are not optimised for waste reduction. Likewise, negative perceptions among designers may hinder the adoption of waste reduction strategies. Designers may resist incorporating DoW principles into their designs, resulting in missed opportunities to reduce waste. Li, Tam, Zuo, and Zhu (2015) found that designers' attitude and perceived behaviour control have a positive and significant effect on their behaviour on construction waste reduction. To address these challenges, comprehensive training for project stakeholders, especially designers and project managers, is essential. On the other hand, the absence of ICT tools can hinder efficient waste management as design becomes less optimised. The adoption of ICT tools can enhance waste reduction efficiency, and promoting a positive perception of DoW within the industry is crucial for sustainable construction practices.

Enablers of designing out waste in construction

This study identified three significant enablers for DoW practices: good communication and coordination, using Building Information Modelling (BIM), and the utilisation of prefabrication, precast, and 3D printing. Effective communication and coordination emerged as the most influential enabler, underscoring the significance of clear and collaborative communication channels among diverse designers from various disciplines. Effective communication bridges the gap between stakeholders, ensuring seamless integration of design adaptations and waste reduction strategies across different project phases. Furthermore, effective communication has the potential to mitigate the negative perceptions held by designers, fostering a more receptive attitude towards the adoption of DoW. Similarly, BIM provides a collaborative platform for project teams to share comprehensive design and construction data, streamlining design coordination and reducing errors. BIM enhances communication and collaboration among project team members, allowing real-time updates and design modifications. This streamlines the design change process and minimises errors or clashes that may arise from manual revisions. BIM also aids in managing complex designs by providing a virtual model for stakeholders to visualise and analyse the design more comprehensively. This result aligns with previous studies highlighting the effectiveness of BIM in overcoming design-related barriers and improving project outcomes, as indicated by Sacks et al. (2018) and Succar (2009). Lastly, the study emphasises the significant role of prefabrication, precast, and 3D printing techniques as enablers of DoW in construction. These construction methods optimise material utilisation and minimise on-site construction activities, aligning seamlessly with DoW principles.

Conclusion

This study identifies two key constructs influencing Designing out Waste (DoW) in construction, namely Design-related Barriers and Lack of Experience and Skills. Design-related Barriers encompasses complex design, change in processes and practices of design, and design changes. Complex designs may lead to errors, inefficiencies, and material wastage, necessitating better planning, design review, and communication. Changes in design processes can result in errors and excess packaging, while design changes may lead to re-work and excess inventory. To address this barrier, an effective change management process with clear communication and thorough design evaluation is essential. The second construct, Lack of Experience and Skills, includes the following barriers lack of experience, negative perceptions towards DoW, limited ICT tools, and a lack of awareness. Comprehensive training and the adoption of ICT tools are essential to mitigate these challenges.

This study also identifies three enablers for DoW practices: good communication and coordination, Building Information Modelling (BIM), and utilisation of prefabrication, precast and 3D printing. Effective communication bridges gaps between stakeholders and enhances designer perceptions. BIM streamlines design coordination and reduces errors. Innovative construction methods optimise material usage and reduce on-site activities, subsequently mitigating construction waste. However, this study did not observe a moderating influence of the enablers on the relationship between barriers and DoW practices. This suggests the importance of further research to explore specific enabling factors to overcome the identified barriers in subsequent studies. The limitation of this study is that it focused on construction professionals in NSW, making it challenging to generalise the results to the entire Australian construction industry. Therefore, future research should consider expanding the sample to include professionals from other states and territories.

In conclusion, this study underscores the importance of addressing barriers and leveraging enablers to enhance DoW practices in construction. The research contributes by highlighting the multifaceted nature of barriers and the potential for specific interventions to enhance DoW practices. Addressing barriers and leveraging enablers can lead to more efficient design and construction process, ultimately reducing waste and contributing to a greener future.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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