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Designing out waste implementation in the wall system of residential projects in New Zealand

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ABSTRACT

The construction industry accounts for approximately half of all landfill waste in New Zealand (NZ). Designing out waste (DoW) approach has been introduced to minimise waste generation at the design stage, including five key principles: design for off-site construction, reuse and recovery, materials optimisation, waste-efficient procurement, and design for the future. However, the differential applicability of these principles across various building elements poses significant challenges to their practical implementation, while existing guidelines offer only broad and nonspecific recommendations. This study addresses this gap by investigating the application of DoW principles to wall elements, including framing, insulation, lining, and cladding, in residential construction, a sector that accounts for the largest share of NZ construction activity and where wall systems are the major source of material waste. Through a desktop study and fourteen semi-structured interviews, this research investigates the feasibility of applying each DoW principle to materials used in wall systems. Furthermore, five key project factors influencing DoW implementation were identified: project budget, regulatory compliance, accessibility of waste processing infrastructure, material availability and supply chain collaboration, and technical requirements. These factors highlight the importance of project context in determining which DoW strategies can be effectively adopted. The study offers practical and specific guidance to support more effective integration of DoW strategies from the design stage, ultimately contributing to waste minimisation in residential construction.

1. Introduction

The global growth of the construction industry, driven by urbanisation and city redevelopment, has generated massive volumes of construction and demolition waste (CDW) [1]. Previous studies reveal that construction and demolition activities are responsible for approximately 30–40 % of the global annual solid waste generation, with this waste growing at a faster rate than that of other industries [2]. Notably, CDW contributes to roughly 35 % of the total waste disposed of in landfills worldwide [3], creating substantial obstacles to sustainable construction development. At the project level, CDW adds to both workload and costs due to tons of material waste and the need for waste management, ultimately impacting the profitability and productivity of the project. Furthermore, CDW causes detrimental impacts on the environment nationally and globally, including expanded landfills, resource depletion, contamination in soil and groundwater, and even air pollution [1].

The literature highlights various causes of CDW across different stages of the project lifecycle. From the design stage, poor decision-

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making during the design phase, such as design changes, errors, complex designs, and insufficient knowledge of standard material sizes, is responsible for approximately one-third of CDW [4]. Mistakes in design and drawings often result in rework, while improper material procurement, including ordering errors and purchasing non-compliant materials, further increases waste [5]. Material waste also arises during transportation, storage, and unloading due to inadequate storage methods, limited space, and inefficient logistics [6]. During the construction phase, unskilled labour, equipment misuse, and frequent design changes contribute significantly to waste generation [7]. Additionally, insufficient supervision and poor stakeholder coordination exacerbate errors and rework, leading to waste generation [8]. At the buildings' end-of-life, demolition activities account for 50 % of the total CDW [9].

Among numerous strategies to avoid waste generation throughout the project lifecycle, designing out waste (DoW) is recognised as a decisive and effective approach for CDW minimisation from the design stage [4]. Five DoW principles were introduced as a guideline for construction practitioners to minimise waste from the design stage, including design for reuse and recovery, design for off-site construction, design for materials optimisation, design for waste-efficient procurement, and design for future [10]. These principles have been widely adopted, such as in the UK [10], New Zealand (NZ) [11] and Ireland [12]. However, the current DoW guidelines provide broad recommendations, while the applicability of DoW principles differs among building elements. This variation results in a wide array of DoW options, making it difficult for designers to identify and select suitable solutions for their projects. Therefore, to facilitate the practical application of DoW, further research is needed to explore how to implement these principles in each building element [13].

In NZ, the construction sector generates up to half of the waste disposed of in landfills and cleanfills [14]. In response, the government and industry have implemented measures to mitigate the environmental impacts of this substantial volume of CDW. Particularly, the levy historically applied only to waste disposal at municipal landfills; however, from 2022, the new waste disposal levy has been expanded to construction and demolition fills, starting at $20 per tonne and increasing to $30 per tonne by July 2024. The Government Waste Minimisation Fund allocated resources to enhance recycling infrastructure and promote waste minimisation [15]. Furthermore, waste minimisation is considered a focus area of the building sector in NZ's first emission reduction plan towards net-zero emissions by 2050 [16]. Current efforts in the NZ construction industry mainly address CDW after it has already been generated, focusing on low-priority actions within the waste management hierarchy; and the waste generation rate remains a significant concern. Greater emphasis is needed on waste minimisation from the design stage [17]. However, insufficient knowledge and experience of designers are identified as a key factor contributing to CDW generation during this phase [18]. Therefore, educating designers on various strategies for integrating building materials to minimise CDW is crucial [19].

Residential buildings constitute the largest proportion of total construction activity in NZ, accounting for approximately 60 %, followed by non-residential buildings and infrastructure [20]. The number of building consents is expected to rise steadily, with over 200,000 new dwellings projected over the next six years [21]. This growing trend places considerable pressure on CDW management within the NZ construction industry. Therefore, residential construction has been selected as the focus of this study, given its substantial contribution to CDW generation. Moreover, wood and gypsum plasterboard account for the main proportions of waste generated on residential construction sites [17] with the wall system being the primary source of this waste. This is due to the widespread use of timber framing as the dominant structural material in new housing in NZ, accounting for approximately 90 % of the market [22] as well as the common use of wood-based products for wall cladding [23]. In addition, gypsum plasterboard is the most prevalent material for internal wall linings [24]. In this context, promoting DoW practices in wall elements presents a significant opportunity to reduce CDW in residential projects. Therefore, this study aims to explore how to implement DoW principles in wall elements with wood-based framing in NZ residential projects. Furthermore, the selection of appropriate DoW solutions also depends on project-specific characteristics [13]. To support the selection process, this study also explores project factors influencing DoW implementation.

The objectives of this study were as follows.

1. Investigate DoW implementation in the wall system with wood-based framing
2. Identify project factors affecting DoW implementation in the wall system with wood-based framing

This paper is structured as follows: Section 2 provides the scientific literature relevant to the topic of the study. Section 3 describes the methods adopted for data collection and data analysis. Section 4 analyses how five DoW principles can be applied to wall elements, including wall frame, insulation, lining and cladding. Section 5 discusses project factors that influence the implementation of DoW principles in the wall system, highlighting the key considerations for selecting suitable DoW options tailored to a specific project. Section 6 presents the conclusions of this study.

2. Literature review

2.1. Designing out waste principles

Aiming to minimise CDW from the early design stage, five principles for DoW were developed to guide construction practitioners. These principles include Principle 1: design for reuse and recovery, Principle 2: design for off-site construction, Principle 3: design for materials optimisation, Principle 4: design for waste efficient procurement, and Principle 5: design for future [10]. Over the last two decades, there has been a gradual increase in research focused on DoW strategies in construction projects [13]. This section presents a literature review of recent studies on the implementation of DoW.

2.1.1. Design for off-site construction

Off-site construction, also known as prefabrication, involves manufacturing entire buildings or building components in controlled environments before transporting and assembling them at construction sites. This approach replaces traditional on-site construction methods [25]. The controlled factory environment in prefabrication offers a significant advantage in minimising waste by addressing common challenges of traditional construction methods, such as excessive material cutting, overordering, poor workmanship, installation losses, design changes, and weather-related delays [26,27]. In NZ, prefabricated systems are classified into five categories based on the extent of off-site fabrication, including component, panel, volume, hybrid, and complete building. Components are small-scale items assembled off-site, such as wall frames or roof trusses. Panels are panelised units that do not enclose useable space, such as cladding panels or panel systems. Volumes are volumetric units that enclose useable space, such as bathroom pods or plant rooms. Hybrid systems combine volumetric and panelised units, often including component and site-built elements. Finally, complete buildings are fully prefabricated volumetric constructions, such as single houses or sections of multi-unit buildings [26–28]. Empirical findings in the literature have highlighted the significant potential for waste reduction through prefabrication [13]. Lu and Yuan [29] reported, through in-depth case studies in prefabrication factories, that waste generation in the manufacturing and transportation of prefabricated components was below 2 % by weight. Similarly, Tam and Hao [30] found reductions of 74–87 % for formwork waste and 51–70 % for concrete waste. Cheng, Huang [26] further demonstrated that the full adoption of prefabricated components could reduce formwork waste by up to 90 %.

2.1.2. Design for reuse and recycle

Design for reuse and recycling focuses on both identifying opportunities to reuse existing materials and components from the construction site or other projects, as well as incorporating materials with recycled content into new buildings [10]. This approach not only minimises waste by extending the life of materials but also reduces the demand for virgin resources. To ensure the reliability and safety of reused or recycled materials, it is essential to verify their critical properties, ensuring compliance with specified standards and performance requirements in new construction projects [31]. However, the construction industry remains hesitant to adopt reusable and recycled materials due to designers' insufficient awareness of their durability, market availability, and specification requirements [32]. The absence of comprehensive guidelines, standards, and quality assurance for structural elements, as well as underdeveloped markets for salvaged materials, further constrain material reuse [9,33].

2.1.3. Design for future

Design for future considers the adaptability and deconstructability of the building in the future. Design for adaptability facilitates the flexibility of building spaces as it is easy to modify the spatial configuration; hence, less waste is generated due to demolition activities in future changes [34]. Design for deconstruction is a proactive approach aimed at reducing demolition waste by enabling the reuse and recycling of building materials and components during maintenance, refurbishment, or when the building reaches the end of its lifecycle [35]. Demountable connections, material durability, reusability and recyclability are the key factors in deconstruction [35,36]. However, despite its potential to substantially reduce construction and demolition waste, design for deconstruction remains underutilised. Akinade, Oyedele [37] emphasised that its practical implementation is still limited, while other studies suggest that designers often overlook design for deconstruction during the design process [9].

2.1.4. Design for resource optimisation

Design for resource optimisation focuses on materials resource efficiency to minimise resource consumption and reduce waste generation [10]. A key strategy involves dimensional coordination and standardisation, where designers incorporate standard material sizes available in the market during the design phase to minimise the need for cutting and reduce offcuts [13]. This approach not only helps prevent unnecessary offcuts but also improves the constructability of the building, thereby further avoiding waste generation [34]. For example, Wu, Zhang [38] demonstrated that aligning floor layouts with standard material dimensions through dimensional coordination can reduce tile waste by up to 12 %. Improving spatial planning in the design phase leads to a 6.59 % reduction in waste generated from concrete masonry blocks [39]. Furthermore, choosing durable and eco-friendly materials helps reduce waste generation and minimise environmental impacts throughout the project lifecycle. In contrast, using non-durable materials can result in increased waste due to breakage during construction and the need for frequent maintenance [40].

2.1.5. Design for resource-efficient procurement

Optimising material procurement to minimise construction waste involves supplier commitment, low-waste purchasing practices, efficient material delivery, precise material specifications, and accurate bills of quantity [41]. A critical element of this process is fostering collaboration with suppliers dedicated to waste reduction initiatives, including adopting take-back schemes, which facilitate the return and reuse of surplus materials, and promoting the use of minimal or environmentally friendly packaging to reduce packaging waste [42].

2.2. Project factors influencing DoW implementation

The implementation of DoW principles varies across projects and is shaped by project-specific contextual factors. Understanding these factors is essential to ensure that design decisions are both practical and effective in minimising CDW [13].

Economic considerations are among the most influential determinants of DoW adoption. The short-term, profit-oriented nature of the construction industry often prioritises immediate financial returns over long-term sustainability objectives [43]. Meanwhile, the low residual value of end-of-life materials reduces the economic attractiveness of take-back schemes and reprocessing, discouraging material recovery and reuse [33]. Conversely, when appropriate financial incentives are introduced, designers and contractors demonstrate a stronger commitment to waste minimisation practices [44].

Legislation and standards also play a critical role in enabling DoW. In the UK, for example, compliance with sustainability codes has encouraged the integration of resource-efficient practices in the construction industry [45]. However, the absence of stringent legislation mandating deconstructable design has limited the widespread implementation of DfD, even in contexts where CDW management frameworks are well established in the UK [9]. In China, most existing regulations focus on waste treatment rather than prevention, and the lack of clear standards for reused and recycled materials further restricts their practical application [46].

Market maturity for recycled and reused materials is another significant factor influencing the feasibility of DoW. Existing literature indicates that markets for salvaged and recycled materials remain underdeveloped in both developed and developing economies [3,43,46]. Designers' limited knowledge of application methods, combined with concerns regarding quality assurance, performance consistency, and warranty provisions, further constrains market demand for reused and recycled materials [45,47]. To address these challenges, recent research advocates the establishment of certified material or component banks, which can provide traceability, quality verification, and performance assurance for salvaged components [48].

Furthermore, infrastructure and technological capacity are critical enablers of DoW implementation. Countries such as the United States, Japan, Germany, and Singapore have developed mature CDW recycling systems that support efficient material recovery and reuse [46]. In geographically dispersed regions such as Australia, limited access to nearby recycling facilities increases transportation costs and often makes recycling economically unviable [49]. Strengthening local recycling infrastructure and technological capacity is therefore essential to support the broader adoption of DoW strategies. Table 1 presents a summary of factors influencing the implementation of DoW, as identified through the literature review.

2.3. Summary and point of departure

Although research on minimising construction waste from the design stage has grown over the past two decades, designers still face challenges in translating DoW principles into practical design decisions [13]. Early research relied on literature synthesis and expert judgement to develop conceptual frameworks and guideline-based recommendations, offering high-level principles for waste minimisation at the design stage [10,51,52]. More recent work has shifted towards semi-structured interviews and questionnaire surveys to explore design strategies for construction waste minimisation [33,36,40]. In addition, case study research has been widely used to assess the implementation and outcomes of specific DoW strategies in real project contexts, often quantifying the waste reduction potential associated with individual strategies such as prefabrication [30,53,54] or improved coordination of design dimensions [39,55].

Despite the methodological diversity in the existing literature, there is a lack of studies that consolidate all five DoW principles into a decision-oriented framework that considers their practical applicability. Current DoW guidelines provide broad, high-level recommendations, while the applicability of DoW principles varies significantly across different building elements. This variability leads to a wide range of potential DoW options, making it difficult for designers to identify, compare, and select solutions that are both context-appropriate and practically implementable during the early design stages. Moreover, limited attention has been given to element-specific analyses that translate DoW principles into actionable design choices. As a result, designers are often required to rely on generic guidance or isolated case examples, which constrains the practical uptake of DoW in design practice.

To address these methodological and practical gaps, this study adopts a qualitative research design that integrates desktop research with semi-structured expert interviews. The desktop study enables a systematic mapping of wall materials and corresponding DoW strategies across all five DoW principles, while the expert interviews provide industry-based validation and contextual insights into

Table 1
Summary of key factors influencing DoW implementation reported in the literature.

Factors	Barriers	Enablers
Economic	• Short-term and profit-oriented focus [3,43]. • Low residual value of salvaged materials [33,43]. • High cost associated with take-back and recycling schemes [33]. • Project budget constraints [33,43,45].	• Financial incentives encouraging waste minimisation [33,44].
Legislation and standards	• Absence of mandatory legislation for DfD [9]. • Regulatory focus on waste treatment rather than prevention [46]. • Lack of clear standards and guidelines for reused and recycled materials [46].	• Supportive legislation to promote CDW minimisation [33,45,47]. • Established standards and guidelines for DoW implementation [33].
Market maturity for recycled and reused materials	• Immature markets for reused and recycled materials [3,43,46]. • Concerns about quality, performance consistency, and warranty of reused and recycled materials [45,47].	• Establishment of certified material or component banks [48]. • Material traceability, quality verification, and performance assurance mechanisms [33,48].
Infrastructure and technological capacity	• Limited access to nearby recycling facilities [3,43,46,49]. • High transportation costs in geographically dispersed regions, reducing the economic viability of recycling [49].	• Mature CDW recycling systems supporting efficient material recovery and reuse [46,50] • Strengthened local recycling infrastructure and technological capacity [49].

their practical applicability. By focusing on wall elements in NZ residential projects, this study moves beyond generic recommendations and fragmented strategy-based evidence, offering material-specific and element-level guidance that supports practicable design decision-making grounded in both documented evidence and practitioner experience.

2.4. Wood-based wall system in NZ houses

In NZ, platform timber framing is the most common housing construction approach for the wall system with four main components: structural wall framing, insulation, lining and cladding [24], as illustrated in Fig. 1.

Timber-framed houses have become the norm in NZ since the 1960s, with around 90 % of residential buildings being constructed by timber-framing [56]. Approximately 90 % of wall framing that arrives at construction sites is either precut or prenailed [22]. Wall framing widely employs treated timber due to its durability and resistance to insect infestations, fungal attacks, and general decay. Among timber species, treated radiata pine is the most commonly used, owing to its cell structure, which makes it exceptionally receptive to chemical treatments that enhance its resilience [57]. In accordance with the Building Regulations 1992, structural components of a building are required to have a minimum lifespan of 50 years [58]. Treated radiata pine meets this standard, ensuring it can withstand the demands of long-term use in timber-framed buildings. However, when treated timber is disposed of in landfills, preservative chemicals may leach out, contaminating soil and groundwater and posing a risk to human health and the environment. Additionally, the use of laminated veneer lumber (LVL) has been steadily increasing, now accounting for approximately 12 % of timber framing [22]. To enhance structural resilience against earthquake and wind loads, wall-lining materials are fixed to the frame members. In NZ, gypsum plasterboard is the most common material for internal wall linings [24]. NZ plasterboard is made from natural gypsum, recycled paper materials and additives, making it easy to cut in different sizes and providing an ideal base for painting or decorative finishes [59].

The external wall assembly is completed by adding layers that control thermal, moisture, and air to the structural timber framework. Thermal control is achieved by installing insulation blankets between the structural framing members in order to reduce heat transfer, ensuring improved energy efficiency within buildings [24]. The NZ insulation market is dominated by non-biodegradable materials, with fibreglass making up nearly 90 % and polyester accounting for most of the remainder [22]. Although NZ is one of the world's leading producers of wool, the adoption of wool as a biodegradable insulation material remains limited [60]. Building wrap is fitted around the entire building to control air leakage and manage the air pressure differential between the outside and inside. Cladding is then fixed to the framing via the cavity system to reduce the air pressure differential and provide moisture protection [24]. Over the past decade, weatherboard has continued to increase its market share over finish brick, becoming the most common wall

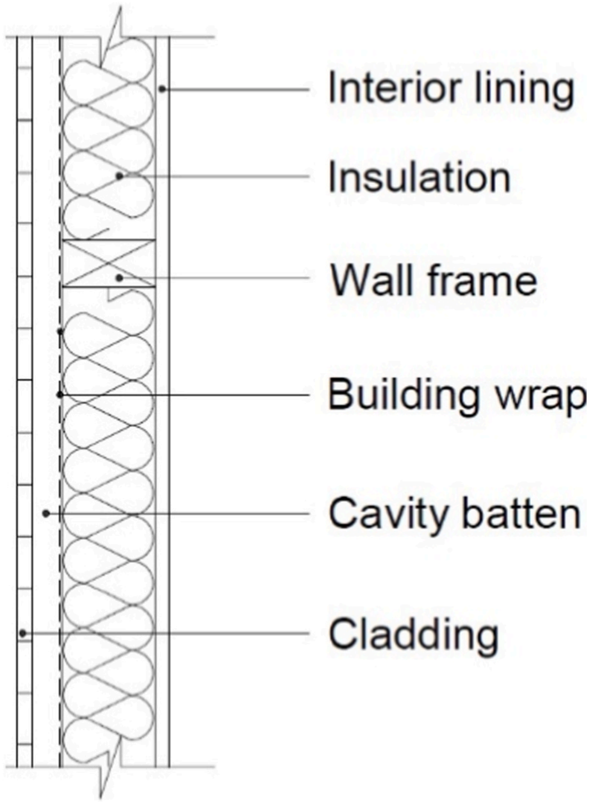

Fig. 1. Cross-section drawing of a typical timber framing wall in NZ.

cladding, with a 42 % share, three-quarters of which is timber, and the remainder consisting of fibre cement and uPVC. Additionally, metal, plywood, non-weatherboard fibre-cement, and plaster are adopted in wall cladding [22].

Furthermore, the adoption of engineered wood products (EWP) has been on the rise, driven by NZ's commitment to achieving net-zero carbon construction and maximising the efficient use of timber resources [61]. EWPs are made by joining smaller wood pieces together with structural adhesives under pressure. The wood components used can range from wood flakes to full wood planks. Some EWPs can be made using lower-grade radiata pine compared to what is needed for sawn timber. Structural EWPs offer a sustainable alternative to treated pine for wall framing, including laminated veneer lumber (LVL), glulam, and cross-laminated timber (CLT). Additionally, products like plywood, oriented strand board (OSB), strand board, particleboard, and medium-density fibreboard (MDF) are employed for bracing and cladding applications [62]. Moreover, structural insulated panels (SIPs) are an alternative to traditional wall framing, consisting of a foam core enclosed between two EWPs panels. As a prefabricated building material, SIPs are reported to have significant potential for reducing construction waste in NZ [63].

3. Research method

This study employed desktop research and semi-structured interviews to enhance researchers' understanding of complex situations by cross-validating data from different sources [64,65]. The research began with a desktop study to develop a list of available materials for each wall element and to explore how DoW principles can be implemented with each material. This initial analysis informed the development of interview questions to further investigate the practical implementation of DoW principles. Following each interview, the collected data were analysed, and if any new materials or brand-specific products emerged, additional internet searches were conducted to supplement the findings with secondary data. The data from desktop research and interviews were continuously compared to identify patterns, ensure consistency, and provide a more robust and comprehensive analysis of the findings. The research process is presented in Fig. 2.

3.1. Data collection

3.1.1. Desktop study

Desktop research is a technique to investigate and analyse existing information from secondary resources, such as government documents, industry studies, enterprise files, news, and books [66]. The website of the NZ government, the Building Research Association of NZ (BRANZ), material manufacturers, and material suppliers were searched for material information and applicable DoW solutions for each wall element. A total of four government documents, six BRANZ reports, and thirty-two company files were collected. The selection of these documents is provided in Appendix A.

3.1.2. Semi-structured interviews

Based on the findings of the desktop study, a material list was developed for each wall element, and relevant Dow solutions were

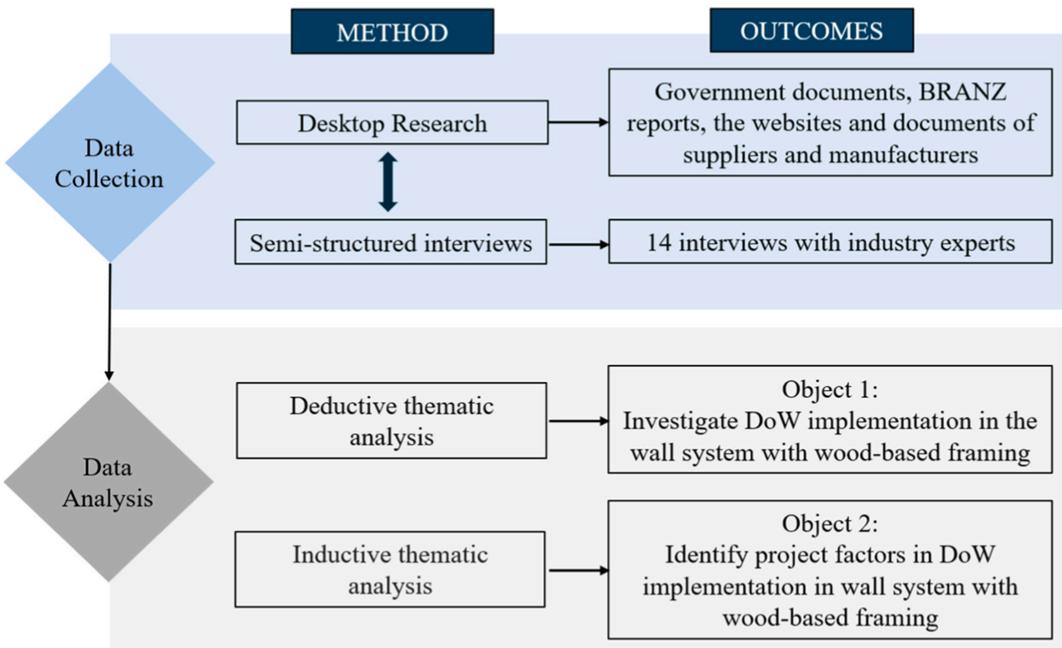

Fig. 2. Research process.

identified. To gain deeper insights into the application of the five DoW principles and the additional materials used for wall elements, fourteen semi-structured interviews were conducted with industry experts from September 2024 to March 2025. Expert interviews are a widely used method for gaining insights into the experiences and perspectives of individuals within a specific field [67]. To ensure the collection of appropriate data, a purposive sampling technique is used, where participants are selected based on their specific experiences, perspectives, or expertise, rather than their demographic representation of the broader population [68]. The recruitment process involved multiple approaches. First, potential participants were identified through information provided by the authors' colleagues. Secondly, attendee lists of the construction industry workshops on waste were extracted from the workshop output reports to identify suitable interviewees. Thirdly, the authors engaged with industry professionals by attending events focused on CDW minimisation. Additionally, publicly available contact information on LinkedIn was utilised to reach additional candidates. Finally, a snowball sampling technique was employed, where participants were asked to recommend other suitable experts. The interviewees were selected based on their knowledge and experience (more than five years) in the NZ construction industry, as well as their expertise in minimising CDW in residential projects.

The interviewees' consent was obtained prior to the interviews, and no audio recordings were made without their approval. Data saturation was achieved in the final two interviews, as no new data were found, indicating that additional participants were unnecessary. A total of fourteen online interviews were conducted, each lasting between 45 and 60 min. Table 2 provides an overview of the interviewees' profiles, including their positions and years of experience.

The interview questions were formulated based on the initial findings from the desktop study to explore how DoW principles can be applied to each material used in wall elements. Participants were also encouraged to recommend additional materials. Furthermore, the interview questions were designed to inductively capture the project factors affecting DoW implementation through further discussions with participants on potential implications or concerns when implementing DoW principles in each material. The interview questions were sent to participants in advance, allowing them time to prepare and thoughtfully formulate their responses.

3.2. Data analysis

To analyse the transcribed interview data, deductive thematic analysis was employed to address research objective 1, while inductive thematic analysis was utilised for research objective 2, as illustrated in Fig. 2. NVivo 14, a qualitative software package, was used to organise and code information, analyse data, identify themes, and interpret findings.

3.2.1. Deductive thematic analysis

The first research objective is to explore how five DoW principles can be applied to each material used in wall elements, where five DoW principles serve as a prior coding manual to code and organise data. The coding process follows a deductive thematic analysis approach proposed by Crabtree and Miller [69]. First, the interview transcripts were read and re-read to develop familiarity with the data. Second, the data were coded based on a coding manual derived from the five DoW principles: design for off-site construction, design for reuse and recycle, design for future, design for resource optimisation, and design for resource-efficient procurement. Third, all participant statements related to applying each DoW principle to each material were grouped together as a subset of the interview data, from which themes could be generated. Fourth, the subset of data was read repeatedly, and reflections were made until interpretations began to emerge. Fifth, the crystallisations formed in the previous step were then refined into themes.

3.2.2. Inductive thematic analysis

To achieve the second study objective, the data analysis uses an inductive coding approach to thematic analysis. This approach differs from the deductive thematic analysis in the early stages, as initial codes are generated from the data rather than being predefined. The data analysis process follows six steps proposed by Braun and Clarke [70]. Step 1 involves reading and re-reading the data and noting down initial ideas. In step 2, initial codes were generated. The code labels were assigned to portions of the transcribed texts. Based on the conceptual commonality, the code was developed, and all relevant textual data were collated into this code. In step 3,

Table 2
Profiles of interviewees.

Code	Organisation type	Title in organisation	Years of experience
P1	Construction company	Waste manager	18
P2	Design consultancy	Structural engineer	10
P3	Waste management consultancy	Operations and development manager	5
P4	Local government	Regional CDW minimisation advisor	35
P5	Local government	Senior waste planning specialist	45
P6	Construction company	Director	18
P7	Construction company	Director	25
P8	Housing provider	Waste manager	7
P9	Design consultancy	Director	20
P10	Material supplier	Account manager	21
P11	Waste management consultancy	Waste specialist	25
P12	Waste management consultancy	Waste specialist	7
P13	Material supplier	Account manager	25
P14	Construction company	Project manager	13

conceptually correlated codes were collated into one potential theme. Then, the themes were reviewed in step 4 and defined in step 5. Finally, five themes and their associated codes were reported according to the analysis above. As presented in Fig. 4.

4. DoW implementation in the wall system

This section presents the findings on applying the five DoW principles to various materials used in wall framing, insulation, lining, and cladding. The analysis explores how each principle can be tailored to different material types, highlighting their potential for CDW minimisation. Fig. 3 summarises the material options and potential DoW strategies applicable to wall systems, with implementation dependent on the material selection for each wall element. Detailed applications of these principles for each material are summarised in Appendix B.

4.1. Wall frame

Based on interview data, various wood-based materials are available in the NZ market for wall framing in residential projects, with preservative-treated radiata pine being the most used. This is due to its numerous benefits, including wide availability, compliance with building codes, cost-effectiveness, and ease of handling due to its lightweight nature and softness. EWPs and SIPs are less common recently; however, driven by NZ's net-zero carbon goals and efficient timber use, they are expected to grow in popularity as alternatives to traditional treated timber framing. EWP frames and SIPs utilise lower-grade timber than treated radiata pine, thereby promoting resource efficiency by making use of wood that would otherwise remain underutilised. Moreover, EWPs panels are pre-cut to size, including door and window openings, before being delivered to sites; however, they need additional insulation to meet energy efficiency requirements (P7). Douglas fir, once commonly used as untreated timber, has become relatively rare in current construction practices. The application of the five DoW principles varies across different materials, as discussed below.

All interviewees agreed that off-site construction contributes more significantly to waste minimisation than on-site material handling and cutting. This is due to various aspects of prefabrication that help reduce waste in the timber-based construction industry in NZ, as highlighted in the study by Luo and Shahzad [71] study. Improved supervision and Computer Numerical Control machines are key in reducing offcuts that would otherwise go to waste. Additionally, leftover and surplus materials are more likely to be repurposed for future use rather than sent to landfills. A sheltered factory environment further protects materials and finished products from weather-related damage. Moreover, careful packaging and transportation of prefabricated components help minimise waste during delivery to construction sites. Treated timber and EWP frames are mostly pre-cut and pre-nailed before being delivered to construction sites, representing the lowest level of prefabrication [28]. Higher levels of prefabrication, such as pre-assembled wall panels or complete building modules, remain relatively limited in residential projects. Participants also noted that SIPs and EWPs panels can help reduce waste generation more effectively, as wall panels are prefabricated in factories. In contrast, due to the limited use of untreated timber, like Douglas fir, it is generally framed on-site.

Regarding design for reuse and recycling, respondents noted that new residential projects typically require new materials rather than reused ones. This preference is primarily due to building code compliance, which mandates that structural materials have a

	Wall Frame	Wall Insulation	Wall Lining	Wall Cladding
Material options	• Preservative-treated timber • EWPs • SIPs • Untreated timber	• Fibreglass • Polyester • Wool • Polystyrene	• Gypsum plasterboard • EWPs • Fibre cement • Ceramic tiles • Recycled waste board	• Preservative treated timber • Non-preservative treated timber • EWPs • Fibre cement / uPVC • Steel sheet / Aluminium • Brick veneer / Plaster
Design for off-site construction	• Utilise prefabrication (pre-nailed frames, panels, and complete buildings).	• Precut insulation to standard stud spacings. • Promote prefabricated wall panels and complete buildings.	• Promote prefabricated wall panels and complete buildings.	• Promote prefabricated wall panels and complete buildings.
Design for reuse & recycle	• Not implemented.	• Select insulation with high recycled content.	• Select lining materials with high recycled content.	• Select cladding materials with high recycled content.
Design for future	• Not implemented.	• Not implemented.	• Not implemented.	• Not implemented.
Design for resource optimisation	• Comply with dimensions in NZ Building Standards. • Select certified sustainable timber and EWPs. • Divert treated timber waste to biofuel.	• Select recyclable insulation to enable recycling of offcuts and waste. • Select insulation produced from renewable resources (e.g., wool).	• Align with standard material sizes, order custom sizes from manufacturers when possible. • Select certified sustainable timber and EWPs. • Select recyclable materials to enable recycling of offcuts and waste.	• Align with standard material sizes. • Select certified sustainable timber and EWPs. • Select recyclable materials. • Select cladding materials with long-term resistance to weathering. • Divert treated timber waste to biofuel.
Design for resource-efficient procurement	• Use reusable timber pack covers and avoid plastic wrap through just-in-time delivery.	• Support take-back schemes for recycling offcuts and packaging.	• Pallet return policies.	• Pallet return policies.

Fig. 3. DoW strategies for the timber-framed wall system.

minimum lifespan of 50 years [58]. Thus, design for deconstruction is also often not considered, as opportunities to reuse deconstructed framing in new projects are limited due to the lack of certification standards for reused building materials. Furthermore, although wall panels such as SIPs and EWPs panels can facilitate the deconstruction process, participants highlighted that the absence of systems for certifying the quality of reused materials remains a significant barrier. As P4 stated, "*they should theoretically be easier to deconstruct because they're penalised systems*; however, P12 concerned that "*the biggest obstacle is the material passport and certification for reuse*". This concern highlights the need for robust frameworks and standards to support the use of reused materials in the industry.

For design for resource optimisation, experts recommended adhering to the standard dimensions specified in timber-framed building standards NZS3604:2011 [72] to optimise cutting and minimise offcuts. Timber longer than 600 mm can be reused for noggings or repurposed in neighbouring developments for framing [17]. Moreover, EWPs can be manufactured to precise sizes required for buildings, thereby avoiding waste generation on-site (P10). When waste generation cannot be avoided, treated pine waste can be processed for biofuel in Auckland, the country's most populous region. However, in other regions, it is often sent to landfills due to a lack of infrastructure. P12 also suggested that nearby regions could shred treated timber into smaller pieces and transport it to Auckland for biofuel production, thereby lowering overall transportation costs. Regarding waste minimisation, respondents tend to prefer treated timber over EWPs because the waste from treated timber can be processed into biofuel. In contrast, due to the lack of recycling options for EWPs, all EWP waste is currently directed to landfills, despite EWPs offering improved carbon performance and more efficient use of timber. Meanwhile, untreated timber offers more recycling options, such as composting, landscaping chips, or animal bedding. However, P12 highlighted a challenge in separating untreated timber from treated timber products on-site. As a result, they are often mixed and processed as treated timber. Furthermore, experts emphasised the critical importance of promoting certified sustainable timber products, such as those certified by the Forest Stewardship Council and the Programme for the Endorsement of Forest Certification, to ensure they are sourced from renewable and responsibly managed forests.

In relation to design for resource-efficient procurement, participants noted that suppliers offer the option of delivering timber either plastic-wrapped or unwrapped. Therefore, encouraging just-in-time delivery can minimise packaging waste by ensuring materials arrive only when needed. Suppliers also provide reusable timber pack covers as a sustainable alternative to single-use plastic timber wrapping. They are supplied free of charge on condition that they are returned once no longer needed on-site. Furthermore, while factory wrapping is required for EWP framing to protect against moisture damage, it is unnecessary for SIPs and EWP wall panels.

4.2. Wall insulation

According to the interview findings, four insulation materials available in the NZ market for residential projects are fibreglass, polyester, wool, and polystyrene. Fibreglass, polyester, and wool insulation are suitable for light timber-framed walls, whereas polystyrene insulation is employed in SIPs. Among these materials, fibreglass is the most economically and widely used insulation option. In contrast, polyester presents a more sustainable alternative, though it comes at a higher cost. Polyester insulation is more commonly preferred by public clients, who are often more focused on sustainability, compared to private clients who may prioritise cost-effectiveness (P9). Wool, a bio-based material, provides additional environmental benefits as it is both renewable and biodegradable. However, respondents noted that the adoption of wool insulation remains limited, due to its high cost.

Participants agreed that off-site construction is feasible when wall panels or complete buildings are prefabricated. P6 and P1 emphasised that manufacturing in a controlled environment is particularly beneficial for maintaining insulation cleanliness for reuse and recycling. Currently, insulation materials are pre-cut to fit standard stud spacings as specified in NZS3604:2011 (P10). In relation to design for reuse and recycling, all studied insulation materials can be manufactured using recycled content. Fibreglass insulation contains a high proportion of recycled glass, whereas polyester and wool insulations utilise recycled polyester fibre and wool waste to manufacture new products. Polystyrene insulation can also be produced from recycled polystyrene waste.

Regarding design for deconstruction, experts recommended installing insulation without using fixings like staples to facilitate the efficient disassembly and reuse of materials. However, P6, P7, and P9 noted that this approach is more suitable for polyester insulation due to its durability and ability to retain shape. In contrast, fibreglass and wool insulation tend to slump over time. Another concern raised during the interviews regarding polystyrene in SIPs is the need to design for deconstruction to facilitate the disassembly of wall panels. Without such considerations, demolition may result in widespread dispersion of polystyrene (P3). Additionally, P5 highlighted that end-of-life solutions for SIPs are limited due to the adhesion between polystyrene and oriented strand board, making separation challenging. Furthermore, there are currently no established guidelines or certification systems for reusing entire SIPs.

In terms of design for resource optimisation, interviewees recommended that framing should follow the standard stud spacings outlined in NZS 3604:2011 to accommodate available insulation sizes in the market. Additionally, experts preferred polyester insulation, as its offcuts can be easily reassembled or reused due to its ability to retain a firm shape (P9). Furthermore, all the insulation materials, except for fibreglass, are recyclable. Thus, takeback schemes are available for recycling offcuts of polyester, wool, and polystyrene, but not for fibreglass. In addition, packaging is crucial for fibreglass, polyester, and wool insulation, as these materials must be compressed to optimise transport space and kept dry to preserve their quality. Suppliers also offer takeback schemes for recycling the packaging materials.

4.3. Wall lining

The findings indicate that gypsum plasterboard remains the dominant choice for wall lining in NZ residential projects, though alternative materials are emerging to address sustainability or specific functional needs. The widespread use of gypsum plasterboard is due to its cost-effectiveness, ease of installation, and ability to provide a smooth, even surface suitable for finishing applications. In addition, a NZ-based company has developed an innovative solution by converting waste into construction boards as an alternative to gypsum plasterboard. These boards are low-carbon and environmentally sustainable, made from recycled materials such as used beverage cartons, soft plastics, and coffee cups, helping to divert waste from landfills [59]. Other alternative materials to gypsum plasterboard are employed for specific applications; however, they remain a relatively small proportion of the market share. For instance, fibre cement lining and ceramic tiles are used in moisture-prone areas, such as bathrooms, due to their resistance to moisture. Wood-based products are incorporated into feature walls to enhance aesthetic appeal, while some participants mentioned using plywood or particleboard in garage spaces. OSB can be utilised in SIPs for both structural and lining purposes.

The offsite construction method is applicable for lining materials once wall panels or a complete building are prefabricated. In the context of design for reuse and recycling, one factory in NZ has recently begun recycling gypsum waste into new plasterboard. However, the recycling rate remains low, with only approximately 10 % of gypsum waste being repurposed. An alternative approach involves using innovative construction boards made from packaging waste and soft plastic, which help divert waste from landfills and reduce reliance on natural resources for plasterboard production. In contrast, other lining materials, including EWPs, fibre cement, and ceramic tiles, are produced using virgin raw materials, and there is currently no infrastructure in NZ to repurpose the waste generated from these materials. Furthermore, although design for deconstruction is unlikely to be considered, experts also recommended using exposed screws instead of nails and adhesives for fixing linings, as this makes disassembly and material separation easier. However, if screws are covered by plastering and painting, as on gypsum plasterboards, disassembly becomes more challenging than when using nails (P7).

In terms of resource optimisation, experts highlighted that manufacturers provide lining materials in various sizes. By aligning design dimensions with material sizes, designers can reduce material waste during construction. A local gypsum plasterboard manufacturer offers custom sizes for orders of more than 100 sheets; further minimising waste associated with offcuts. Additionally, manufacturers' recommendations for optimising material usage should be included. For instance, one leading plasterboard producer advises horizontal installation of plasterboards to enhance efficiency and minimise waste. During the interviews, a key concern is the treatment and disposal of lining material waste. From a waste minimisation perspective, industry professionals prefer gypsum plasterboards due to their recyclability. Gypsum waste can be repurposed for agricultural applications or reprocessed into new plasterboard products, thereby contributing to a circular economy. Another sustainable alternative is the use of boards made from recycled materials. Although technically recyclable, these boards face practical challenges, as only one dedicated manufacturing factory exists. This creates logistical and financial barriers, particularly for projects located in remote areas. In contrast, other lining materials, including EWPs and fibre cement, present greater sustainability challenges due to the lack of recycling infrastructure. Therefore, all associated waste is sent to landfills. Ceramic tile waste can be used for hardfill applications, offering an open-loop recycling option when material waste is not recycled to produce the same products. This practice does not alleviate the extraction of natural resources required for producing new materials [17]. The absence of recycling options for EWPs and fibre cement highlights the urgent need for further research and investment in waste management infrastructure to support more sustainable practices in the NZ construction sector.

The interview findings indicate several solutions for resource-efficient procurement. A return policy has been implemented to keep untreated timber pallets in circulation. When placing an order, customers are charged a fee for the pallets, which is refunded upon return of the pallets. Moreover, while gypsum plasterboard suppliers do not currently offer take-back schemes, gypsum waste can be collected in dedicated bags or bins and sent to manufacturers for recycling into new plasterboards. However, the recycling capacity is limited, accommodating only approximately 10 % of the total gypsum plasterboard waste generated by the construction industry. Recycled construction boards offer a fully circular solution, as all offcuts and end-of-life products can be remanufactured into new boards. Despite this potential, reverse logistics remains a significant challenge due to the presence of only one manufacturing facility in NZ and the product's relatively small market share.

4.4. Wall cladding

Interviewees identified various cladding materials used in NZ residential projects, which were categorised into wood-based, fibre cement, uPVC, metal, brick, and plaster. Among these, wood-based cladding is the most widely used, followed by fibre cement and brick. Wood-based cladding encompasses preservative-treated timber, non-preservative-treated timber, and EWPs. Respondents agreed that preservative-treated timber products dominate the market. Besides, non-preservative-treated timber is gaining popularity as a more sustainable option, with heat treatment instead of conventional chemical methods. Additionally, using plywood, a type of EWP, is increasingly driven by NZ's net-zero carbon goals and efficient timber use (P4). While interviewees agreed that UPVC is less commonly used in residential projects, despite being highly recyclable. Fibre cement and brick claddings are also preferred for their durability and their ability to be painted in dark colours. As noted by P9, "*Our main cladding is we specify between brick and the fibre cement claddings. Fibre cement claddings also allow to be painted dark colours, which is really important to us because it gives us an extended sort of colour palette*." Metal cladding options include steel and aluminium. Corrugated iron, a common form of steel cladding, is generally more affordable than aluminium. However, experts tend to favour aluminium due to its durability and resistance to scratching compared to corrugated iron (P9).

According to interview findings, off-site construction methods can be applied to wood-based materials, fibre cement, and uPVC cladding once wall panels or complete buildings are prefabricated. In the case of metal cladding, sheets are pre-cut in factories before being transported to construction sites for final assembly. In contrast, bricks and plaster are generally constructed on-site. P7 explained that due to the heavyweight of bricks, they should generally be constructed on-site unless they are used in small panels as part of larger walls. Regarding design for reuse and recycling, metal and uPVC cladding may contain recycled content, while most other cladding materials rely on natural resources for their production.

When it comes to designing for the future, participants stated that design for deconstruction at the end of project life is not considered. At the end of a building's life, sheet cladding like corrugated iron sheet is the easiest to disassemble (P06). In contrast, other types of cladding often require labour-intensive de-nailing, which makes deconstruction less considered during the design stage. However, experts paid more attention to disassembling and replacing damaged cladding during maintenance. Weatherboard cladding offers advantages in renovation processes, as individual boards can be replaced more easily than entire metal sheets. P7 added that using exposed screws instead of nails can facilitate the removal of damaged cladding during renovation. However, the expert also noted that if the screws are painted over, disassembly can become more difficult than when nails are used: *"I've changed to using screws on some of our weatherboards to enable if there's damage to the weatherboards that can be changed a bit easier … But the fact that a screw that's been painted over and … so much harder to take out than nails"*.

For resource optimisation, interviewees agreed that incorporating standard material sizes available in the market with the building dimensions minimises offcuts from cladding installation. When offcuts cannot be avoided, treated timber waste can be processed for biofuel in Auckland; however, it is landfilled elsewhere due to the lack of infrastructure. Non-preservative-treated timber without pre-coating can be recycled as untreated timber (P4). However, it is often pre-coated in factories to improve cost efficiency and ensure consistent quality (P10). Experts also emphasised that uPVC, corrugated iron, and aluminium cladding are highly recyclable; hence, offcuts can be repurposed into new products. Bricks can be crushed into a basecourse, while fibre cement is disposed of in landfills. P4 added that fibre cement weatherboards would be one of the worst products by weight in the skip bins, as they are very heavy. Furthermore, experts also emphasised the importance of selecting cladding materials that not only comply with durability standards in the building code but also perform well throughout the building's lifecycle to minimise maintenance needs (P7). Long-term durability is crucial due to the cladding's direct exposure to environmental elements such as sunlight, rain, and moisture. Fibre cement and bricks are often favoured over wood-based materials because they are more resistant to weathering, decay, and moisture absorption, thus requiring less frequent maintenance and offering greater long-term performance. However, a disadvantage of brick veneer cladding is its susceptibility to cracking during earthquakes, which raises concerns about its performance in seismic regions. On the other hand, wood-based cladding offers an additional sustainability advantage by utilising renewable resources when certified sustainable timber products are used. Nevertheless, it requires periodic repainting or resealing to preserve its condition and appearance over time (P9). Regarding metal cladding, designers prefer aluminium to corrugated iron, especially in the ground floors, due to its durability and resistance to scratching.

In relation to resource-efficient procurement, cladding materials generally do not require plastic covering due to their resistance to moisture, except for bricks, which need some protection to prevent damage during transport (P10). Additionally, a pallet return policy

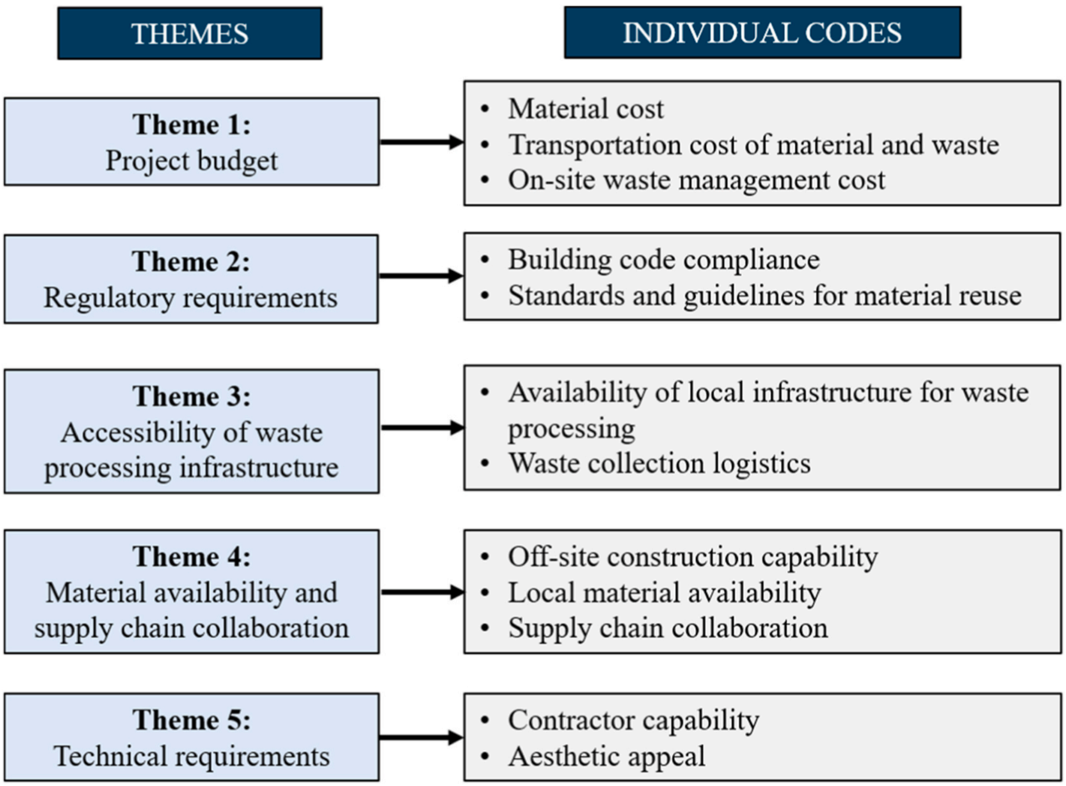

Fig. 4. Project factors affecting DoW implementation.

is widely implemented, allowing pallets to be returned to suppliers for reuse across multiple deliveries, thereby reducing packaging waste and promoting circular resource use.

5. Project factors affecting DoW implementation in the wall system

Section 4 presented the implementation of DoW principles for each material in the wall system. However, the selection of suitable options is dependent on project-specific characteristics [13]. Therefore, this section discusses factors that influence the implementation of DoW principles in the wall system, highlighting the key considerations for selecting suitable DoW options tailored to a specific project. Five themes emerged from the inductive thematic analysis, including project budget, regulatory requirements, the accessibility of waste processing infrastructure, material availability and supplier collaboration, and technical requirements. Each theme contains individual codes developed from the coding process to support the theme, as shown in Fig. 4. Understanding these factors is crucial to ensuring that the chosen materials are appropriately tailored to the specific characteristics of each project.

5.1. Project budget

The interview data emphasised the critical need for the project budget to accommodate additional costs incurred during the implementation of DoW, including increased expenditures on materials, transportation, and on-site waste management. First, experts indicated concerns about material costs in the decision-making process. As P4 stated, "*people are looking for the cheapest option to be able to make a compliant home at the cheapest possible price*". The transportation cost of materials and waste is another consideration. NZ is a larger country; when it comes to remote areas where material suppliers and waste processing infrastructure are not available locally to support desirable materials, forcing the use of such materials will increase the cost of material delivery, take-back scheme, and CDW collection to waste processing facilities. Further concern is about the additional costs of on-site sorting, especially in the deconstruction process. Separating materials for reuse at the end of project life is labour-intensive, which is unlikely to be paid off in selling deconstructed materials for reuse; hence, interviewees indicated that design for deconstruction tends not to be considered currently. One waste manager stated: "*You deconstruct it and separate all the materials and then de-nail it and clean up anything that might still be attached to it. You've probably spent more in labour than you would in being able to resell the material*" (P1). This aligns with existing literature, which points to cost pressures and low residual material value as major barriers to DoW adoption [33,43]. Preferable material options to support DoW implementation may increase project costs; hence, appropriate selection should be aligned with the project budget and client expectations.

5.2. Regulatory requirements

Interviewees stressed that building code compliance is a critical consideration in DoW implementation. Accordingly, building materials and fixings must meet durability requirements to obtain building consent. As a result, the reuse of previously used materials in new buildings is not recommended. One expert explained, "*There would need to be some changes to the building code to enable you to take materials from an end-of-life building and then put them into a new building that you're then saying is going to last for 50 years … It's difficult to reuse unless you reuse it for a non-condensable purpose*" (P4). Moreover, demountable connections are one of the key factors in deconstruction [35,36]; however, experts argued that fixings also need to meet building compliance to obtain building consent. As P6 stated that using adhesives and nails in fixings to meet the durability requirements makes deconstruction harder. Furthermore, the process of recertifying materials for use in new construction projects is challenging due to the lack of standards and guidelines. For instance, participants highlighted the potential of wall panels like SIPs to simplify deconstruction and facilitate the reuse of entire walls without the need for material separation. However, the reuse of such panels would require the development of appropriate standards and guidelines. Many companies prefer using new materials due to concerns over warranties and liability. As a result, even though digital platforms exist to facilitate the exchange and reuse of surplus materials, the reuse of materials that need recertification remains limited [59]. These findings further substantiate earlier studies which showed that the absence of stringent legislation mandating deconstructable design and the lack of clear standards for reused and recycled materials remain major barriers to DoW adoption, as observed in both the UK and China [9,45,46].

5.3. Accessibility of local waste processing infrastructure

Interview findings reveal that the limited accessibility of local waste processing infrastructure is a critical constraint to effective DoW implementation in NZ. While recyclable materials are theoretically an effective strategy to divert CDW from landfills, their practical application is significantly influenced by the proximity and capacity of regional recycling facilities. One participant emphasised the logistical and financial barriers, stating "*There's no one that would collect it and take it here because to pay for it to go to Auckland to be recycled is very expensive*" (P12). For instance, timber constitutes a significant proportion of waste generated on residential construction sites [17]. However, there is only one facility in Auckland that processes timber waste into biofuel. Although some nearby regions can shred timber for transportation to Auckland, this is not economically viable for more distant or rural areas, resulting in widespread landfilling of treated timber waste. This highlights the importance of considering the accessibility of local recycling facilities when selecting reusable and recyclable materials for construction projects. Without adequate regional facilities, the environmental benefits of using recyclable materials may be undermined by transportation costs.

These findings echo and extend existing literature, which identified infrastructure and technological capacity as fundamental enablers of DoW adoption. Countries such as the United States, Japan, Germany, and Singapore have established advanced recycling systems, allowing efficient material recovery [46]. In contrast, geographically dispersed regions such as Australia face similar barriers to those observed in NZ, where distance, limited infrastructure, and high transportation costs undermine the economic feasibility of recycling [73].

5.4. Material availability and supply chain collaboration

The interview findings indicate that material availability is a key determinant of DoW implementation. Experts agreed with the previous studies that off-site construction has significant potential to reduce waste generation [13]; however, its application in NZ remains limited, often restricted to pre-nailed timber frames. Prefabricating wall panels and complete buildings enables off-site integration across all wall components, thereby enhancing waste reduction. Similarly, Zhang, Pan [74] suggested that a higher level of prefabrication within a building reflects the use of a greater number of prefabricated components, allowing more on-site work to be shifted to controlled factory settings and thus significantly reducing waste generation. Nevertheless, participants emphasised that market availability for such prefabricated systems is constrained, particularly in regional and remote areas.

Furthermore, interviewees emphasised the importance of using recyclable and locally sourced materials to divert construction waste from landfills through recycling processes. The use of locally sourced materials increases the likelihood of returning unused materials and waste to manufacturers for recycling into new products. Meanwhile, the use of imported materials presents logistical challenges, often resulting in recyclable materials being disposed of in landfills due to the absence of feasible return pathways. Additionally, supply chain collaboration is critical for minimising packaging waste and facilitating take-back schemes. Suppliers can support resource-efficient procurement by eliminating packaging and providing take-back schemes for packaging and unused materials. Without active collaboration and commitment from suppliers, achieving effective resource-efficient procurement design is unlikely. This reinforces existing literature, which points to the importance of mature markets for salvaged and recycled materials in enabling DoW [3,43,46]. The interview results also extend prior research by underscoring the practical significance of local supplier capability and commitment as enablers of DoW implementation.

5.5. Technical requirements

Contractors play a crucial role in the effectiveness of DoW implementation during the construction stage, both in preventing waste generation and ensuring that waste is diverted in alignment with the intended design solutions. To achieve this, contractors must possess the requisite skills to handle and install the materials specified during the design stage. For example, NZ carpenters who are accustomed to working with traditional timber framing may face difficulties when installing newer, more innovative materials such as SIPs. These results support existing research indicating that the use of products with recycled content and advanced construction systems requires specialised expertise across the supply chain, from the design team through to skilled contractors [47]. Additionally, contractors need a clear understanding of how DoW strategies should be executed on-site to meet waste minimisation objectives established during the design process. For instance, untreated timber cladding requires additional attention to separate it from treated timber on sites. If not properly managed, treated and untreated timbers are often mixed and subsequently disposed of as treated timber, undermining the recycling effort. Approximately 80 per cent of construction firms are classified as small and medium-sized enterprises, many of which lack the capacity to employ dedicated waste managers or to invest time in researching material diversion and recycling practices [59]. Aesthetic considerations also influence material selection and can hinder the adoption of more sustainable options. For instance, steel sheet cladding offers multiple advantages in terms of waste reduction, such as factory pre-cutting to reduce offcuts, ease of installation and disassembly, and high recyclability. Nevertheless, interviewees noted that such materials are often rejected for residential projects due to their perceived lack of aesthetic appeal and are instead more commonly used in commercial applications, such as warehouses.

6. Discussion and implications

6.1. Discussion

This section summarises the critical findings of the study. Regarding DoW implementation, designing for off-site construction holds significant potential to reduce on-site waste through factory-controlled prefabrication [13]. In NZ, however, its application remains largely confined to basic forms, such as pre-cut and pre-nailed framing, which represent the lowest level of off-site construction. A similar trend is observed in Australia, where component-based prefabrication remains the most prevalent approach to off-site construction. This approach presents relatively few challenges, with only minor on-site interface issues, in contrast to the numerous barriers associated with higher levels of prefabrication, including quality concerns, higher costs, limited skills, as well as industry culture and market constraints [75]. Insulation, lining, and cladding materials can be pre-cut in factories; otherwise, they are delivered to sites in standard material sizes, leading to additional on-site waste. To enhance the benefits of off-site construction, higher levels of prefabrication, such as panelised and complete building prefabrication, should be promoted. This advancement would incorporate other elements, including insulation, lining, and cladding, during the factory manufacturing process. These findings align with previous research, which has identified off-site construction as a key dimension of DoW [18,76], and emphasise that the proportion of prefabrication incorporated into a building directly influences the extent of waste minimisation achieved [27].

Previous studies highlighted that design for deconstruction is a key measure to prevent waste from demolition activities, which is responsible for half of the waste generated in the construction industry [9]. Although design for deconstruction is theoretically advantageous, its practical application in NZ is constrained by the Building Code's durability requirements. These regulations limit the reuse of materials from deconstructed buildings in new residential construction, thereby discouraging the adoption of design for deconstruction principles. Storey and Pedersen [77] suggested overcoming this barrier requires the development of accepted standard specifications and certification processes for reused components and materials. Without standardised guidelines and regulatory support, industry practitioners remain reluctant to specify or use reused materials due to concerns about liability and performance. This also hinders the implementation of designing for reuse in wall elements. Currently, the most practical application of design for reuse and recycling is the use of materials with high recycled content. Similar challenges related to the lack of supportive regulations and standards for design for deconstruction and the use of reused or recycled materials have also been identified in other countries [9,45,46].

The findings are consistent with the literature, which indicates that material optimisation in design can be achieved by aligning with standardised material sizes to minimise off-cuts [13]. Resource efficiency can be further enhanced by promoting the use of certified sustainable timber products, ensuring that these are sourced from renewable and responsibly managed forests. Incorporating recyclable materials facilitates the diversion of off-cuts and construction waste from landfills. Moreover, selecting cladding materials with high long-term weathering resistance enhances durability, thereby reducing lifecycle replacement frequency and the associated material and waste impacts. Design for waste-efficient procurement depends on supply chain collaboration, where suppliers can play a crucial role in reducing packaging waste and facilitating the return of surplus materials.

Selecting an effective DoW solution requires not only a clear understanding of its waste reduction potential but also a systematic consideration of project-specific factors that shape its feasibility and effectiveness. This study identified five key factors influencing DoW implementation: project budget, regulatory requirements, infrastructure accessibility, material availability and supply chain collaboration, and technical requirements. These findings reinforce existing literature on enabling conditions for DoW [9,43,46], while providing a more structured set of decision-support factors for practical implementation. Collectively, these factors determine the level and effectiveness of DoW strategies adopted. The DoW implementation framework presented in Fig. 5 synthesises the key findings of this study, providing key DoW strategies and project factors affecting the DoW implementation.

6.2. *Theoretical implications*

This study contributes to existing knowledge of construction waste minimisation through design by implementing DoW principles. First, one of the most novel contributions of this research is the detailed, material-level mapping of DoW principles to specific wall elements used in NZ residential sector. Unlike previous DoW guidelines, which tend to be broad and generic [13], this study

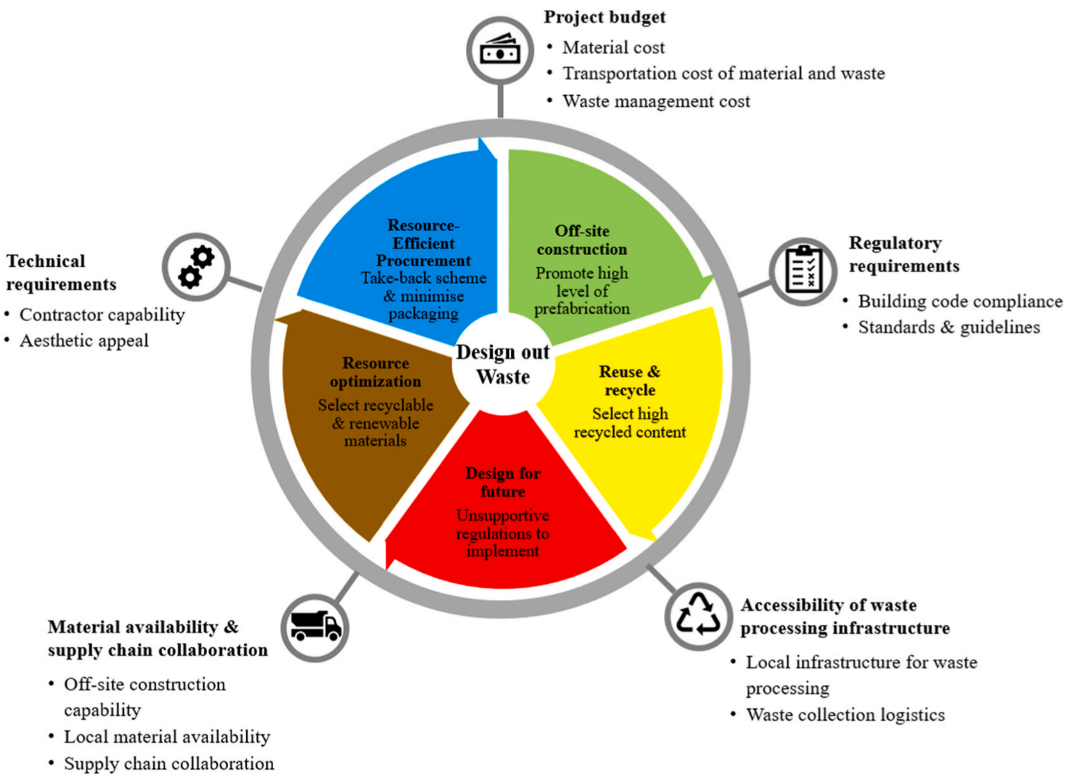

Fig. 5. Dow implementation framework.

disaggregates the implementation strategies for each of the five DoW principles across a range of commonly used materials. By developing these mappings through expert interviews and desktop analysis, the study provides clear, practice-oriented guidance moving from general intent to actionable strategies. This level of detailed guidance has been mostly absent in previous literature, making this study a critical step toward more practical and technically informed DoW implementation in real-world construction projects. The second key contribution of this study is the identification of five project factors that influence the feasibility and successful implementation of DoW strategies: (1) project budget, (2) regulatory requirements, (3) accessibility of local waste processing infrastructure, (4) material availability and supply chain collaboration, and (5) technical requirements. While previous studies proposed DoW strategies without considering the feasibility, this research emphasises the situational dependencies that either enable or hinder implementation. Finally, the methodological structure of this study, combining desktop research with semi-structured interviews, presents a replicable model for exploring DoW strategies in other building elements. Future research can apply this approach to other elements such as foundations, roofs, and flooring systems, thereby contributing to the development of a more comprehensive and holistic DoW implementation framework.

6.3. Practical implications

This study provides specific and practice-oriented recommendations for key construction stakeholders, including designers, suppliers, contractors, and policymakers. The lack of designers' knowledge and experience in minimising waste is identified as the leading cause of CDW generation [44]. Moreover, designers' subjective attitudes and personal hesitancy towards adopting waste minimisation measures remain significant challenges [78,79]. The findings offer specific and practical DoW measures with a list of material choices with corresponding DoW strategies that can potentially be applied to minimise material waste from the design stage. Five project key factors also serve as a decision-support tool for design teams, allowing them to assess the appropriateness of specific DoW options against the unique constraints of each project. Suppliers are encouraged to support waste-efficient procurement through take-back schemes, just-in-time delivery logistics, and reusable or minimal packaging. For contractors, the study highlights the need for upskilling in new material handling techniques, such as the installation of SIPs, as well as in on-site waste management, to facilitate more effective waste reduction.

In the policy domain, this research emphasises the need to enhance industry capabilities in prefabrication, reform regulatory frameworks that hinder material reuse and deconstruction, and expand recycling infrastructure, particularly in geographically dispersed regions. Although derived from the NZ context, these policy implications are transferable to countries facing similar challenges, provided that policy instruments are tailored to local regulatory capacity, market maturity, and geographic conditions. To enhance international applicability, these policy directions require context-specific implementation. In developed economies with established waste minimisation frameworks, DoW can be advanced through mandatory legislation and standards for DfD as well as for reused and recycled materials, the promotion of advanced off-site prefabrication, and the use of fiscal instruments to stimulate market demand and large-scale infrastructure investment. Meanwhile, developing economies may benefit from staged approaches, beginning with pilot projects and simplified guidance, progressing to capacity building, enabling incentives, and regulatory alignment, alongside the gradual introduction of off-site construction methods suited to local skills and supply chains, and eventually supporting the formalisation of reuse and recycling markets and targeted investment in supporting infrastructure.

7. Conclusion

DoW approach presents a promising strategy for minimising CDW by addressing waste prevention from the early planning stage and supporting the planning of on-site waste management during the construction phase. However, existing guidelines lack detailed material-specific instructions on how to implement DoW in practice. To address this gap, this study provides a structured and practical framework for implementing DoW principles in the wall systems of residential buildings, an area that accounts for a significant share of construction and demolition waste in NZ. By integrating a desktop study with expert interviews, the research demonstrates that the feasibility of DoW strategies is shaped not only by their waste reduction potential but also by five key project factors: project budget, regulatory requirements, accessibility of waste processing infrastructure, material availability and supply chain collaboration, and technical requirements.

This research contributes to both theory and practice by implementing DoW principles at the material and element level, providing practical guidance to designers and contractors, and framing enabling conditions for policy and market interventions. From a policy perspective, strengthening prefabrication capacity, reforming regulations that hinder reuse and deconstruction, and expanding recycling infrastructure in geographically dispersed regions are critical. Although these insights stem from the NZ context, they are broadly applicable to countries facing similar barriers, such as immature reuse markets, unsupportive regulation, and uneven infrastructure development.

To reduce the scope of the research to a manageable quantity, this study only focused on the residential sector, which is responsible for the largest proportion of construction waste generation in NZ. This study only concerns DoW implementation in the wall system. Future research should expand to other building elements, such as roofing, flooring, and foundations, to develop a more comprehensive DoW implementation framework.

CRediT authorship contribution statement

Nguyet Tong: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Niluka Domingo:** Writing – review & editing, Supervision, Conceptualization. **An Le:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Desktop study

Government Documents

No.	Name	Year	Source
1	Building Code compliance	1992	https://www.building.govt.nz/building-code-compliance
2	Timber and wood-based products for use in building - NZS 3602:2003	2003	https://www.standards.govt.nz/shop/nzs-36022003
3	Timber-framed buildings - NZS 3604:2011	2011	https://www.standards.govt.nz/shop/nzs-36042011
4	Residential building supplies market study – Final report	2022	https://comcom.govt.nz/_data/assets/pdf_file/0014/300704/Residential-Building-Supplies-Market-Study-Final-report-6-December-2022.pdf

BRANZ Reports

No.	Name	Year	Source
1	Physical characteristics of new houses 2020	2020	https://www.branz.co.nz/pubs/research-reports/sr465/
2	Usage and uptake of engineered wood products in New Zealand	2020	https://www.branz.co.nz/pubs/research-reports/sr453/
3	BU681 Introduction to engineered wood products (EWPs)	2023	https://www.branz.co.nz/pubs/bulletins/bu681/
4	SR468 Fire performance of structural insulated panels (SIPs) for residential buildings	2022	https://www.branz.co.nz/pubs/research-reports/sr468fire-performance-of-structural-insulated-panels-sips-for-residential-buildings/
5	Understanding waste generation in the New Zealand construction sector: Scoping study	2023	https://www.branz.co.nz/pubs/research-reports/er82/
6	Assessing the long-term performance of structural insulated panels (SIPs) in New Zealand	2024	https://www.branz.co.nz/pubs/research-reports/sr485/

Company files

No.	Name	Company Source	Description
1	Interior linings catalogue	A	Material supplier
2	Cladding catalogue	A	Material supplier
3	Official website	A	Material supplier
4	Official website	B	Material supplier
5	Official website	C	Material supplier
6	Product information sheets	D	Timber manufacturer
7	Official website	D	Timber manufacturer
8	Design guide	E	SIPs manufacturer
9	Official website	E	SIPs manufacturer
10	Product information sheets	F	EWPs manufacturer
11	Official website	F	EWPs manufacturer
12	Product information sheets	G	Insulation manufacturer
13	Official website	G	Insulation manufacturer
14	Product information sheets	H	Insulation manufacturer
15	Official website	H	Insulation manufacturer
16	Official website	I	Insulation manufacturer
17	Product information sheets	J	Insulation manufacturer
18	Official website	J	Insulation manufacturer
19	Design tips for minimising construction waste	K	Lining manufacturer
20	Official website	K	Lining manufacturer
21	Product brochure	L	Lining manufacturer
22	Official website	L	Lining manufacturer
23	Product information sheets	M	Lining manufacturer
24	Official website	M	Lining manufacturer
25	Environmental Product Declaration (EPD)	N	Cladding manufacturer
26	Official Website	N	Cladding manufacturer
27	Product information sheets	O	Cladding manufacturer

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No.	Name	Company Source	Description
28	Official website	O	Cladding manufacturer
29	Product information sheets	P	Cladding manufacturer
30	Official website	P	Cladding manufacturer
31	Product information sheets	Q	Cladding manufacturer
32	Official website	Q	Cladding manufacturer

Appendix B. Implementation of DoW principles in different wall elements

Implementation of DoW principles in wall frame

W.E	Material alternatives	Availability	DoW principles				
			Off-site construction	Reuse & recycle	Deconstruction & flexibility	Resource optimisation	Resource-efficient procurement
Wall Frame	Preservative-treated timber framing (radiata pine)	Most common framing material in NZ.	• Approx. 90 % of wall framing is pre-nailed or pre-cut. • Some companies offer prefabricated wall panels or complete buildings, though market share remains limited.	• Reuse is not feasible due to NZ Building Code (50-year lifespan for structural materials). • No recycled-content products.	• Unlikely to be considered currently.	• Adhere to the standard dimensions specified in NZS3604:2011. • Off-cuts diverted to biofuel in Auckland; elsewhere landfilled due to infrastructure gaps. • Promote the use of certified sustainable timber products.	• Order no plastic wrap and just-in-time delivery • Use reusable timber pack covers.
	Untreated timber (douglas fir)	Previously used; now rarely used.	• Manually constructed on-site due to its very limited market share.	• Same as treated timber.	• Same as treated timber.	• Biodegradable and compostable, thus easy to recycle, such as composting, landscaping chips, or animal bedding.	
	EWPs framing - laminated veneer lumber (LVL), glulam, and cross-laminated timber (CLT)	Small market share; expected to grow.	• Can be produced in exact sizes required on sites for buildings. • Can be prefabricated the same as treated timber (pre-nailed, wall panels, and complete buildings).	• Same as treated timber.	• Same as treated timber.	• Adhere to the standard dimensions specified in NZS3604:2011. • Order exact sizes required for buildings. • Offcuts are sent to landfills. • Promote the use of certified sustainable timber products.	• Factory-wrapped to prevent moisture damage.
	Structural Insulated Panels	Small market share; expected to grow.	• Panels are prefabricated.	• Reuse is not feasible due to NZ Building Code (50-year lifespan for structural materials). • Recycled polystyrene content is available; recycled EWPs are not.	• Potentials for panel deconstruction, but no standards and guidelines for panel reuse.	• EWP offcuts are sent to landfills; however, polystyrene can be recycled. • Promote the use of certified sustainable timber products.	• No plastic packaging. • Just-in-time delivery system.

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W.E	Material alternatives	Availability	DoW principles				
			Off-site construction	Reuse & recycle	Deconstruction & flexibility	Resource optimisation	Resource-efficient procurement
	EWP panels	Uncommonly used; requires additional insulation for energy compliance.	• Panels are pre-cut to size, including door and window openings.	• Same as treated timber.	• Potentials for panel deconstruction, but no standards and guidelines for reusing panels	• Offcuts are sent to landfills. • Promote the use of certified sustainable timber products.	• No plastic packaging used. • Just-in-time delivery system.

Implementation of DoW principles in wall insulation

B.E	Material alternatives	Availability	DoW principles				
			Off-site construction	Reuse & recycle	Deconstruction & flexibility	Resource optimisation	Resource-efficient procurement
Wall Insulation	Fibreglass insulation	Approx. 90 % of NZ insulation market for housing.	• Precut to standard stud spacings (NZS3604:2011).	• High recycled-glass content.	• Unlikely to be considered currently.	• Offcuts are sent to landfills. • Framing must align with standard stud spacings to accommodate insulation sizes.	• Packaging is required. • Only packaging is recycled.
	Polyester insulation	Most of the remaining 10 % of the NZ insulation market for housing.	• Precut to standard stud spacings (NZS3604:2011).	• High recycled polyester fibre content.	• No staples support deconstruction for reuse or recycle, however unlikely to be considered currently.	• Offcuts can be recycled. • Framing must align with standard stud spacings to accommodate insulation sizes.	• Packaging is required. • Takeback schemes for recycling of both offcuts and packaging.
	Wool insulation	Environmentally friendly but more expensive, limiting adoption.	• Precut to standard stud spacings (NZS3604:2011).	• High recycled wool and polyester fibre content.	• Unlikely to be considered currently.	• Offcuts can be recycled. • Use a renewable resource from NZ wool.	• Packaging required. • Takeback schemes for recycling of both offcuts and packaging.
	Polystyrene insulation	Only used in SIPs. SIPs hold a small market share; expected to grow.	• Prefabricated in SIPs	• Recycled polystyrene content.	• Deconstruction of panels is possible; however, no standards and guidelines for reusing SIPs recently.	• Polystyrene offcuts can be recycled.	• Factory manufacturing reduces packaging waste. • Takeback schemes for recycling polystyrene.

Implementation of DoW principles in wall lining

B.E	Material alternatives	Availability	DoW principles				
			Off-site construction	Reuse & recycle	Deconstruction & flexibility	Resource optimisation	Resource-efficient procurement
Wall lining	Gypsum Plasterboard	The most widely used interior lining material in NZ.	• Applicable if wall panels/ complete buildings are prefabricated	• Recycled gypsum plasterboard is available; however, only about 10 % of gypsum waste is currently recycled into new boards.	• Unlikely to be considered currently	• Align with standard material sizes. • Horizontal installation to enhance efficiency and minimise waste.	• Custom sizes are available for orders over 100 sheets. • Pallet returns policy

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B.E	Material alternatives	Availability	DoW principles				
			Off-site construction	Reuse & recycle	Deconstruction & flexibility	Resource optimisation	Resource-efficient procurement
						• Offcuts can be recycled into new products or in the agriculture industry.	
	Recycled Waste Board	A low-carbon, innovative material made from recycled waste, but still a small market share.	• Applicable if wall panels/ complete buildings are prefabricated.	• Manufactured from recycled waste, such as used beverage cartons, soft plastics, and coffee cups.	• Unlikely to be considered currently. • Using exposed screws instead of nails/ adhesives can facilitate material separation.	• Align with standard material sizes. • Offcuts can be recycled into new products.	• Pallet returns policy
	EWPs (Plywood, Particle board, Medium-density fibreboard, Oriented strand board)	Driven by NZ's net-zero carbon goals and efficient timber use, but still a small market share.	• Applicable if wall panels/ complete buildings are prefabricated.	• No recycled-content products.	• Unlikely to be considered currently. • Using exposed screws instead of nails/ adhesives can facilitate material separation.	• Align with standard material sizes. • Offcuts are sent to landfills. • Promote the use of certified sustainable timber products.	• Pallet returns policy
	Fibre Cement lining	Commonly used in moisture-prone areas.	• Applicable if wall panels/ complete buildings are prefabricated.	• No recycled-content products.	• Unlikely to be considered currently	• Align with standard material sizes. • Offcuts are sent to landfills.	• Pallet returns policy
	Ceramic tiles	Used as an alternative to fibre cement in wet areas.	• Applicable if wall panels/ complete buildings are prefabricated.	• No recycled-content products.	• Unlikely to be considered currently.	• Offcuts can be used for hardfills.	• Pallet returns policy

Implementation of DoW principles in wall cladding

B.E	Material alternatives	Availability	Applied DoW principles				
			Off-site construction	Reuse & recycle	Deconstruction & flexibility	Resource optimisation	Resource-efficient procurement
Wall Cladding	Preservative-treated timber	The most used in NZ.	• Applicable if wall panels/ complete buildings are prefabricated.	• No recycled-content products.	• Deconstruction at the end of project life is unlikely to be considered. • Weatherboards with exposed screws to facilitate future replacement.	• Align with material dimensions. • Off-cuts in Auckland diverted to biofuel; elsewhere typically landfilled. • Promote the use of certified sustainable timber products.	• Pallet returns policy
	Non-preservative treated timber	Commonly used in NZ.	• Applicable if wall panels/ complete buildings are prefabricated.	• No recycled-content products.	• Same as treated timber cladding.	• Align with material dimensions. • Without pre-coating, can be	• Pallet returns policy

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B.E	Material alternatives	Availability	Applied DoW principles				
			Off-site construction	Reuse & recycle	Deconstruction & flexibility	Resource optimisation	Resource-efficient procurement
						recycled as un-treated timber waste. • Promote the use of certified sustainable timber products.	
	Engineered Wood Products (Plywood)	Commonly used in NZ.	• Applicable if wall panels/ complete buildings are prefabricated.	• No recycled-content products.	• Same as treated timber cladding.	• Align with material dimensions. • EWP offcuts are sent to landfills. • Promote the use of certified sustainable timber products.	• Pallet returns policy
	Fibre cement	Commonly used in NZ.	• Applicable if wall panels/ complete buildings are prefabricated.	• No recycled-content products.	• Same as treated timber cladding.	• Align with material dimensions. • Offcuts are sent to landfills. • Preferable due to long-term durability.	• Pallet returns policy
	uPVC	Less commonly used.	• Applicable if wall panels/ complete buildings are prefabricated.	• High recycledcontent.	• Same as treated timber cladding.	• Align with material dimensions. • Highly recyclable material.	• Pallet returns policy
	Steel sheet	Not preferable for cladding.	• Precut before being delivered to the site.	• High recycled content.	• Easy to disassemble at the end of the project life.	• Align with material dimensions. • Highly recyclable material.	
	Aluminium	Preferred over steel sheets	• Applicable if wall panels/ complete buildings are prefabricated.	• High recycled content.	• Same as treated timber cladding.	• Align with material dimensions. • Highly recyclable material. • Preferable due to long-term durability.	• Pallet returns policy
	Brick veneer	The second most used in NZ, but its market share is declining.	• Not applicable	• No recycled-content products.	• Long-term durability	• Offcuts can be used for hardfills. • Preferable due to long-term durability.	• Packaging is required. • Pallet returns policy
	Plaster	Commonly used in NZ.	Not applicable	No recycled-content products.	Not applicable	Not applicable	• Pallet returns policy

Data availability

The authors do not have permission to share data.

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