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New circularity indicator for decision making in the stockpile management of construction and demolition waste: Perspectives of Australian practitioners

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ABSTRACT

Despite the increasing popularity of the circular economy, there remains a lack of consensus on how to quantify circularity, a critical aspect of the practical implementation of this model. To address this gap, this article examines the industry's perspective and efforts toward implementing the circular economy in real-world scenarios. We conducted 40 interviews with engineers, project leaders, and top-level managers in the Australian construction sector. Using Saldaña's coding approach, we analysed their views on circular economy practices and efforts within their organisations. Our findings reveal while waste minimisation, reduction of greenhouse gas emissions, and cost considerations are widely regarded as essential indicators of a successful circular economy model, the significance of waste storage and long-term stockpiling while awaiting treatment has been overlooked or under-emphasised in industry practices and academic literature. Stockpiling of waste has often been seen as a staging process in waste treatment. However, based on industry insights, it accumulates to the point of mismanagement when it becomes a safety and environmental concern. Addressing this oversight, we propose a storage circularity indicator that allows incorporating waste storage and stockpiling in circular economy models. Our research contributes to various environmental and waste management aspects, supporting policies and strategies for solid waste management and excessive stockpile prevention. By emphasising the significance of storage circularity, we clarify waste prevention techniques and address socio-economic issues such as the urgent need to reduce long-term stockpiling of solid waste. This work highlights the importance of decision-support tools in waste management to facilitate the implementation of circular economy principles. Our proposed storage circularity indicator promotes industrial collaboration, aligning with the concept of industrial symbiosis to optimise resource use and minimise waste generation. By discussing these topics, we aim to contribute to the advancement of more robust waste management strategies and policies that promote sustainable production and consumption practices.

1. Introduction

There are numerous definitions of the term "circular economy", but it is referred to as "a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible" European Parliament (2015). Although this concept has been recently used in both research and industry, there is still uncertainty about how "circular economy" is defined and how organisations can apply it.

This work endeavours to address this gap by delving into the industry's perspective and efforts towards implementing the circular economy, particularly within the realm of waste management. Focusing on the Australian context, where the circular economy agenda has acquired traction, the research aims to shed light on stakeholders' understanding of circular economy metrics and their practical implications for managing construction and demolition (C&D) waste. This focus is crucial given the significant contribution of C&D waste to the overall waste stream, representing 44% of total waste materials (27 Mt) in the state of Victoria alone (DELWP, 2020).

Establishing a robust framework for a circular economy necessitates cohesive efforts, impacting all sectors and policy realms (Kurniawan et al., 2022). Within this framework, the research seeks to explore how

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circular economy principles can effectively reduce waste generation and optimise resource utilisation. This involves examining the adoption of strategies such as waste minimisation, recycling, and reuse, as well as integrating circular design principles into different processes. By engaging building contractors, consulting agencies, and local governments, this work aims to capture diverse perspectives and experiences related to circular economy practices in the Australian context.

The research aligns with broader policy objectives outlined by the state of Victoria, which has articulated strategic goals for transitioning to a circular economy to enhance environmental sustainability and economic resilience (DELWP, 2020). By identifying barriers, opportunities, and best practices in circular economy implementation, the work seeks to inform policy development and industry practices, contributing to the advancement of sustainable waste management strategies and policies at both local and national levels. To the authors' knowledge, no similar research has been conducted on the Australian environment in previous studies.

The structure of the article reflects a systematic approach to investigating circular economy practices and their implications for environmental management. Section 2 summarises the insights from the literature review on the circular economy definition, widely used frameworks and metrics, providing a theoretical foundation for the subsequent empirical analysis. Section 3 explains the research methods adopted to gather and analyse data, including the conduct of interviews with key stakeholders and the application of coding techniques to extract themes and insights from qualitative data. Section 4 presents the research findings, highlighting key themes and patterns emerging from stakeholder perspectives on circular economy practices in the C&D waste sector. Drawing on these findings, Section 5 discusses the results, challenges, opportunities, and strategic considerations for advancing circular economy goals in solid waste management. It also identifies research limitations and sets the path for further research. Lastly, Section 6 draws conclusions based on the findings.

2. Circular economy, circular economy frameworks and metrics

Before analysing circular economy metrics and models, it is imperative to clearly understand the concept's adopted definition. Currently, more than one hundred different definitions of circular economy exist in the literature (Kirchherr et al., 2017). These definitions vary from very simple to very complex and focus on different aspects of the concept. Debates persist over whether circular economy should be viewed primary as an economic system (Kirchherr et al., 2017), an industrial system (Ellen MacArthur Foundation, 2013; Ghisellini et al., 2016), or as a strategy focused on the minimisation of waste inputs (Geissdoerfer et al., 2017). This diversity of definition leads to significant confusion not only among the general public but also within the academic community. Thus, this research will adopt "the ultimate definition of circular economy" proposed by Nobre and Tavares (2021) to provide a consistent framework for analysis.

Despite the clarity that this definition aims to provide, there is a critique that circular economy is a rather theoretical concept and is difficult to implement. In response to these challenges, numerous circular economy frameworks and methods have been developed to make the concept more applicable and actionable. The most common framework has been developed by the Ellen MacArthur Foundation, 2019, which introduces the material circularity indicator based on the material flow analysis. Another popular framework is that of life cycle assessment (Rebitzer et al., 2004), which focuses on the environmental impacts of human activities.

There has been considerable research on the application of circularity assessments at different levels. At the material level, Ghosh et al. (2023) explore the optimisation of resource usage in manufacturing, while Huang et al. (2022) focus on the impacts of material choices on sustainability in construction. Mouga and Fernandes (2022) investigate the reusability of construction materials, and Ribul (2021) assesses material recovery processes in electronic waste management.

In the product dimension, Okumura (2022) examines product lifecycle extension strategies, Shevchenko et al. (2022) analyse the durability and repairability of consumer electronics, and Vimal et al. (2021a) investigate product redesign for enhanced circularity. At the organisation level, Droege et al. (2021) discuss organisational strategies for circular economy adoption, Franco et al. (2021) explore corporate sustainability reporting on circular practices, while Gupta et al. (2021) and Vimal et al. (2021b) focus on the integration of circular economy principles into business models.

At the national level, Ahmed et al. (2022) review policies promoting circular economy in developing countries, Galarcio-Noguera et al. (2021) assess national frameworks for waste management, Lara-Topete et al. (2022) consider the economic impacts of circular economy practices, and Scheel et al. (2020) evaluate national performance metrics for circularity.

Despite this broad scope, practical circularity assessments remain limited in the body of literature, often focusing on specific sectors and levels of analysis. For instance, Adabre et al. (2023) analysed the circular economy transition at the construction project level, but no model or framework was proposed in that study. Medina and Fu (2021) developed a new framework, but focused explicitly on construction projects. Abadi et al. (2021) developed a project circularity framework that was solely based on a literature review, which was followed up by model development with only 12 metrics (Abadi and Moore, 2022). Last, Többen and Opdenakker (2022) focused on initiating and defining project stages. Therefore, there is a gap in the assessment of the success of the circularity, particularly in the construction sector.

Regarding the framework and model elements, one of the most recent and highly cited reviews on the topic has been developed by Corona et al. (2019), who have mapped the circularity indices, circular economy assessment frameworks, and indicators. They suggested that the new circular economy assessment frameworks should be based on the widely used sustainability frameworks, such as the material flow analysis (MFA) and life cycle assessment (LCA). Also, Saidani et al. (2019) developed a taxonomy of circularity indicators at micro, meso, and macro scales, providing a structured approach to understanding and applying these metrics. However, the application of circular economy models in industry remains fragmented, with different sectors exhibiting unique challenges and requirements.

Del-Aguila-Arcentales et al. (2022) provided a list of circular economy indicators, including those proposed by the Organisation for Economic Co-operation and Development (OECD). Increasingly more complex reviews included up to 365 metrics at a micro level (Vinante et al., 2021), and new indicators and metrics are still appearing in the body of literature (Hatzfeld et al., 2022; Ibáñez- Forés et al., 2022). New research articles on the circular economy are getting published and becoming frequently available in scientific databases. However, there is still no uniform agreement on what models are feasible to be applied and what indicators and metrics can be measured.

Esbensen and Velis (2016) highlight the need of reducing variability in waste-derived materials to enhance their market value, featuring the critical role of advanced sorting, disassembling, and shredding operations in achieving material value recovery. Elia et al. (2017) critically analyse existing index methods for measuring circular economy strategies, identifying significant gaps, especially at the micro level, and proposing a systematic approach to selecting a suitable methodology that could improve the accuracy and applicability of circularity assessments.

Moraga et al. (2019) discuss the need for specific, coherent indicators to measure circular economy progress and introduce a novel framework for classifying indicators by common circular economy strategies. This approach could significantly enhance the specificity and effectiveness of metrics in construction sector assessments. Di Vaio et al. (2023) explore the integration of circular economy principles within accounting models, emphasising the crucial role of digital technologies in tracking and managing waste resources. This insight advocates for the development of more robust and transparent frameworks for reporting circularity metrics. Agovino et al. (2024) assess the impact of European Union's waste management regulations on circular economy objectives, highlighting the influence of policy in industry practices and emphasising the need for effective regulatory frameworks in the construction sector.

These enriched insights and established frameworks provide a comprehensive foundation for advancing the understanding of circular economy metrics in the construction industry. However, recent studies either focused on the theoretical analysis of the research articles or industry reports, such as with 24 (Grobler et al., 2022) reports (van Bueren et al., 2022) going beyond this number, peer reviewed text(Kirchherr et al., 2017) and surveys with expert researchers (Nobre and Tavares, 2021). While relevant insights on circular economy have been reported based on academic expert elicitation, participative approaches, including industry representatives, are seldom addressed in the literature. Therefore, this article aims to close this knowledge gap by interviewing Australia's construction sector representatives to acquire insights from those directly involved in implementing circular economy projects in their organisations. This research will provide a significant opportunity to enhance practical application and advance the understanding of circular models and metrics that are useful and relevant to organisations in the construction sector.

3. Method

3.1. Data collection

To achieve the aim of this work, data were collected using semi-structured interviews with the industry participants and representatives from the local government. Given the qualitative nature of the work, determining the sample size relied on established precedents from relevant literature rather than power analyses. Previous studies addressing similar topics reported sample sizes ranging from 12 to 47 interviews. For example, Kanters (2020) interviewed 12 architects and consultants from 4 different European countries. Cruz Rios et al. (2021) interviewed 13 architects from 12 organisations. Similarly, Densley Tingley et al., (2017) interviewed 13 architects, fabricators, structural engineers, and contractors. The largest number of interviews conducted on the topic was 47 expert interviews by Kirchherr et al. (2018) with only a third of them (14 respondents) in the "business" category, 15 scholars and 15 representatives of the government. Therefore, a sample size of 40 interviews was considered being sufficient to achieve data saturation and feasible to be conducted within the time and resource constraints. This research received human research ethics approval (Reference Number, 2022-24518-30205-3) and was conducted in strict accordance with good research practice.

Participants in this work represent the adult population currently living in Australia, encompassing various work categories, level of work experience and genders. Efforts were made to recruit representatives from small, medium, and large businesses, as well as governmental agencies and local councils, particularly those with relevance to the construction sector and building materials. The recruitment process was conducted via email and LinkedIn, with invitations sent along with consent forms and plain language statements. The plain language statement can be found in the Supplementary Materials section. The contact details of the representatives of governmental agencies and local councils were obtained from their official websites. Snowball sampling was used to expand participant recruitment (Etikan et al., 2016).

Forty participants were recruited through email and LinkedIn outreach. Each participant engaged in a semi-structured interview lasting approximately 30–60 min. The interviews were conducted online and in-person and were audio-recorded for transcription. All responses were de-identified and assigned unique codes for subsequent analysis following transcription.

Table 1 presents an overview of the semi-structured interview guide, divided into two blocks. The first block centred on collecting demographic information from the interview participants, facilitating subsequent data analysis. Meanwhile, the second block encompassed questions designed to elicit participants' insights into addressing the research question (RQ) outlined for this work. For a comprehensive understanding of each question, please refer to the detailed interview protocol in the Supplementary Materials section.

3.2. Data analysis

Qualitative data analysis was conducted to achieve the aim of the research. The analysis included systematic coding of the text data (transcribed interviews) and identification of the recurring themes and patterns in the qualitative data analysis computer software package NVivo. The text data was coded manually using Saldaña's multi-step approach (Saldaña, 2013). In the first step, the exploratory coding was conducted to identify the key concepts in relation to the circular economy and its potential metrics (including subcodes as required). In the second step, focused coding was conducted to identify the circular economy concepts and metrics of circularity. Similar concepts were merged, and the codes were grouped based into categories based on the emergent themes to form a hierarchy (including subcategories as required). In the third step, the categories were further segregated based on the respondent's sentiment (positive or negative) into high-level categories. Last, the categories were combined into themes. The summary of the adopted approach is shown in Fig. 1.

4. Findings

Table 2 presents a summary of the key themes identified in the discussion of how circular economy could be measured in organisations and their explanation. Most respondents emphasised the fact that the metrics vary from project to project. Still, the most common metrics would include the amount of waste generated and used, energy consumption, the amount of recycled materials used, greenhouse gas (GHG) emissions, transport, and storage requirements. Fig. 2 demonstrates a summary of the findings related to the economic elements for circular economy models. Fig. 3 presents the summary of the respondents' opinions on the GHG emissions as a metric for circularity.

Out of all the interviews with the representatives of organisations performing construction and infrastructure works, 50% identified storage and stockpiling of waste as one of the essential metrics to be included in future models for the circular economy (Fig. 4). This figure excludes twelve respondents from organisations providing solely consulting services because this topic would not apply to them as the only waste generated in their operations is the standard waste generated in offices (such as used paper, food waste from employees' lunches or electronic waste due to obsolete electronic devices).

Out of the remaining 50%. 21.4% of the respondents could not tell us if there is any problem with waste storage or stockpiling because of their position in the organisation. These respondents had limited knowledge because they only focused on certain types of projects. It included junior engineers who had recently started their careers within the organisation or specialist professionals (e.g., electrical engineers) who were not

Table 1
Interview guide.

Demographic questions	
Question 1	What business sector best represents your organisation?
Question 2	What services or products is your organisation providing?
Question 3	What state or territory is your organisation registered in?
Question 4	What is your position in the organisation?
Circular economy indicators and metrics (RQ)	
Question 5	What metrics apply to the business processes in your organisation?
Question 6	What metrics do you currently measure in your organisation?

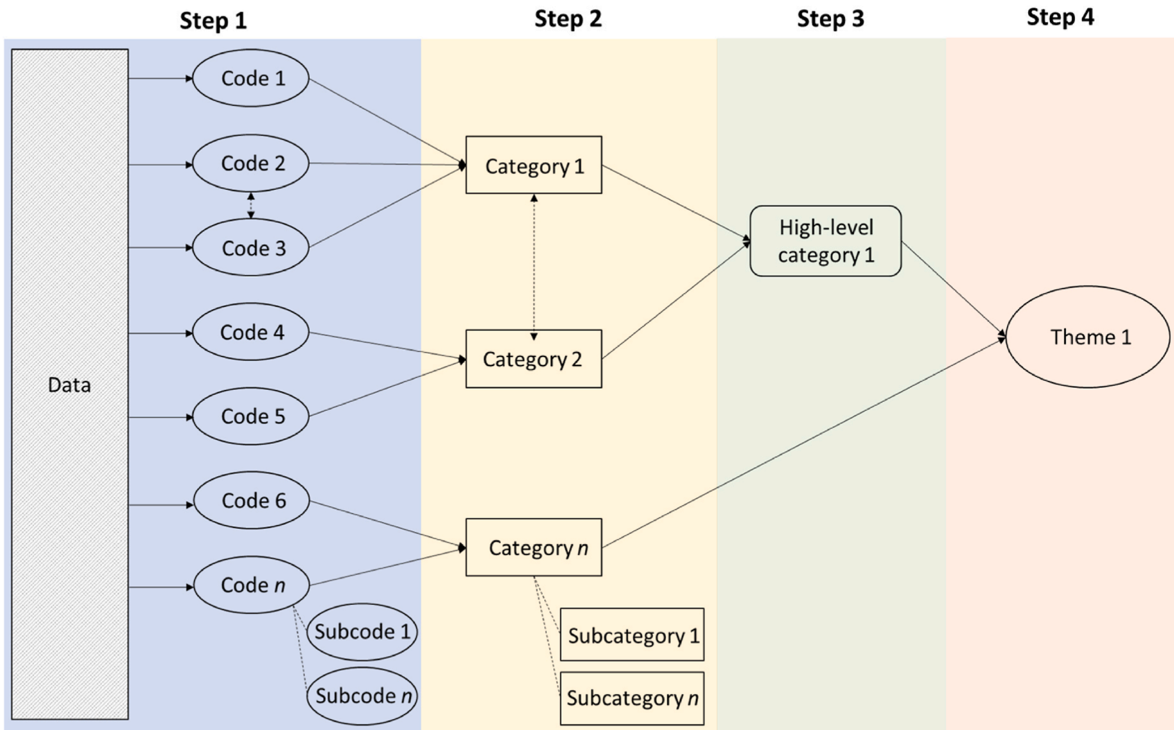

Fig. 1. A summary of the data analysis approach. Adopted from (Saldaña, 2013).

directly involved in the activities requiring a lot of waste.

Among the 28.6% of respondents who did not see waste storage as a problem, 10.7% of the participants mentioned that they have a contractor to pick waste up from their sites, making it a problem for a waste contractor. 17.9% of the interviewees claimed there is no problem with waste storage as the organisation has plenty of space.

5. Discussion

5.1. Emissions, cost, quality

Based on the response data, the vast majority (70%) of the industry representatives, notably those directly performing C&D works (100% of such respondents), are concerned about the environmental impacts of their organisations' activities, particularly carbon dioxide (CO_2) emissions. The decarbonisation of various sectors, including infrastructure and construction, has become a focal point in discussions among businesses and governments. Therefore, this area received numerous responses and is more familiar to industry professionals. For example, more than half of the interview respondents (55%) mentioned that emissions are being estimated in their organisation, and 40% of the participants confirmed that they have specific emissions reduction targets set to be achieved in the next 10–30 years. As one informant reported:

> *"One of our goals, from a sustainability policy, is to reduce supply chain emissions, to reduce our emissions by 50% by 2030 and to achieve net zero by 2040."*

The findings of this work point to a general lack of emphasis on GHG emissions related to recycled materials. While 40% of the respondents reported they had strategic goals and targets for reducing GHG emissions, only 15% related them to using recycled materials. This finding has important implications for developing a more realistic circular economy model. The lack of evidence in this area suggests that further emphasis can be put on GHG emissions related to reprocessing waste materials to bring them back to use and close the loop. However, it is essential to analyse how much GHG emissions are released during the process of bringing a material back to use, suggesting a critical area for future research. It is also critical to recognise that recycling is often preceded by other processes, such as separation, which itself carries emissions costs. Not all separated waste can be recycled, a point stressed by recent studies highlighting the complexities and inefficiencies in the separation processes that precede recycling (Pluskal et al., 2021).

It is currently a common approach to compare the environmental effects of reuse, recycling, and re-manufacturing against the impact of sending waste to landfills to justify how projects meet ecological requirements and targets. However, it is still unclear whether waste reprocessing is more harmful to the environment than landfilling. Therefore, it is essential to analyse and compare the long-term environmental impacts of using virgin materials and products against the recycling or re-manufacturing waste materials and products. Based on our data, 85% of the respondents do not consider emissions related to recycling in their processes. It implies a common perception that recycling is more environmentally friendly than landfilling. However, some recycling processes are so complex that more energy is currently spent on them, emitting more than the emissions related to landfills. For example, refrigerator recycling releases large volumes of trichlorofluoromethane (CFC-11), a greenhouse gas associated with the depletion of the ozone layer (Xiao et al., 2016). This complexity challenges the common perception that recycling is always more environmentally friendly than landfilling.

In summary, recycling is undeniably successful in decreasing the amount of waste disposed of at landfills. However, more research must be conducted to reveal the overall environmental impact of recycling and re-manufacturing.

Another notable aspect relates to economic factors. The overwhelming majority of the interviewed industry representatives (87.5%) emphasised the significance of economic considerations within circular economy models. Commenting on implementing circular economy in the organisation, one interviewee stated:

> *"Additional cost, additional effort, additional resources"*

Table 2
Summary of the analysis of interview data: Circular economy metrics.

Themes	Sub-categories	Representative quotes	Explanation
Waste	Waste recycled, waste reused, waste generated, waste diverted from landfill, waste minimisation, waste hierarchy, zero-waste strategy, contaminated waste	"Limit the number of materials going to landfill", "We look at how we reduce waste", "There needs to be recycling as part of any waste generated on a construction site".	This theme encompasses various aspects of waste management, including recycling, reuse, diversion from landfills, zero-waste strategies, and management of contaminated waste, which form the core of the circular economy concept.
Materials	Use of recycled materials, local materials, materials with lower embodied carbon, 9R framework	"How much material did we retain by keeping an asset so that can be measured in cubic meters or tonnage. How much material did we not generate at all can be measured in tonnage." "We also consider how to use recycled materials on other projects."	Focusing on material usage, this theme emphasises the utilisation of recycled and locally sourced materials, as well as those with lower embodied carbon, within project frameworks.
Energy	Energy consumption, clean energy use, renewable energy use, energy efficiency, limited control over the electricity mix	"We are looking at options for green power, we are going through what is most efficient", "We don't actually get a lot of say in the office building over what they do"	Energy considerations encompass energy consumption, the utilisation of clean and renewable sources, and efforts to enhance energy efficiency, both in office spaces and on-site operations.
Greenhouse gas emissions	Emission targets, emissions related to recycled materials, emissions related to transportation, embodied carbon, net zero, decarbonisation	"We are using the net zero, embodied carbon, and net zero operational carbon", "We have a decarbonisation plan with targets."	Focused on reducing greenhouse gas emissions, this theme centres on the adoption of net zero and decarbonisation plans, concepts widely grasped by industry representatives.
Transport	Transport for projects, transport use by employees, fuel consumption, work from home, minimise driving, transport optimisation, minimising travel, local vs interstate/ international	"There's a policy to actively encourage people to use active transport or active modes of transport", "Optimise the travel routes to make sure that we are not driving too much"	Transport considerations involve two main perspectives: employee commuting and transportation needs for projects, each requiring distinct approaches.
Labour	Local employment, local labour priority, social procurement policies, labour shortages, job creation, man hours	"At the moment, also, it's hard to get labour. Yes, there's a shortage.", "Supporting local jobs where we can."	Labour-related factors highlight the social aspect of the circular economy, intertwined with economic (labour-related costs) and environmental considerations (labour-related emissions).
Storage	Waste storage, storage of materials, stockpiling of waste, a bottleneck, limited space	"We try to stockpile for a short amount of time, and then get off site as quickly as possible just to eliminate risk."	This theme focuses on the storage of waste and materials, including stockpiling practices and challenges related to limited storage space. It emphasises the importance of minimising stockpiling duration to reduce risks associated with storage.
Economic considerations	Cost of products, material cost, labour cost, profit, quality vs cost	"Our main driver is profitability. So basically the economic and the economics only.", "We are looking at things like cost, efficiency"	Economic factors are also examined from two perspectives: the costs of implementing circular strategies and the profits gained from their execution.

In terms of costs, organisations are concerned about the implications of using recycled materials if preferred over virgin materials (mentioned by 35% of the respondents). For example, one interviewee said:

"Obviously, it's not cheaper in terms of sustainability."

As recycling involves additional processing and treatment of materials to maintain the required quality, the cost of these materials usually includes a premium. Since the price of "sustainable" materials and products is generally higher than that of new materials, only environmentally conscious organisations are seriously considering using those materials. For other organisations, unless specifically requested by the client, there was no benefit of using recycled materials, according to the interviewees.

There were significant concerns about the quality of recycled materials (22.5% of the respondents). As one interviewee remarked:

"One of the challenges will be the quality."

Ensuring the end product's high quality in the construction sector is essential. It is crucial to ensure that the infrastructure is safe to use over the operational life. Since many of the recycled materials are still relatively new to the market, there is a lot of uncertainty over how durable they are and if they can provide at least the same quality characteristics as the non-recycled materials, particularly physical and mechanical properties. Various organisations are currently combining recycled and virgin materials to solve this issue. It is common in asphalt (Abe et al., 2023), concrete (Maalouf et al., 2018) and façade applications (De Masi et al., 2021). Both downcycling and upcycling are possible within the construction sector (Pilipenets et al., 2022). However, due to the high risk to public safety, downcycling is usually a preferred option (Monsù Scolaro and De Medici, 2021).

Based on these findings, it can be concluded that economic considerations are an essential part of a successful circular economy model, particularly for businesses. As a "business" is usually referred to as an activity to make a profit (HarperCollins, 2023) and as gross profit is usually measured as the difference between revenues and costs (Chan, (n.d.)), it is crucial to include cost as an element of a successful circular economy model.

5.2. A novel circular economy metric: waste storage and stockpiling

An important consideration raised during the interview process was the inclusion of waste storage requirements as part of circular economy models. As shown in Figs. 4 and 50% of the interview participants consider waste storage and stockpiling a problem and a bottleneck in their operations. As one interviewee put it:

"It's very important because the storage is one of the keys for sustainability."

Storage could be defined as a temporary holding of materials, and waste storage is the holding of waste until it gets treated, disposed of or stored in a different place (Muralikrishna and Manickam, 2017). As half of our interviewees mentioned waste storage when responding to the interview questions, the authors find it essential to discuss the most common challenges related to storage in the construction sector and strategies and solutions that could mitigate them.

5.2.1. Challenges

Based on the data, it can be deduced that waste storage and

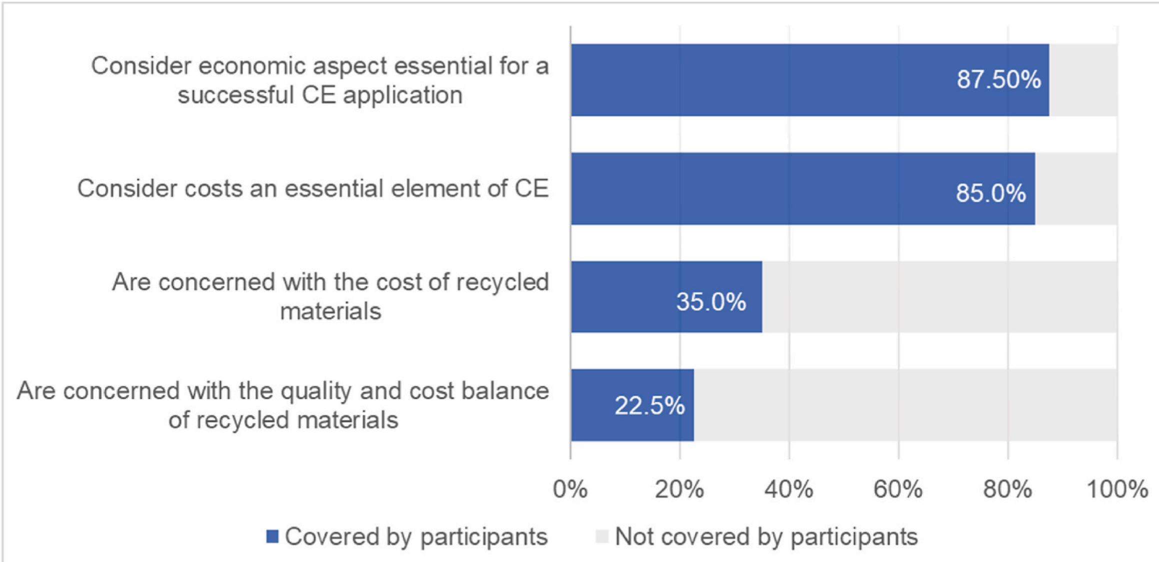

Fig. 2. Economic concerns of the interview participants related to the circular economy based on the percentage of mentions among the respondents.

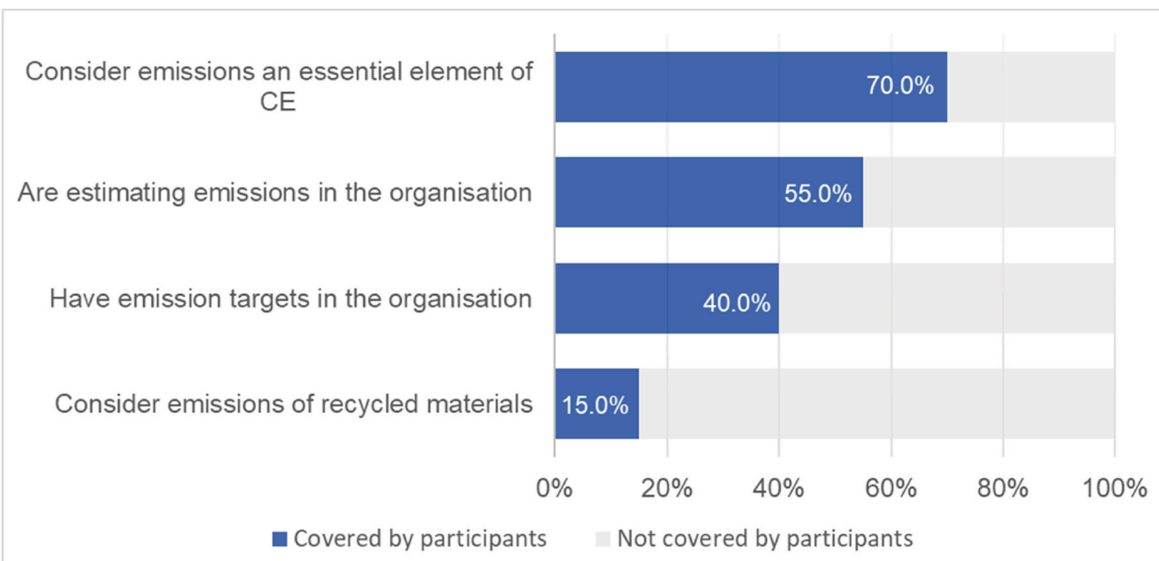

Fig. 3. Interview responses for GHG emissions as part of the circularity based on the percentage of mentions among the respondents.

stockpiling are of particular interest to C&D companies as they handle large volumes of waste developed in their operations daily. This could be a huge problem because of several reasons. First, large amounts of waste collected at a site could be a severe bottleneck in the process of waste reuse and recycling (Singh et al., 2022). Even when an organisation has a contract with a waste contractor, there could still be limits on how much waste can be removed from a site per day (Hyder Consulting, 2011). Second, some of the waste might be contaminated, posing a significant risk to human health and safety, particularly to organisations' employees (EPA South Australia, 2022).

It is essential to distinguish between primary waste and stored waste, as they are usually treated differently within waste management systems. While primary waste is typically treated or disposed of immediately after being generated, stored waste (also referred as storage waste) involves the temporary emplacement of waste materials with the intention of processing them at a later time (OECD, 2024). Storage in the context of waste management is essential for several reasons. For instance, storage of nuclear waste facilitates volume reduction to minimise shipping and disposal costs, as well as immobilisation to allow for the decay of radioactivity, reducing potential environmental contamination (International Atomic Energy Agency, 2008). In addition, as per (DEE, 2018), stored waste often contains high concentrations of recyclable materials compared to the primary municipal waste. For instance, electronics and vehicles are often stored prior to getting processed for recovery of useful materials (EPA Victoria, 2020; US EPA, 2017).

In the Australian context, stored waste has shown an increasing trend, in particular waste tyres and post-consumer plastic (DCCEEW, 2022). While specific data on the proportion of stored waste is not readily available, this trend emphasises the need for focused attention on storage practices.

Our analysis highlights several concerns related to waste storage in line with this trend. Firstly, there are technical constraints when appropriate waste processing technologies have not been yet perfected or even developed (Ragauskas et al., 2021). Even when such technologies are available, limited processing may lead to waste storage for

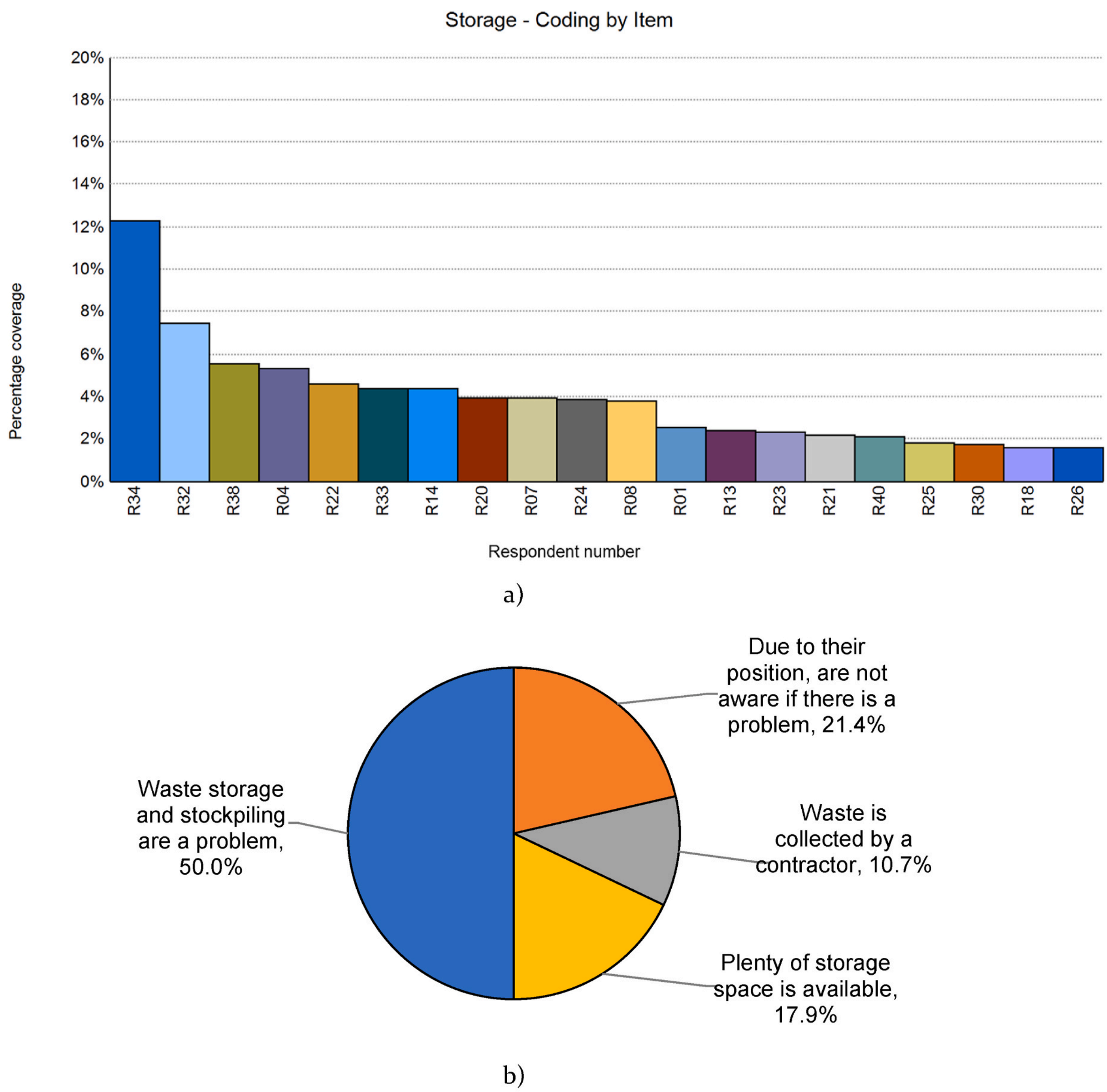

Fig. 4. Interview responses for storage as a new circularity metric: a) percentage coverage for a waste "storage" mentions vs respondent number, b) detailed breakdown of the key subcategories identified within the storage theme.

extended periods of time. Secondly, economic constraints play a significant role in the efficiency of waste storage. For instance, recycling e-waste requires specialised technology to extract valuable materials (e.g. gold, silver, and copper) safely and efficiently (Lisbona and Snee, 2011). The high upfront investment cost and maintaining such technology represent a significant economic challenge for small enterprises or municipalities and can limit their capacity to process e-waste efficiently.

In addition, prolonged storage of waste in warehouses may indicate issues and inefficiencies in waste management systems (Saldivar, 2023). In such cases, waste warehouses may serve to temporarily conceal the accumulation of unprocessed waste, suggesting potential operation delays and ineffective use of space, highlighting the need for improved management practices in waste processing.

5.2.1.1. Environmental concerns. Recent events related to stockpiling of waste have shown this to be a problem in Australia, especially when storing waste tyres (Big Rigs, 2023; NSW EPA, 2023), end-of-life electrical goods (Meiklem, 2023), and post-consumer soft plastic waste (Morton, 2023). Contaminated waste is difficult to process, and handling such waste has special requirements from the environmental protection authorities (Krishnaswamy et al., 2020). For example, when left on site, contaminated soil may leak into the ground and contaminate groundwater, posing a problem for public health and safety.

Another common issue related to storage is the risk of waste catching a fire (Taylor, 2023; Vedelago, 2023). This would not only adversely affect the air quality but also be dangerous for the employees and nearby residents. There are certain limits on stockpiling volumes and sizes to reduce the risk of these issues. For instance, in the Australian Capital Territory, the storage of end-of-life tyres should be under 25 tonnes per site at a time. In contrast, in Victoria, the size of an outdoor tyre waste pile should not exceed 20m × 6m x 3m (L x W x H) (Randell and Latimer, 2018). It is also important to note that incorrect waste stockpiling can not only cause problems to the people and environment but also bring financial consequences for the organisation itself as certain fines are in place for failing to comply with the requirements (State Government of Victoria, 2019). There have still been instances of inappropriate waste handling of combustible waste (EPA Victoria, 2021b) and excessive stockpiles (McKnight, 2023) that necessitates further improvement in the waste management field.

5.2.1.2. Socio-economic issues. The presence of waste storage facilities and stockpiles can impact land use patterns and property values in surrounding areas. Depending on the scale and management practices, they may significantly influence nearby property values and land use decisions, potentially exacerbating socio-economic disparities. For example, there is a growing opposition to locating landfills in urban areas due to their perceived negative impacts. Research has demonstrated that the presence of a nearby landfill can lead to a decrease in property values, ranging from an average of 2.7% for smaller landfills to as much as 13.7% for larger ones (Ready, 2010). According to Abhyankar et al. (2023), this negative effect persists unless properties are at a distance of over 10 km from the landfill site. Similarly, waste stockpiles at construction or warehouse sites can diminish the appeal of neighbouring properties over time, affecting nearby communities in the long term. The location of waste storage facilities and stockpiles can disproportionately impact marginalised communities, leading to environmental justice concerns. Low-income or minority communities may bear a disproportionate burden of waste storage and its associated environmental and health risks.

Living in proximity to waste treatment facilities can often lead to various health concerns, including eye irritation, respiratory issues, and discomfort due to unpleasant odours (Aatamila et al., 2011). While waste stockpiling may not entail chemical treatment processes, certain types of waste can still release harmful chemicals into the surrounding environment, contaminating the air, soil, and water sources, leading to similar outcomes for the residents. Thus, it is imperative to minimise the existence of waste storage facilities and stockpiles to maintain socio-economic balance and bring long-term benefits to the community.

5.3. Implications for environmental management

5.3.1. Waste storage and waste valorisation

The concept of valorisation in waste management refers to the process of extracting value or utility from waste materials (Tejaswini et al., 2022). While waste storage itself may not directly contribute to valorisation, it plays a crucial role in facilitating subsequent valorisation processes. Effective waste storage ensures that materials are preserved in a suitable condition for potential future valorisation activities, such as recycling, repurposing, or energy recovery. For example, proper storage techniques can prevent contamination or degradation of recyclable materials, ensuring they retain their value and can be effectively processed into new products or materials.

It is imperative to consider the costs associated with waste storage. While stockpiling serves a logistical purpose, it is typically considered a non-value-adding step. Essentially, waste storage is more about addressing logistical needs and convenience rather than adding tangible value to the materials themselves (Kurniawan et al., 2023). Regardless of the storage method employed, the waste's inherent value remains unchanged. The primary aim of waste management is to handle and process materials efficiently to minimise environmental impact and resource loss rather than enhance the value of the final products. Therefore, it is essential for organisations to evaluate the costs and benefits of different storage methods to ensure optimal resource allocation and sustainable waste management practices. Considering the costs associated with waste storage is essential for assessing valorisation initiatives' overall feasibility and profitability. By understanding the financial implications of storage, organisations can make informed decisions about which valorisation pathways to pursue and how to optimise their waste management strategies to maximise returns on investment.

5.3.2. Prevention of waste stockpiling and optimisation of waste storage

There are different strategies to control and reduce storage and stockpiling. According to the waste hierarchy, avoiding and reducing waste is the first option to consider. In organisations providing consulting services, waste does not pose a significant problem due to the nature of the work provided. In contrast, in organisations involved with C&D, storage and stockpiling of waste pose a very significant problem.

The first strategy is '*designing out waste*'. It has been a popular concept in recent years. However, based on our interview findings, various organisations still struggle with its implementation. The main reasons are lack of understanding and lack of motivation by the employees involved in the design. This problem lies in the gaps in the education of young engineers. In the past, universities did not include core subjects related to sustainability or circular economy as part of the curriculum for science students. Most subjects would focus on basic technical skills essential for future engineers. Universities have gradually included sustainability concepts and SDGs in engineering education (Leifler and Dahlin, 2020). For example, the University of Melbourne has developed a framework for embedding sustainability knowledge in the curriculum to ensure a new generation of students become "leaders for a sustainable future" (Arkoudis et al., 2018). Therefore, sustainability-aware engineers have joined the labour market. However, it will still take time before professionals with a solid sustainability awareness dominate the Australian labour force. Therefore, two recommendations can be formed. First, all engineering-related university programs should have sustainable and circularity concepts introduced as early as the first year of the undergraduate degree and reinforced throughout the rest of the course. Second, the current labour force should undergo additional training and upskilling on sustainability and circular economy and their practical implementation. Incorporating circular design principles into engineering education ensures that future engineers can develop systems where resource recovery processes are meticulously planned to minimise energy input requirements (Kisser et al., 2020). This approach fosters sustainable engineering practices and prepares students to design innovative solutions that prioritise resource efficiency and environmental stewardship from the outset.

Another vital strategy involves '*optimising stockpiling volumes*', recognising that stockpiling is primarily a temporary stage in waste treatment processes. Therefore, efforts should be made to minimise it whenever feasible. This could be implemented by streamlining the work with waste management contractors and limiting the storage space on site. Limiting the available storage space on-site can help prevent excessive accumulation of waste, encouraging timely disposal or processing of materials. There are currently policies in place to prevent excessive stockpiling and optimise solid waste management techniques. However, there is a need for continuous monitoring and enforcement to ensure adherence to these policies. Fostering greater awareness among stakeholders about the environmental and socio-economic impacts of excessive stockpiling is essential for encouraging proactive measures and promoting responsible waste management practices. Ultimately, addressing this issue requires a multifaceted approach involving regulatory measures, stakeholder engagement, and public education initiatives.

Another approach is fostering '*industrial symbiosis*', a collaborative approach where different industries or organisations exchange waste materials, by-products, and resources to minimise waste generation and maximise resource efficiency (Dou et al., 2021). Efficient storage practices are essential for ensuring the availability and accessibility of these materials when needed by other participants in the symbiotic network. For instance, if a manufacturing plant generates surplus raw materials or by-products not currently required in its operations, rather than discarding them, the facility can store them appropriately for potential utilisation by neighbouring industries. Proper storage preserves the quality and usability of these materials, facilitating their future application within the industrial symbiosis network.

Coordinated storage practices enable the efficient exchange and distribution of materials among symbiotic partners. For example, a waste-to-energy facility may require a consistent supply of organic waste materials from agricultural producers or food processing industries. By establishing storage agreements and logistics networks, these partners can ensure the timely delivery of waste materials to the facility, optimising its operations and maximising energy production.

Overall, effective storage management is integral to the success of industrial symbiosis initiatives, as it ensures the availability, quality, and accessibility of waste materials and by-products for resource exchange and utilisation among participating industries and organisations.

5.4. Waste storage as part of circular economy models and calculations

Our significant finding highlights a notable oversight in existing circular economy (CE) models, as they have largely neglected the impact of storage, particularly the mismanagement of stockpiling. Failure to fully account for the effects of storage on the circularity of materials can pose substantial risks to the success of implementing circular economy strategies. Bottlenecks in downstream processing of waste or unexpected increases in demand may exacerbate issues in storage management, potentially undermining the efficiency and sustainability of circular practices.

Considering these challenges, it is imperative that stockpiling considerations be integrated into circular economy models to ensure their comprehensiveness and effectiveness. Decision-support tools in waste management play a crucial role offering analytical frameworks and methodologies to assess and optimise storage practices. These tools provide valuable insights into the optimal allocation of resources, risk management strategies, and contingency planning, enhancing the resilience of circular systems. The subsequent sub-sections outline solutions for integrating waste storage and stockpiling into decision-support tools and circular economy models.

Waste storage and stockpiling have not yet been included in any circularity assessments. The available techniques to measure waste storage and stockpiling are limited to governmental guidelines, online calculators such as the one by Sustainability Victoria, (n.d.), and a few research articles (Llatas, 2011). Most of the waste storage calculations are created for the assessment of household waste generation and dwelling potential to store waste, which leads to a decision on what size bins should be used on a property. In some council areas, for example, the City of Melbourne, waste compactors are used to ensure that the amount of waste generated and collected does not exceed the maximum storage capacity. This is useful for locations such as high-rise residential buildings with numerous tenants and large volumes of waste consolidated in one place. However, waste storage and waste compactor use are highly correlated with the waste collection frequency. When waste generation is estimated to be high, the waste collection frequency is increased to avoid excessive amounts of waste being left uncollected in the building.

In commercial developments, waste and waste storage calculations are usually the developer's responsibility, with average waste generation rates estimated by the local government. For example, a convenience store is estimated to generate 300L/100 m^2 of floor area/d in garbage and 150L/100 m^2 of floor area/d in commingled recycling (The City of Melbourne, 2021). Like residential buildings, commercial buildings may use waste compactors when generating over 25,000 L of waste and when the waste collection is three times a week is not adequate. Also, commercial developments may use balers (for materials like cardboard) or crushers (for materials like glass) to reduce storage space.

For commercial applications, it is essential to note that waste storage and stockpiling metrics will be significantly influenced by the type of services provided. As shown in the previous section, organisations providing consulting services typically are not involved in generating or managing waste in their daily operations. Therefore, if the weekly waste volumes are within the amount of the building, it could be collected by the council without involving an external contractor. In contrast, C&D companies produce large amounts of waste on-site, which requires either a large storage capacity or a constant collection by a waste contractor. Due to their nature, C&D waste has special requirements from the environmental protection authorities. For instance, EPA Victoria requires organisations to keep records of waste transported and received from waste facilities to track the correct treatment of waste (EPA Victoria, 2021a). There are tools available to calculate stockpiling volumes. For example, The Engineering Toolbox (Engineering ToolBox, 2009) calculates volumes of coned and rectangular piles based on the mass and density of the stockpiled material. However, the C&D waste calculations should be based not only on the volumes but also on the mass. Apart from the traditional C&D waste, additional waste volumes should be accounted for in the case of damages of breakages on site. The calculation suggested by (Llatas, 2011) is specific to building-related C&D waste and considers the construction waste, the volume of soil removed and packaging waste. However, these calculations should only be used for new projects where the amount of material and its packaging could be readily estimated beforehand. It could also be used for refurbishment projects. The packaging-related element of the equation could be crucial in sustainability and circular economy assessments, as excessive packaging could significantly harm the environment. However, in case of demolition, the packaging element could be removed from the equation, as no new materials or products are introduced. This highlights the need to tailor waste calculation methods to specific project types. The following section outlines a proposal for incorporating storage into decision-support tools and circular economy models, focusing on the perspective of risks.

5.5. Introducing the storage circularity indicator

Due to several factors, storage plays a pivotal role in the risk assessment of circular processes. Firstly, in a circular economy, materials are utilised for as long as possible, necessitating storage during various stages, such as use, reuse, and recycling. The storage conditions can influence the quality and usability of these materials, impacting the overall efficiency of the circular process. Secondly, certain materials involved in circular processes, such as electronic waste, can be hazardous, making proper storage essential to mitigate associated risks (Kazancoglu et al., 2022). Thirdly, businesses are legally bound to manage and prevent unnecessary risks, including material storage-related ones, with non-compliance potentially resulting in legal penalties. Lastly, efficient storage practices can contribute to minimising waste, maximising resource use, and enhancing the economic viability of circular processes. Therefore, a storage circularity indicator can help address these concerns by providing a comprehensive assessment of storage-related risks.

The formula for calculating the storage circularity indicator has been consistent with the other indices' style, such as the material circularity index by Ellen MacArthur Foundation, 2019. The formulation for incorporating storage as an element of circularity differs primarily due to the lack of readily available data. This scarcity of data presents challenges in adhering to the same approach used for other metrics. The unique nature of storage, which involves both temporal and spatial dimensions, necessitates a distinct formula that can accurately capture its impact on circularity. Several studies have demonstrated the value of integrating complementary social, economic, and other factors into circularity assessments in an unconventional way. For example, Huysveld et al. (2019) assessed recyclability benefit rate through the analysis of environmental saving and environmental burdens. Fregonara et al. (2017) assessed the level of disassembly through a score system between 0 and 5. Huysman et al. (2017) calculated the circular economy performance indicator through the assessment of the environmental benefits. Gonzalez Junca et al. (2021) assessed social circularity through the analysis of social impacts. Including these factors provide a more holistic view of the system under study and enable more informed decision-making, further underscoring the need for a different formula for the storage metric.

$$SCI = 1 - SRI \tag{1}$$

where: SRI – storage risk indicator (unitless)

The key criterion is based on the risks and hazards involved in storing materials and products. The storage risk indicator is calculated through risk severity and likelihood, commonly used by project managers in risk management plans. This ensured that materials, products, and waste are stored safely, and any potential adverse impacts are identified and minimised. The procedure for risk assessment can be found at Business Victoria (2023).

The storage risk indicator can be calculated as follows:

$$SRI = \frac{\sum_{i=0}^{n} (Risk\ severity_i \cdot Risk\ likelihood_i)}{(Risk\ severity_{max} \cdot Risk\ likelihood_{max}) \cdot n} \quad (2)$$

.

The guideline for stockpile management (EPA SA, 2020), outlines 13 different categories of risks associated with storage and stockpiling (Table 3). Therefore, these risks should be considered when calculating the SRI and SCI. Table 3 proposes the severity scores for each of the listed risks, along with corresponding explanations.

Introducing the Storage Circularity Indicator represents a significant step towards enhancing circular economy implementation by offering a comprehensive assessment of waste storage-related risks. By integrating this indicator into decision-support tools, organisations can strengthen their waste management strategies, ensure regulatory compliance, and promote sustainable resource use.

The storage circularity indicator can serve as the first step in developing new decision-support tools, offering an additional metric for assessing waste storage practices alongside existing parameters. Once the Storage Risk Indicator (SRI) is calculated, decision-support tools can present the results in user-friendly formats, such as visual graphs or risk matrices. This will allow users to swiftly evaluate the overall risk level associated with their storage practices and facilitate informed decision-making. The tools can offer recommendations for mitigating identified risks, such as implementing safety measures, enhancing storage conditions, or adopting alternative storage methods. However, further research is necessary to explore how this indicator can be seamlessly integrated into different tools and frameworks.

By incorporating the storage circularity indicator into circular economy models, organisations can enhance their waste management strategies, ensure compliance with regulatory requirements, and promote sustainable resource use. The proposed method underscores the importance of addressing waste storage challenges in achieving circularity goals and advancing towards a more sustainable future.

5.6. Applicability of the proposed method beyond Australia

The proposed method, while developed with an Australian context in mind, holds potential applicability across diverse geographical locations. This adaptability is primary, due to the incorporation of a risk management practice within the storage circularity indicator calculations, which is a universally relevant approach. For instance, similar risks associated with stockpiling are noted in diverse global settings, reflecting the method's robustness and transferability. Bester et al. (2022) highlighted comparable risks when conducting a study of stockpiles of a British mining company operating internationally in countries such as South Africa, Brazil, Canada, and Chile. Further examples include the general waste management practices in Singapore, as noted by the Waste Management and Recycling Association of Singapore (WMRAS (2023)), and the guidelines for industrial waste management issued by the Environmental Protection Agency (EPA, 2016) in the United States. Although their focus was predominantly on human health and safety, the underlying risk factors align closely with those defined in our research. These instances illustrate that, while specific regulatory, cultural, and infrastructural contexts may differ, the fundamental challenges and strategies associated with waste storage and stockpiling

Table 3
Proposed severity of storage risks.

#	Identified risk	**Severity (1 to 5)**	Explanation of the severity score
1	Pollution of waters, leaching or runoff of contaminants and particulates	5	Water pollution can have severe and long-lasting environmental consequences, affecting ecosystems, human health, and biodiversity. Contaminants and particulates can persist in water bodies, leading to widespread damage.
2	Heat generation with potential to cause fire	5	Heat generation can lead to fires, which pose immediate threats to human safety, property, and the environment. Fires can spread rapidly and have catastrophic consequences.
3	Generation of litter	3	While littering can detract from aesthetics and may attract vermin, its direct impact is generally less severe than other risks. However, the accumulation of litter over time can contribute to environmental degradation.
4	Dust emissions	4	Dust emissions can lead to respiratory issues, visibility problems, and air pollution. Prolonged exposure to high dust levels can have adverse health effects on workers and nearby residents.
5	Odour emissions	3	Odour emissions can cause discomfort and nuisance to nearby communities, but they typically do not pose significant health risks. However, persistent odours can impact quality of life and property values.
6	Biogas emissions	3	Biogas emissions contribute to greenhouse gas emissions and can affect air quality. While they may not pose immediate health risks, long-term exposure can contribute to climate change and environmental degradation.
7	Vermin	3	Vermin can cause property damage and spread diseases, but their impact is generally manageable with proper pest control measures. However, they can still pose risks to health and safety.
8	Adverse visual amenity	2	Adverse visual amenity detracts from aesthetics but typically does not have direct health or safety implications. However, it can impact community well-being and property values.
9	Stockpile instability	5	Stockpile instability can lead to accidents, injuries, and environmental damage. Collapsing stockpiles pose immediate risks to workers and bystanders and can result in widespread harm.
10	Inadequate platform stability and suitability	5	Inadequate platform stability increases the risk of accidents, falls, and structural failures. It compromises worker safety and can lead to severe injuries or fatalities.

(*continued on next page*)

Table 3 (*continued*)

#	Identified risk	Severity (1 to 5)	Explanation of the severity score
11	Excessive accumulation of material	4	Excessive accumulation of material can increase the risk of fire hazards, environmental pollution, and operational disruptions. It can also hinder access to maintenance and emergency response.
12	Abandonment of stockpiles and avoidance of regulatory regime	5	Abandonment of stockpiles and non-compliance with regulations can result in legal consequences, environmental liabilities, and public scrutiny. It undermines proper waste management practices and poses significant risks.
13	Mischievous or criminal vandalism	2	While vandalism can cause property damage and disruption, its severity is generally lower compared to other risks. However, it may still indicate broader issues with site security and community relations.

are often similar.

When considering the application of this method in other regions, it is crucial to account for regional differences in waste management infrastructure (e.g., frequency of collection, the equipment used, transportation, availability of land), regulatory frameworks (e.g., specific requirements, penalties, incentives), and cultural factors (e.g., environmental awareness, perceptions on waste). Developed countries usually have more advanced waste management systems with necessary plants and new technologies at their disposal. In contrast, in developing countries, the technology and infrastructure would be less advanced, potentially leading to a higher rate of waste dumping or incineration.

In terms of the regulatory frameworks, the regulatory environment in developed countries, with the established waste management directives, presents a different set of challenges and opportunities compared to other regions with less formalised regulations. On the other hand, although many developing countries have necessary waste management regulations in place, they might lack enforcement of such regulations.

Similarly, cultural attitudes towards recycling and waste management can significantly influence the effectiveness of implementing the proposed method. Some cultures, such as Japan, will have a higher environmental awareness and, therefore, adopting the proposed method would be more likely compared to developing countries where perceptions on waste still require a shift (Hu et al., 2024). To summarise, it is essential to tailor the storage circularity indicator to accommodate these regional differences to ensure effectiveness and acceptance across different cultural and regulatory landscapes.

5.7. Limitations and further research

The current research only samples responses from the construction and infrastructure sector within Australia, predominantly from respondents based in Melbourne. This geographic concentration and the qualitative nature of the interviews highlights the exploratory nature of this study. While the circular economy concept is also embraced by other sectors, including manufacturing, defence, services, and government, the findings from this study may not directly translate to these sectors due to unique industry-specific challenges.

To address these challenges, future research should extend beyond the construction sector to include a broader range of industries, each with distinct recycling challenges and requirements. This expansion would provide a more comprehensive understanding of the applicability and effectiveness of the storage circularity indicator across different economic activities.

Future research should expand the pool of respondents from other localities in Australia. It is recognised that different state governments have different regulations. This diversity is crucial as different state governments have varying regulations and recycling initiatives, which can influence the implementation and success of circular economy strategies.

Regarding the treatment of stored versus primary waste, there is a recognised need to empirically verify whether stored waste allows for more preferred treatment methods, such as material recovery, compared to primary waste. This verification has not yet been thoroughly explored and represents a crucial area for future research, emphasising the potential for improving circular economy practices through optimised waste storage strategies. The proportions of stored waste relative to the total waste should be also further investigated.

Further research should also explore more detailed strategies for calculating waste storage and stockpiling and assess their feasibility to include in circular economy models. This exploration should aim to develop refined methodologies that can be easily adapted to different industrial contexts and geographical settings. Such studies would not only validate the current findings, but also enhance the practical utility of the storage circularity indicator in promoting sustainable waste management practices globally.

6. Conclusions

This study aimed to identify critical factors for a universal circular economy framework, utilising semi-structured interviews with Australian professionals. The findings are twofold and provide valuable insights into the implementation of circular economy concepts.

Firstly, the findings confirmed the consistency of the opinions of Australian professionals with those presented in studies from other parts of the world. It was confirmed that most respondents see a strong connection between the circular economy, cost, and emissions, with most referring to the decarbonisation and net-zero targets. However, there was no consensus on what constitutes the dominant model of circular economy, suggesting variability in implementation strategies across different organisations.

Secondly, by examining the industry's perspective on circular economy implementation, we identified a previously unexplored variable as a crucial part of implementing circular economy - storage and stockpiling of waste. To the authors' knowledge, this variable was not included in previous frameworks for circular economy and was not yet considered as a major contributor to the circularity assessments. However, the Australian industry professionals emphasised the importance of this concept being included as part of circular economy models due to its significant and adverse impact on the efficiency of organisational operations and the strict rules defined by the environmental protection authority in relation to stockpiling. Therefore, it is recommended that a new variable to measure the adverse effects of stockpiling should be included in future circular economy models to consider significant problems related to waste storage and encourage organisations to find solutions to improve their operations and bring them closer to achieving circular economy. Thus, this study suggests that integrating a storage circularity indicator into circular economy frameworks could enhance operational efficiency, which can ultimately lead to reduced resource consumption and waste generation, aligning with the principles of sustainable production and consumption. The generalised metric can address significant challenges related to waste storage and encourage organisations to develop solutions that can enhance their operations and align them more closely with the principles of circular economy.

Our proposed storage circularity indicator aims to fill this gap by providing a comprehensive assessment of waste management practices, thus enhancing the robustness of circular economy strategies and policies. By adopting a risk management approach, this indicator allows for the consistent evaluation of risks associated with waste storage, encouraging organisations to develop effective solutions that align with the principles of the circular economy.

This work emphasises the importance of decision-support tools in waste management to facilitate the implementation of circular economy principles. The proposed storage circularity indicator promotes industrial collaboration, aligning with the concept of industrial symbiosis to optimise resource use and minimise waste generation.

It should be noted that the current study is exploratory in nature, primarily due to its small sample size and geographic concentration of respondents in Melbourne, Australia. While these factors limit the generalisability of the findings, the study yields valuable insights into the topic of circular economy and lay the ground for future research. The findings contribute to advancing waste management strategies and policies in line with sustainable production and consumption practices. By proposing a new metric and adopting a risk management approach, this work provides practical insights for researchers, practitioners, and policymakers, thus aiding in transitioning towards more sustainable waste management practices and aligning with the sustainable development goals.

Future studies should aim to expand the sample to include a broader geographic range and a variety of industries beyond construction and infrastructure. This expansion would enable a more comprehensive understanding of the applicability and effectiveness of the proposed storage circularity indicator across different contexts. Additionally, further research should explore the integration of this new metric into global circular economy models, considering variations in regulatory, cultural, and operational contexts.

CRediT authorship contribution statement

Olga Pilipenets: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Felix Kin Peng Hui:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Tharaka Gunawardena:** Writing – review & editing, Validation, Supervision. **Priyan Mendis:** Supervision, Funding acquisition. **Lu Aye:** Writing – review & editing, Validation, Supervision, Resources.

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.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

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