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Research Paper

Circular economy life cycle cost for kerbside waste material looping process

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ABSTRACT

Rapid expansion in urban areas has engendered a superfluity of municipal solid waste (MSW) stemming from contemporary civilization, encompassing commercial sectors and human undertakings. Kerbside waste, a type of MSW, has the potential for recycling and reuse at the end of its first life cycle, but is often limited to a linear cycle. This study aimed to assess the life cycle costs of different separation and recycling methods for handling kerbside waste. A new life cycle cost model, drawing from the circular economy's value retention process (VRP) model, has been created and applied to assess the continuous recycling of kerbside glass. The study investigates two key separation techniques, kerbside recycling mixed bin recycling (KRMB) kerbside glass recycling separate bin (KGRSB) and analyses their impact on the life cycle cost of the recycling process. Additionally, the research explores two approaches of recycling and downcycling: closed-loop recycling, which pertains to the recycling of glass containers, and open-looped recycling, which involves the use of recycled glass in asphalt. The results showed when use annually collected waste as the functional unit, the KRMB model incurred lower costs compared to the KGRSB model due to its lower production output. However, when evaluated over a 1-ton production of glass container and asphalt, the KGRSB method demonstrated superior cost performance with a 40–50% reduction compared to the KRMB method. The open-loop recycling method (asphalt) incurred a higher cost compared to the closed-loop recycling method due to its larger production volume over a 21-year period.

1. Introduction

The conundrum of overflowing municipal solid waste (MSW) has become a critical concern in many countries (Saberian et al., 2021; Adedara et al., 2023). A staggering 2 billion tons of solid waste generation is witnessed across the globe annually and over 33 % of this waste is disposed through unsustainable practices (The World Bank, 2018). An average individual worldwide is responsible for a daily solid waste disposal of 0.74 kg which is significant at aggregate level (Kaza et al., 2018). MSW can originate from various sources, including households (Yu and Li, 2020; Banerjee and Sarkhel, 2020), commercial areas such as offices (He et al., 2022; Pathak et al., 2020), and institutions like schools (Caglar et al., 2024; Srivastava and Chakma, 2024). In Australia, MSW is primarily defined as household or municipally collected waste, referred to as "kerbside waste," aligning with the National Waste Report's definition (Australian Government, 2022), but not the broader general term of MSW. In 2016–2017, Australia generated a daunting 76 million tons (MT) of waste, including around 2 MT of glass waste and 13.8 MT of MSW (Australian Government, 2022). Notably, glass occupies 34 % of the kerbside recyclable wastes (Zhang et al., 2024). This significant amount of waste generation underscores the pressing need for effective and efficient waste management strategies. Managing MSW in a safe and efficient manner is becoming increasingly expensive (Olapiriyakul, 2017). This reality makes it essential to develop a practical approach to address the financial aspect of overflowing waste. Such an approach must be in line with the principles of sustainability and must strive to achieve a circular economy. A circular economy aims to create a closed loop of resource use, where waste and resources are kept in use for as long as possible, extracting the maximum value from them before returning them back to the environment. In order to achieve this, it is imperative to implement effective waste management strategies that prioritize safety, efficiency, and cost-effectiveness. The escalating challenge of managing MSW efficiently and sustainably as evidenced by the staggering global and Australian statistics, underscores the urgency for innovative waste management strategies. This situation not only demands a revaluation of current waste disposal methods but also calls for

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a deeper understanding of the cost implications associated with waste management. The cost of managing MSW safely and effectively is rising, presenting a significant financial burden that necessitates a sustainable and cost-friendly viable solution. This is where the importance of integrating a circular economy concept becomes evident. A circular economy, focusing on maximizing resource use and minimizing waste, requires a shift in perspective from traditional waste management to a more holistic, sustainable approach.

In this context, conducting a Life Cycle Cost (LCC) analysis becomes critical for benchmarking the circular economy concept. LCC analysis enables a comprehensive understanding of the costs incurred at each stage of a product's life cycle, from production to disposal. This analytical approach is instrumental in identifying economic opportunities and challenges within circular economic models. By offering insights into the long-term financial implications of adopting circular practices, LCC analysis aids in more informed decision-making and policy development. Such analysis not only contributes to a better grasp of the financial aspects of waste management strategies but also aligns with the overarching goal of achieving sustainability through resource efficiency and waste minimization.

There are various approaches to LCC. A comprehensive comparison of the LCC models is provided in Appendix 1. The conventional life cycle cost (CLCC) method was developed to assess the total cost over a life cycle stage or period to assist with product development decisions (Langdon, 2007; Dhillon, 2009; Gundes, 2016; Jansen et al., 2020). It focused on the total cost of a product for single stakeholders, including acquisition cost, facility management cost, and disposal cost (Mallick et al., 2023; Okumus et al., 2023). However, it was difficult to account for the entire life cycle that often involves multiple players (De Menna et al., 2018; Dhillon, 2009; Heralova, 2017). This method has been widely used across the globe in cost analysis of MSW management including India (Sharma & Chandel, 2021) and China (Li et al., 2016). The environmental life cycle cost (ELCC) model is a tool for estimating the cost aspect of a product or process, either on its own or as part of a broader sustainability assessment (Hunkeler et al., 2008). It is used to support decision-making and cost estimation by linking the cost analysis with environmental analysis. For example, Chen et al. (2019) applied it to analyze sewage sludge in China. An economic perspective on MSW management has been provided by Kang et al. (2023), Ascher et al. (2019) as well as Plastinina et al. (2019), while studies like Tucker et al. (2018), De Feo et al. (2019), Istrate et al. (2019), and Maalouf & El-Fadel (2019) integrated the economic aspect into their studies through a cost-benefit analysis combined with life cycle assessment. In these studies, the cost is expressed in per-unit terms, such as per ton. However, the environmental life cycle cost model often ignores the time value, as the system boundary of the analysis typically focuses on one life cycle. The Material Flow Process Accounting (MFPA) model is a valuable approach within the landscape of life cycle costing, yet it primarily focuses on the flow of materials and energy, aiming to decrease environmental impacts while enhancing economic efficiency (Walls et al., 2023; Zhou et al., 2017). However, this model does not explicitly address the complex inter-industry relationships and the comprehensive recycling procedures that characterize the circular economy, particularly within the context of kerbside waste management.

Circular economy is a sustainable economic model that aims to reduce waste and keep resources in use for as long as possible. The goal of circular economy is to move away from the traditional linear model of take-make-dispose and create a closed loop system where waste and by-products are reused and repurposed. Both Bradley et al. (2018) and Jansen et al. (2020) utilized the "Rs" of circular economy to target various cycles and stakeholders. Bradley et al. (2018) developed the Total Lifecycle Cost (TLCC) model, which combined cost analysis with the 6R-based principles of sustainable manufacturing to examine the economic impacts of material waste. The 6Rs include reduce, recycle, reuse, recover, remanufacture, and redesign. The TLCC model considered the material of multiple recycling circles but lacked comprehensiveness in covering all circular economy activities. Jansen et al. (2020) created the circular economy life cycle costing model (CE-LCC model), which encompasses "10Rs" of circular economy activities and considers different methods of recycling, end-of-use/life, and stakeholders in the recycling process. The "10Rs" of CE-LCC model was based on the concept of VRP model which has been utilised by Reike et al. (2018) and Nasr et al. (2018) to elucidate processes and techniques in the 'circular economy'. The framework of this VRP helps to accurately locate the various activities of the 'circular economy' throughout the waste life cycle. The VRP model is centered around nine key strategies, each denoted by an "R" term, which collectively form a comprehensive approach to managing resources in a circular economy. These strategies range from "Re-fuse" (R0), which emphasizes the importance of avoiding unnecessary purchases, to "Re-mine" (R9), a rare but crucial process of extracting reusable materials from landfills. Each "Rs" strategy addresses a different aspect of product and material life cycle, focusing on prolonging usage, enhancing recycling processes, and efficiently managing resources. For example, "Re-duce" encourages using products for longer periods and consuming less, while "Re-cycle" involves the separate collection and processing of waste. Meanwhile, "Re-manufacture" and "Re-furbish" focus on restoring or upgrading products, often involving the original manufacturers. However, the CE-LCC model by Jansen et al. (2020) lacks practice and clarity in using this method still exists when dealing with waste materials involving multiple industries/life cycles, such as kerbside waste. In line with the sustainability triple bottom line model, which evaluates the environmental, economic, and social dimensions of sustainability (Klöpffer, 2008; Alhaddi, 2015, Tseng et al., 2020), it is critical to analyze the economic and environmental aspects of the kerbside waste material loop. Zhang et al. (2024) developed an environmental life cycle assessment model for the environmental aspect of this process within the circular economy framework. Aligning the cost model with the environmental assessment is beneficial for a holistic understanding.

This paper aims to develop an improved lifecycle cost model specifically designed for the kerbside waste material loop process, addressing notable deficiencies in current methodologies. Traditional LCC models like CLCC and ELCC primarily offer stakeholder-specific cost analyses or align with environmental LCA but miss the broader interconnections in waste management (Sharma & Chandel, 2021; Hunkeler et al., 2008). The CE- LCC broadens the scope by incorporating a multi-stakeholder perspective yet falls short in capturing the comprehensive recycling processes of kerbside waste (Jansen et al., 2020). The same disadvantage happens to TLCC (Bradley et al., 2018). The MFPA approach, despite its focus on material and energy flows, lacks a thorough cost allocation method across the intricate web of circular economy activities (Walls et al., 2023; Zhou et al., 2017).

The novelty and significances of this model are 1) it provides a cost model for kerbside waste material loop process, which encompasses the participation of multiple industries. 2) it covers the costs linked to the different recycling procedures happening at the end-of-use/life phase. The activities were defined using the ten "R-imperatives" of the comprehensive circular economy framework, and the costs were assigned based on the material weight involved in the circular economy activities. 3) It allows for the cost analysis of kerbside waste materials that undergo multiple cycles beyond the first life cycle. 4) it emphasizes the cost analysis of each life cycle stage, thereby offering opportunities to reconcile economic, environmental, and social sustainability analysis. 5) it aligns with the circular economy environmental life cycle assessment model for kerbside waste material loop to build a foundation for a comprehensive evaluation of sustainability performance.

The study began with a literature review to pinpoint the gaps in existing circular economy LCC methods. Building on these insights, we developed a new circular economy LCC model for kerbside waste material loops and applied it to a case in Yarra, Australia. Data collection involved data requests in interviews with industry stakeholders, and the gathered data were analyzed through the new model. Finally, the outcomes were compared to existing methods, leading to our conclusive insights into sustainable waste management practices.

2. Theoretical R-imperative circular economy framework

In the kerbside waste material looping process VRP model plays a key role in determining the identification and allocation of activities that initiate subsequent life cycle stages. It is important to note that the circular economy activities (Rs) are not associated with new product mix-design, but rather are only taken into consideration in the following circumstances: The inception of a new life cycle, and the presence of potential costs (in cases where energy, resources, or transportation are involved).

In this revised circular economy kerbside waste loop cost model (Fig. 1) we conceptualize the initial life cycle of kerbside waste as an R7 (Recycling) phase. This phase involves the segregation, collection, disposal, and sorting of waste. The R7 process in segregation, collection, disposal stage incorporates the use of vehicles, machinery, labour, and equipment, factors that potentially incur various costs. The sorting stage, also an integral part of R7, requires energy, resources, and additional labour for material sorting in facilities, and is linked with waste transfer and transportation costs. The selection of circular economy activities, termed Rs, for later life cycles is influenced by the output of this first cycle. For instance, kerbside glass cullet (waste stream A) processed through open-loop recycling for asphalt production (Product F) or closed-loop recycling for creating glass containers (Product D) is identified as an R7 activity. Moving into the second life cycle, asphalt that undergoes demolition could be classified under R5 (remanufactured and returned to the original manufacturer) for Reclaimed Asphalt Pavement (RAP) production. In contrast, used glass containers might once more be categorized as R7, turning into kerbside waste glass. These R5 and R7 processes collectively instigate the next life cycle.

During the production stage, the focus is primarily on the R8 (Recover Energy) activity. This involves the utilization of organic waste, such as kitchen scraps, in energy generation processes (Production E). The methods employed typically include direct incineration or biogas power generation. This stage marks the end of the first life cycle for these waste materials. The costs encompass this stage associate with the transportation of materials, treatment processes, and the resources required for such activities, including energy, machinery, and labour. Additionally, the by-products resulting from this stage, such as fly ash, are categorized under R6 (Repurposed) once they reach their end-of-use/life stage.

Contrastingly, the consumer in-use stage of the model does not incorporate any specific “R” activities. This phase is characterized by the consumer’s usage of the product, with no direct involvement of recycling or repurposing processes, which means no circular economy activity related cost involved.

The end-of-use/life stage of the model is more complex, involving multiple “R” activities. R0 (Refuse) and R1 (Reduce) are not applicable in this stage as they pertain to the prevention of waste generation and reduction in consumption, which are not directly associated with costs in this context. However, activities such as R2 (Re-sell) and R6 (Repurpose) become relevant. These involve the energy consumption costs related to the collection and transportation of materials for their functional transformation for other purposes. Additionally, R3 (Re-pair) is a significant activity in this stage, involving the repair of products either by users or third parties. This process incurs costs related to transportation and the consumption of materials necessary for the repair. Furthermore, R4 (Refurbish) and R5 (Re-manufacture) are also pertinent to this stage. R4 occurs in non-standard settings, while R5 takes place in standard factory settings, with both activities involving the

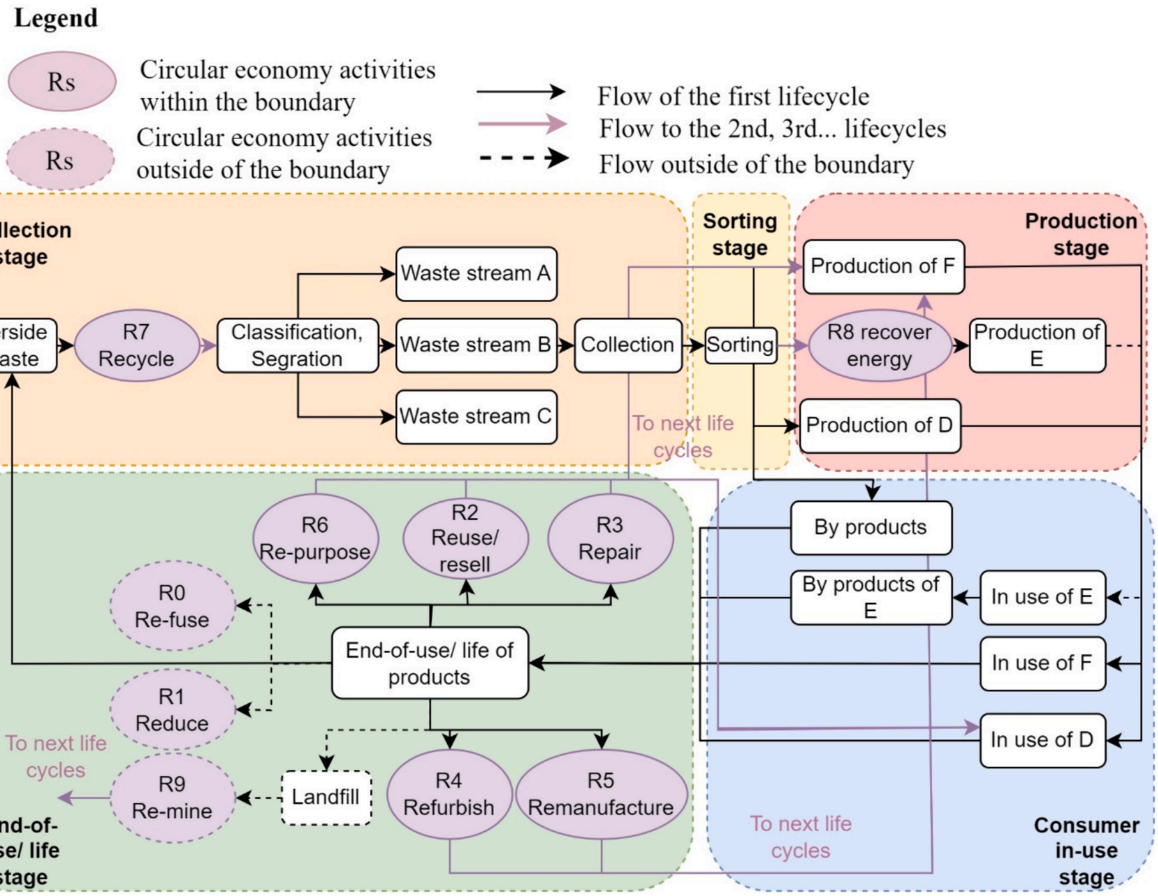

Fig. 1. Circular economy material flow and life cycle stages of kerbside waste material (Zhang et al., 2024).

consumption of energy and resources. Finally, it is important to note that R9 (Re-mine), which describes the process of urban or landfill mining, is not considered within the life cycle boundaries of this model.

3. Study methodology

The cost model for the VRP in the kerbside waste material loop is built upon the material flow within the kerbside waste loop process. Researchers such as Schmidt (2015) and Dunuwila et al. (2018) have linked the cost of products and processes to material flow in their studies. This approach offers the potential for comprehensive cost analysis and alignment with other sustainability assessments that involve material flow considerations. Additionally, our kerbside waste life cycle cost model takes into account inflation rates to address the time value aspect, while also considering the various life cycle stages and stakeholders through which the material flows.

3.1. Time value

The significance of considering the time value in life cycle cost models is well established in the academic literature (Bradley et al., 2018; Jansen et al., 2020; Hunkeler et al., 2008). This is due to the close relationship between the life cycle of a product/asset and its time value. Ignoring the time value of life cycle cost can result in significant differences in predicted values over a period of fifty to sixty years because of the inflation rate. Although the Net Present Value (NPV) approach is widely used for its ability to assess the present value of an investment by discounting future cash flows (Dobrowolski and Drozdowski, 2022), it did not align with our project's goals. Instead, we chose the Future Value (FV) method. This approach projects how costs will accumulate over time, considering the interest rate and the project period. FV is particularly suited to our needs as it allows us to forecast the total future costs associated with the project. This proactive financial perspective is crucial for ensuring that adequate funds will be available to meet future requirements and supports effective financial strategy and resource allocation (Noury et al., 2020). Equation (1) highlights calculation of the future value (FV) where, i is the inflation rate, n is the time, and PV is the present value of the product or asset determined by the total cost of each life cycle which is the regarded as C_{total} in the equation (2).

$$FV_n = PV(1+i)^n \tag{1}$$

3.2. The life cycle stages

In this model, the collection stage is considered as the starting stage of kerbside wastes' life cycle. In contrast, raw materials' extraction is considered the starting stage in traditional life cycle stages. It follows the sorting stage for waste sorting and processing to ready materials for production. After production, the material will be transported to consumers for use eventually going to the stage of end-of-life.

In the model, the cumulative cost of each stage of a product's life cycle is determined by aggregating the costs incurred at each stage. These stages include the collection, sorting, production, consumer use and end-of-life stages. The equation for calculating the total cost of each life cycle stage is presented in Equation (2).

$$C_{total} = \overrightarrow{C_{collection}} + \overrightarrow{C_{sorting}} + \overrightarrow{C_{production}} + \overrightarrow{C_{in-use}} + \overrightarrow{C_{end-of-use/life}} \tag{2}$$

3.3. Cost calculation in each life cycle stage with circular economy

This model is considered from the stakeholder society perspective. Equation (3) represents inventory allocation as shown below;

$$\overrightarrow{F} = k_{Rs_{n_1}} \times Stakeholder_x \overrightarrow{F}_{primary} + k_{Rs_{n_2}} \times Stakeholder_x \overrightarrow{F}_{secondary} \tag{3}$$

The material flow of kerbside waste material undergoing primary and secondary processing by various stakeholders is represented by the vectors $\overrightarrow{F}_{primary}$ and $\overrightarrow{F}_{secondary}$, respectively, if both the primary and secondary process is counted. The allocation coefficient, k, varies depending on the selected circular economy R-imperative (Rs_n, $n = 0-9$) strategy. The conversion of the material flow inventory into cost is represented by the matrix A ($\overline{A}$), which encompasses the cost of labour, equipment, administration, material, and energy prices. This methodology was previously proposed by Schmidt (2015) and can be expressed mathematically as Equation (4):

$$\overrightarrow{C} = \overline{A}(k_{Rs_{n_1}} \times Stakeholder_x \overrightarrow{F}_{primary} + k_{Rs_{n_2}} \times Stakeholder_x \overrightarrow{F}_{secondary}) \tag{4}$$

Throughout various stages of the life cycle, the flow of material and energy consumption among the stakeholders involved in the R-imperatives either primary or secondary process is represented by the vector $\overrightarrow{F_{primary\vee\,\mathrm{secondary}}}$". Equation (5) represents the computation of cost $\overrightarrow{C}$ where Rs represents the VRP activity that initiates the subsequent life cycle stage. The variables k_A, k_B, and k_C each correspond to the allocation coefficient percentage for a specific waste stream. Thus, this equation reflects the assessment of the cost associated with material, energy, labour, equipment, and administration for each stakeholder involved in the VRP activities.

$$\begin{aligned}\overrightarrow{C}_{lifecyclestage} = \overline{A}[k_A \times Rs \sum_{Stakeholder1}^{Stakeholder\alpha} \overrightarrow{F_{primary\vee\,\mathrm{secondary}}} + k_B \times Rs \\ \times \sum_{Stakeholder1}^{Stakeholder\beta} \overrightarrow{F_{primary\vee\,\mathrm{secondary}}} + k_C \times Rs \\ \times \sum_{Stakeholder1}^{Stakeholder\gamma} \overrightarrow{F_{\mathrm{primary}\,\vee\,\mathrm{secondary}}} + \cdots]\end{aligned} \tag{5}$$

For kerbside waste glass container scenario:

In Collection Stage: Involves waste collection and transportation service providers (α_1, β_1). If all kerbside bin waste which contains waste glass containers is collected, the allocation coefficient k_{A_1} and k_{B_1} is 100 % of the R7 activities' material flow vector $\overrightarrow{F}$ for both providers (α_1, β_1).

Sorting Stage: Involves waste sorting and transportation service providers (α_2, β_2) in recycling activity R7. The allocation coefficient (k_{A_2} and k_{B_2}) for glass containers at this stage is the recovery rate of glass cullet in the sorting facility.

Production Stage: In the scenario of waste glass containers, this stage does not mark the beginning of a new life cycle, nor does it involve any R-imperatives. Conversely, in other waste scenarios, such as converting kitchen waste into electricity (R8 activity). Then the use of bottom ash is a secondary process ($\overrightarrow{F}_{secondary}$). The electricity generation by R8 recovery energy is the primary process ($\overrightarrow{F}_{primary}$) in the production stage.

End-of-Use/Life Stage: If glass cullet is repurposed for producing new glass containers, their subsequent disposal in kerbside waste bins initiates a new life cycle with the street collection (R7) activities (R7). Alternatively, if the cullet is incorporated into asphalt production, reaching its End-of-Use/Life stage, it can be utilized as Recycled Asphalt Pavement (RAP) in new asphalt production, thereby initiating another life cycle. In cases where all asphalt pavements undergo remanufacturing (R5), the allocation coefficient k_{A_3} for this process equates to 100 % of the material flow vector $\overrightarrow{F}$.

4. Case study

The case study, as referenced in Zhang et al. (2023), conducted in Yarra City, Australia, is presented in a detailed Appendix 3, 4, 5, and 6. This study is instrumental in aligning the Life Cycle Cost (LCC) model with environmental life cycle assessment, showcasing its practical application in the field of waste management. The study primarily focused on the collection and recycling of kerbside waste glass containers. Initially, in the trial area involving 1400 households, waste glass containers were discarded in mixed recycling bins along with other recyclables like cardboard, metal, and plastic. However, a significant change was introduced during the case study – a separate kerbside recycling bin exclusively for glass containers. This strategic change was aimed at facilitating the separation of glass from other materials, ensuring more efficient recycling processes. The data collected over an eight-month period revealed variability in the volume of waste collected in the separated glass recycling bins, ranging from 3600 kg to 6430 kg, indicating a substantial amount of glass waste generation. The collected glass waste was then transported to a Materials Recovery Facility (MRF) where it underwent sorting, treatment, and processing. Post-processing, the sorted glass cullet found two primary uses: one in the production of asphalt for road surface paving, and the other in the production of new glass containers.

4.1. Scenarios

In the present study, four distinct test scenarios have been established. These are: The KGRSB-Asphalt Model – Asphalt production is facilitated through the separated glass waste obtained from kerbside bins. The KRMB-Asphalt Model – Utilization of mixed kerbside waste from recycling bins for asphalt production. The KGRSB-Glass Model –Production of glass containers from separated glass waste gathered from kerbside bins. The KRMB-Glass Model – Manufacture of glass containers using mixed kerbside waste obtained from recycling bins. These scenarios are selected based on the city councils practice of separate the glass stream from the mix waste stream and also evaluate the cost of using the glass cullet to produce new glass containers and asphalt.

4.2. Goal and scope

The objective of this investigation is to assess and juxtapose the cost associated with the separation, sorting of waste glass, with the purpose of generating asphalt and glass containers. The study accounts for both open and closed loop recycling approaches, as well as studying the alignment of LCC model with the attributional and consequential environmental life cycle assessment. Following three discrete functional units were used in performing this analysis: Firstly, kerbside waste mass collected on an annual basis (the first life cycle, to present the alignment of LCC model with the attributional environmental life cycle assessment). Secondly, 1-ton production of either asphalt or glass containers (the first life cycle, to present the alignment of LCC model with the consequential environmental life cycle assessment). Thirdly, measurements were made of kerbside waste collected under two different recycling models over a 21-year period, with the specific goal of producing either asphalt pavement or glass containers. This study assumed that multiple cycles could occur over a 21-year period for both asphalt pavement and glass containers. The time frame is 21 years because it assumes in this study that the kerbside waste glass is recycled seven times to produce glass containers and the asphalt-wearing course (only the top layer) is maintained four times. During the first year, asphalt/glass containers would be produced from the collected kerbside glass. The second life cycle would involve recycling the asphalt as RAP. The glass containers would be disposed of as kerbside waste glass and then made as glass containers in the new life cycle. For this second life cycle and subsequent life cycles, asphalt and glass containers would be produced using newly recycled kerbside glass cullet. The same collection and sorting process would be applied as in the initial cycle, though the source of the kerbside waste glass cullet may extend beyond the initial trial area due to constraints on weight limitations. However, it does not mean that the materials will looping after 21-year. The time frame is applied as a boundary as a calculation. The process of landfill is not considered either, because it can be R9 (remined) after a long time. This expansion is reflected in the increasing volumes of waste recorded in Tables 1 and 2, which show waste collected from regions beyond the trial area in subsequent years to meet the growing demand for recycled glass cullet.

The study incorporates data from various stages of the waste glass recycling process, including street collection, sorting, production, in-use stage by consumers, and end-of-use/life stages. This data comprises the costs associated with materials, energy, labour, equipment, administration, and transportation incurred by city councils, waste collection service providers, sorting facilities, production service providers, construction companies, and consumers. Initial investment costs are excluded from the primary cost model because our focus is on direct operational costs to reflect societal perspectives, rather than individual investment returns. Also, this methodological choice helps better align the cost and environmental model by avoiding the distortive impact of sunk capital costs, which are typically relevant to individual investor considerations. However, investment cost with 10 years depreciation time is used to calculate the maintenance cost.

5. Inventory analysis for the case

The information employed for this research was acquired through diverse means, including engaging in discussions with pertinent parties such as officers in city council who are overseeing community-recycling initiatives, managers in charge of material recovery facilities, sustainability executives affiliated with a company involved in asphalt production, and a VicRoads official with responsibility for constructing pavement on local roads. The input/output material data, administration cost, and labour information were primarily obtained from these interviews. The material and energy cost information were obtained from online data provided by suppliers.

In the KGRSB model, kerbside glass waste is exclusively processed through a glass sorting facility, achieving a high recovery rate of 95 %, with 5 % attributed to contamination. In contrast, the KRMB model employs a two-stage process for handling waste glass. Initially, the waste is managed at a Materials Recovery Facility (MRF), where only 34 % of the glass is recovered; the remainder comprises cardboards, metals, plastics, and other contaminants, which constitute 66 % of the materials. Subsequent to this stage, the glass cullet that does remain is processed through a glass sorting facility, with a recovery rate of 66 %, however, 34 % remains contaminated.

In glass production, waste glass cullet comprises 64 % of the materials, while the remaining 36 % includes virgin materials such as silica sand, soda ash, limestone, and feldspar. For asphalt production, waste glass accounts for less than 10 % of the mix design.

Appendix 3 and 4 focusing on the asphalt scenario, encompasses data across multiple stages: street collection, sorting, and production. For the street collection stage, it lists an average waste weight per collection of 4158 kg, with 26 annual collections totalling 108,095 kg of waste each year. Vehicle maintenance for three vehicles is noted at 15,000 AUD, and fuel consumption at 300 L per day, priced at 1.95 AUD per litre. Appendix 3 and 4 also include salaries for drivers and loaders, at 80,000 AUD and 60,000 AUD annually. In the sorting stage, 117,000 tons of waste are processed in Materials Recovery Facilities (MRF) annually, with specific diesel and electricity consumption rates per kg of waste. The production stage includes details about the transportation of sorted glass cullet to asphalt producers, alongside the diesel and electricity consumptions for producing glass aggregate. The sources for this data include interviews with city council managers and local MRFs managers, alongside online resources such as fuelprice.io (2017) and Business Victoria (2022). The key literature references used in this study include Huang (2007), and VicRoads (2018). The energy consumption statistics for the processing of materials in the production of asphalt and hot mix asphalt, utilizing recycled materials, are presented by Huang (2007), who obtained them from the UK and Swedish industrial sectors. VicRoads (2018) provides information on the lifespan of local urban roads which is maintained for every 5 years with lifespan about 20 years. The

Table 1
Asphalt scenario cost inventories for 20 years.

KGRSB-A					
	First Year	Year Fifth	Year Tenth	Year Fifteenth	Year Twentieth
Produced weight of asphalt (kg)	1,283,628	6,418,140	32,090,700	160,453,500	0
Consumed waste weight (kg)	**108,095 (Trial area collected waste)**	540,451	2,702,375	13,511,873	0
Cost (AUD)	184,423 (Excluded the demolishing stage)	1,081,364	6,267,985	36,331,562	2,411,110 (Only demolishing)
KRMB-A					
Produced weight of asphalt (kg)	303,200	1,516,000	7,580,000	37,900,000	0
Consumed waste weight (kg)	**108,095 (Trial area collected waste)**	540,451	2,702,317	13,511,586	0
Cost (AUD)	71,412 (Excluded the demolishing stage)	416,856	2,416,254	14,005,502	315,328 (Only demolishing)

Table 2
Glass container scenario cost inventories for 20 years.

KGRSB-G								
	First year	Year Third	Year Sixth	Year Nineth	Year Twelfth	Year Fifteenth	Year Eighteenth	Year Twenty first
Produced weight of glass containers (kg)	155,640	231,028	342,932	509,040	755,606	1,121,602	1,664,879	2,471,305
Consumed waste weight (kg)	**108,095 (Collected in the trial area)**	155,640	231,028	342,932	509,040	755,606	1,121,602	1,664,879
Cost (AUD)	123,978	200,933	325,916	528,641	857,465	1,390,822	2,255,936	3,659,166
KRMB-G								
Produced weight of glass containers (kg)	36,763	37,912	39,096	40,318	41,578	42,877	44,217	45,599
Consumed waste weight (kg)	**108,095 (Collected in the trial area)**	108,126	111,505	114,989	118,583	122,289	126,111	130,052
Cost (AUD)	58,811	64,282	72,438	81,628	91,985	103,655	116,806	131,626

cost of materials and energy was gathered from multiple suppliers.

It is assumed the asphalt road is maintained every five years with the removal of the wearing course 5 years (Zhang et al., 2024), thus in 21 years, the asphalt pavements have been looped four times. The produced asphalt and consumed wastes in every loop (life cycle) and the cost in each loop are presented in Table 1. The calculation details are presented in Appendix 7.

Appendix 5 and 6 cover the glass scenario, spanning every life cycle stage of kerbside waste to the glass container process. It mirrors the asphalt scenario in detailing the average waste weight per collection, vehicle maintenance costs, fuel consumption, and driver/loader wages. The production stage elaborates on the costs of diesel, electricity, natural gas, and raw materials like soda ash and limestone, including the transportation distances for these materials. Appendix 5 and 6 also touch on the in-use and end-of-life stages, discussing transportation costs and the lifespan of glass containers. The data sources for this table are similarly diverse, ranging from interviews with the City Council and local MRFs to references from GlobalPetrolPrices.com (2022), Australian Energy Regulator (2020), and academic studies like those by Carre et al. (2013) for material inputs and outputs. Glass container's three-year lifespan is assumed based on the supermarket observation, interview with local MRF.

In 20 years, it is assumed glass containers looped seven times (Zhang et al., 2024). The produced weight of glass and consumed waste in each loop is presented in Table 2. The calculation details are presented in Appendix 7.

6. Results and discussions

6.1. Asphalt scenarios

In Fig. 2 (a), a comparative assessment of the life cycle cost associated with using waste glass cullet gathered annually, in the production of asphalt is displayed for two models: KGRSB and KRMB.

The annual generated waste is 108,096 kg, which the KGRSB model results in the production of 1,283,628 kg of asphalt. This number of wastes also outputs 303,200 kg of asphalt using the KRMB model. Upon examining the costs related to utilizing annually collected wastes for both models for asphalt production, the results show that the total expenditure for the KGRSB-A scenarios amounts to 194,036 AUD, while the total cost for the KRMB-A model is 75,191 AUD. Fig. 2 (b) presents a comparative analysis of the KGRSB and KRMB models' life cycle cost through the utilization of glass cullet in asphalt production. The findings reveal that the total cost incurred in producing one ton of asphalt using waste glass collected from the trial area for the KGRSB-A scenario is 151.99 AUD, while the corresponding cost for the KRMB-A model is 243.85 AUD. This data highlights the effectiveness of early-stage separation for the kerbside glass cullet in the street collection stage, as the process results in a substantial reduction in the life cycle cost when compared to the traditional KRMB model.

The results in Fig. 2 (a) illustrates the prominent increase in cost of production within the overall life cycle cost in the KGRSB model. This cost is significantly higher when compared to the KRMB model, with amount greater than four times proportion that exceeds fourfold. This substantial disparity can be attributed to the large volume of asphalt generated through the utilization of the KGRSB model, which results in

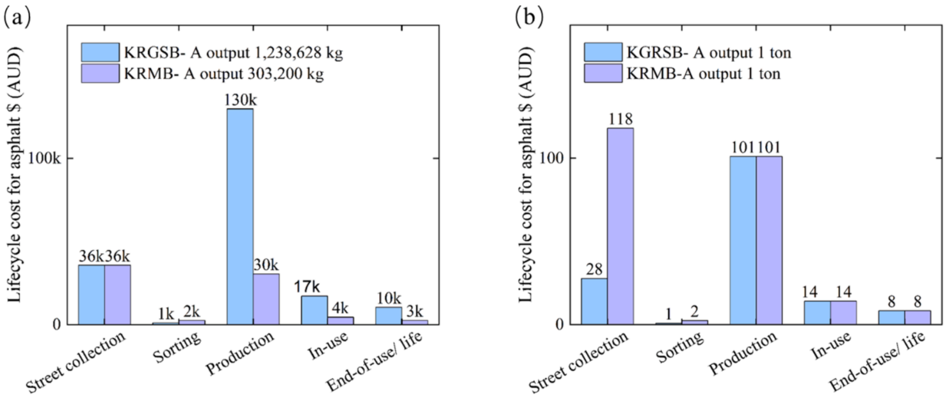

Fig. 2. (a) Life cycle costs of each stage involved in utilizing waste glass cullet, annual collection for asphalt production; (b) Life cycle costs of each stage in utilizing waste glass cullet for 1-ton production of asphalt.

an increased consumption of energy and raw materials in this life cycle stage and the later stages. The cost of these inputs, in turn, significantly contributes to the heightened life cycle cost observed in the KGRSB model. The cost associated with the sorting phase in the KRMB model is elevated as a result of the additional step incorporated in the Material Recycling Facility (MRF). This added step necessitates an increase in both energy expenditure and labour costs, thereby contributing to the higher overall cost of the sorting stage in the KRMB model. The requirement for additional resources, such as energy and labour, not only leads to an increase in the direct cost of the sorting phase but also impacts the overall efficiency and effectiveness of the MRF system. As a result, it is crucial to consider the cost implications of incorporating additional steps in the MRF process for MRKB model, and the large amount of asphalt with KGRSB model, particularly in regards to their impact on the overall cost of the recycling process. Fig. 2 (b) presents a detailed comparison of the costs associated with various stages of the asphalt production process. The assessment is based on the production of one metric ton of asphalt. The findings reveal that the cost of street collection in the KGRSB model is significantly lower when compared to the KRMB model, with a reduction of 76 %. Additionally, the cost of the sorting stage in the KGRSB model is also lower, with a reduction of over 50 %. On the other hand, the cost associated with the production stage, the in-use stage, and the end-of-use/life stage remains unchanged between the KGRSB and KRMB models. This data highlights the importance of incorporating cost-efficient practices in the initial stages of the production process, as it can result in significant savings in the overall life cycle cost. Furthermore, it also underscores the need for a holistic approach to cost management, considering the costs associated with each stage of the production process, from collection to disposal.

6.2. *Glass container scenarios*

A comparative analysis of the cost of producing glass containers throughout their life cycle using waste collected annually in separate glass bins and mixed bins is presented in Fig. 3 (a). The data reveals that the annual production of glass containers through the KGRSB model is 155,640 kg, while the corresponding production through the KRMB model is 36,763 kg. The total cost in the KGRSB-G scenario is 123,978 AUD, whereas for the KRMB-G model, it is 58,811 AUD. This data highlights the significance of the collection method in determining the overall cost of the recycling process. The utilization of separate glass bins for the collection of waste glass cullet results in a substantial increase in the annual production of glass containers and increase in the overall life cycle cost when compared to the traditional KRMB model. Presented in Fig. 3 (b) is a comparative analysis of the life cycle cost of producing glass containers by utilizing waste glass cullet collected in separate glass bins and mixed bins of trial area kerbsides. The results reflect the functional unit of glass container production of 1 ton. The data reveals that the total cost of 1 ton of glass containers production through the KGRSB-G scenario, using collected waste glass in separate glass bins, is 795.93 AUD, which is significantly lower than the total cost incurred through the KRMB-G model, where the collected waste glass is mixed with other waste, which is 1551.68 AUD.

Fig. 3 (a) presents a detailed analysis of the impact of various cost factors on the life cycle cost in the production of glass containers. The findings reveal that the cost of production has the largest impact on the KGRSB model's life cycle cost, which is more than four times higher than that of the KRMB model. This result is primarily attributed to the significantly higher annual production of glass containers achieved

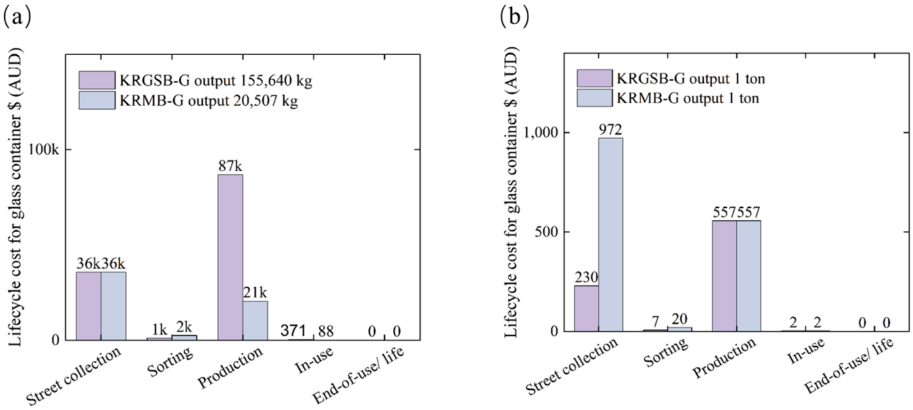

Fig. 3. (a) Life cycle costs of each stage in utilizing waste glass cullet, annual collection for glass containers production; (b) Lifecycle costs of each stage for 1-ton production of glass containers.

through the KGRSB model, which requires a substantial amount of energy and material. Fig. 3 (b) provides a comprehensive analysis of the cost factors involved in the production of 1 ton of glass containers through the KGRSB and KRMB models. The findings indicate that the cost of the street collection stage in the KGRSB model is significantly lower, with a reduction of 75 % compared to the KRMB model. Furthermore, the cost of the sorting stage in the KGRSB model was also reduced by over 50 % compared to the KRMB model. This result highlights the importance of the collection method in minimizing the life cycle cost of the recycling process. The utilization of separate glass bins results in a substantial reduction in the life cycle cost when compared to the traditional mixed bin collection method. The findings underscore the necessity for a well-conceived and optimized early-stage in-community separation program that can effectively reduce street collection and sorting phases' cost. These stages can significantly influence the overall cost of the recycling process. The findings also suggest the need for continuous improvement in the collection and sorting processes to promote sustainable and cost-effective recycling practices in the glass container production industry.

6.3. *Comparison of open-looped and closed-loop recycling (multiple loops in 21 years)*

Fig. 4 presents a comparative analysis of the long-term sustainability benefits of recycling kerbside waste glass for the production of asphalt and glass containers over a period of 21 years. This analysis provides a comprehensive evaluation of the performance of waste glass cullet's closed/ open-loop recycling.

The waste glass cullet is processed through seven rounds of R7 activities in the closed-loop recycling scenario, representing a full life cycle of the glass container production. On the other hand, the waste glass cullet is processed to produce asphalt and the asphalt goes through four rounds of R5 activities in the open-loop recycling scenario. The comparison of the results of these two recycling scenarios provides valuable insights into the sustainability benefits of closed/ open-loop recycling.

The results depicted in Fig. 4 compare the cost of asphalt and glass containers made of kerbside waste glass cullet for 21 years. The analysis considers four scenarios, which are based on the 3rd functional unit. The annually collected wastes with KGRSB-A and KRMB-A models looping every five years. Wastes in KGRSB-G and KRMB-G models looping every three years.

In order to reflect the typical service life scenarios for urban roads, the KGRSB and KRMB models for the asphalt scenarios are limited to a 20-year service life. At year 20, consideration will not be given to further recycling activities outside of the system boundaries defined in the study, and the cost of the final cycle will only include the use/end-of-life phase. However, it is worth noting that because the removed pavement still has the opportunity to be remanufactured as RAP, the process of it being landfilled as waste is not considered. Whereas the materials in the KGRSB-G and KRMB-G models are recycled every three years in the glass container scenario, for the purposes of comparison with the asphalt scenario, they will undergo seven cycles lasting up to 21 years.

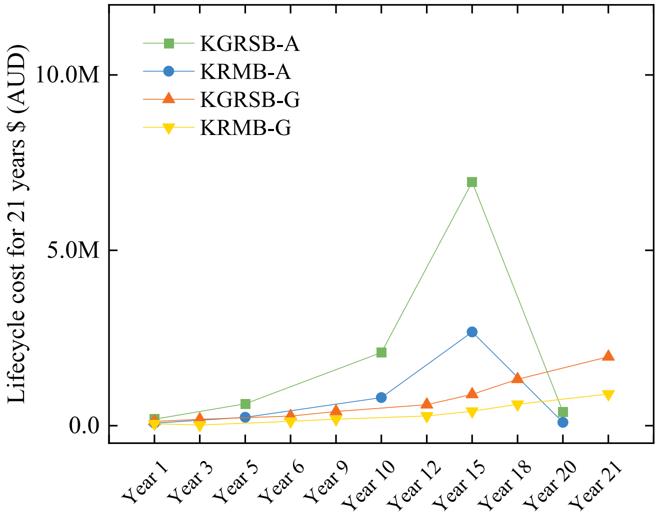

Fig. 4. Life cycle cost of KGRSB/ KRMB-A, and KGRSB/ KRMB- G.

The Fig. 4 demonstrates that the KGRSB-A model, with a cost of 46,276,443 AUD, incurs the highest cost among all the scenarios due to the substantial production of 200,245 tons of asphalt and consumption of 16,863 tons of waste over the 21-year period. On the other hand, the KRMB-G model has the lowest cost of 719,464 AUD while consuming 940 tons of waste and producing only 328 tons of glass containers.

The findings suggest that comparing to the KRMB model, the KGRSB model is associated with a greater cost, primarily due to its higher production output and consequent waste consumption. On the other hand, the cost of street collection and sorting is reduced in the KGRSB model for 1-ton asphalt and glass production, as shown in Fig. 2 (b) and Fig. 3 (b), due to the implementation of separate glass bins.

6.4. *Sensitivity/ uncertainty analysis*

Fig. 5 shows the results of the sensitivity/uncertainty analysis in the KGRSB and KRMB models represented by the asphalt and glass scenarios. The sensitivity/uncertainty analyses are based on the variation of the R activity assignment coefficients.

Within the asphalt scenario, the Fig. 5 shows four different allocation factors for R5 (remanufacturing). When the allocation coefficient k is set at 100 %, it means that all demolished asphalt waste is sent to a local manufacturer to ensure that it is fully reintegrated into the next life cycle as RAP. This scenario shows a rapid increase in cost. As the k is reduced to 75 %, 50 % and finally to 25 %, the cost of each category decreases accordingly. This trend suggests that the reduced recycling efficiency of the asphalt (a reduced percentage of asphalt reused as RAP results in lower costs. As the k decreases to 25 %, the increase in costs becomes stable. Both the KGRSB and KRMB models show this pattern, suggesting that different recycling efficiencies have a consistent effect on costs.

For the glass scenario, when the allocation factor k for R7 is 100 %, this means that during the street collection phase, all used glass container waste is disposed of in the kerbside bin before starting the next life cycle. This glass container waste will not be R2 (reuse/resale), R3 (repair) and R6 (R-use). For the KGRSB model, the same calculation applies to the k for R7 = 75 %, 50 % and 25 % for the street collection phase. A rapid increase in costs occurs when the allocation factor k for R7 = 100 %. Costs decrease as R7 decreases. This pattern is followed in both the KGRSB model and the KRMB model, as the allocation factor k of R7 is 75 % and the increase in costs stabilises.

6.5. *Interpretation of results and discussion*

In the collection phase, labour and transportation cost make up a significant part of the cost. As suggested in the inventory, during the sorting phase, the most significant expenses are related to electricity costs, especially in the Material Recovery Facility (amounting to 1816 AUD) and the glass sorting facility (amounting to 481 AUD), and labour costs, particularly in the KGRSB model (amounting to 454 AUD) and the KRMB model (amounting to 376 AUD).

The findings of this investigation of functional unit annually collected wastes suggest that, comparing to the KRMB model, the KGRSB model exhibits a superior recycling rate relative to the KRMB model in the sorting phase. This implies that the KGRSB model's quantity of recycled glass surpasses that of the KRMB model. Given the fixed proportion of recycled glass in the production of asphalt, comparing to KRMB model, the KGRSB model results in a greater output of asphalt. The utilization of resources and energy increases as production levels

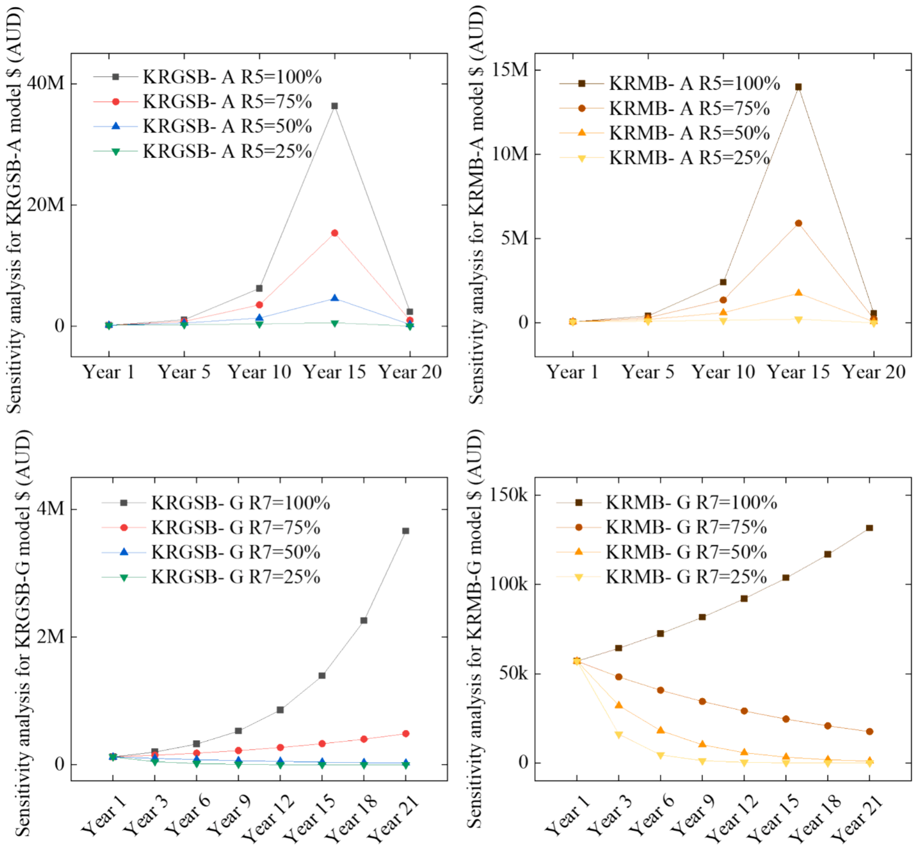

Fig. 5. Sensitivity analysis of cost based on the rate of R5 and R7 for KGRSB-A, KRMB-A, KGRSB-G, and KRMB-G.

rise, as manifested by the costs of materials and energy. This functional unit is also reflecting the alignment with the attributional environmental LCA study. It shows the same result pattern as the environmental impact results that kerbside recycling separate bin had higher environmental impacts comparing to the kerbside recycling mixed bin (Zhang et al., 2024).

As the results for the functional unit of 1 ton of product show, both the closed-loop recycling method (glass containers) and the open-loop recycling method (asphalt) are more cost saving compared to the mixing bin method. The closed-loop recycling method reduces the cost by about 49 % and the open-loop recycling method reduces the cost by about 38 %. Compared to open-loop recycling, the cost of producing 1 ton of glass containers is significantly higher, five times the cost of asphalt production with the KGRSB model and six times the cost with the KRMB model. This functional unit is also reflecting the alignment with the environmental LCA study. It shows the same result pattern as the environmental impact results that kerbside recycling separate bin had lower environmental impacts comparing to the kerbside recycling mixed bin with an environmental impact reduction of 40/%-60 % (Zhang et al., 2024).

Over a 21-year period, the study shows that producing asphalt from waste glass containers is more costly than producing glass containers. However, this does not necessarily mean that closed-loop recycling (glass containers) is superior to open-loop recycling (asphalt) in terms of cost impact. From a waste consumption perspective, closed-loop recycling has a lower ability to consume waste compared to open-loop recycling. In terms of production, the amount of glass container production over 21 years is much lower than the production of asphalt, and the cost per 1-ton production throughout the life cycle is higher for glass containers than for asphalt.

In summary of the findings, the cost of municipal waste glass-derived asphalt and glass containers is substantially influenced by early-stage separation procedures. The KGRSB model can reduce the cost by 40–50 %. Cost hotspots are in the areas of materials and labour, while energy costs are mainly driven by electricity expenses. Over a 21-year period, asphalt production has a higher cost due to the larger production volume. However, on a per-ton basis, the cost of producing glass containers is higher than that of producing asphalt.

In this study, LCC models are grounded in the VRP model as the environmental LCA model presented in (Zhang et al., 2024), which is essential for managing kerbside waste effectively. By aligning these models, it becomes feasible to synergistically combine environmental indicators with cost. Such as method presented in Patel et al., 2024 with GHG emission per unit price. This integrated approach allows for a multi-dimensional analysis that encapsulates both the cost-effectiveness and the environmental impact of waste management practices, providing a clear, quantifiable link between sustainability and cost viability (Liu et al., 2020). To draw holistic conclusions that impact MSW management and planning, this integrated modelling approach can be instrumental. By assessing the intertwined environmental and cost outcomes of different waste management strategies, policymakers and urban planners can devise more informed, sustainable, and cost-efficient feasible waste management plans. For instance, understanding the trade-offs between various recycling rates and their associated costs and environmental benefits can guide the optimization of recycling processes within the urban planning framework. This, in turn, can lead to more effective allocation of resources, enhanced policy formulation, and ultimately, a more sustainable urban waste management system that aligns with both environmental objectives and cost constraints. Thus, by leveraging the combined insights from the environmental LCA and LCC models, stakeholders can make balanced decisions that foster an integrated approach to MSW management, aiming to reduce environmental impact while enhancing cost efficiency.

This study primarily applies the “R” strategies from the VRP model to kerbside glass waste. Each "R" strategy introduces unique challenges and complexities, from cost implications to environmental impacts, which enrich the modelling process. This increased complexity offers substantial benefits by enabling more detailed, context-specific analyses that accommodate the unique characteristics of different waste materials. Comparing to 3R (Zhou et al., 2017) models and 6R models (Bradley et al., 2018), this study integrating a diverse range of "R" activities, it can equip decision-makers with a nuanced understanding of various waste management options. This holistic approach not only supports the optimization of recycling processes but also aids in effective resource management and policy development. Adopting this comprehensive modelling approach fosters a deeper exploration of the circular economy, helping to align environmental sustainability with cost viability across various waste management contexts.

7. Conclusion

This study conducted a 21-year evaluation of the life cycle cost implications associated with kerbside waste materials, utilizing the Value Retention Process (VRP) model to define the costs related to material flows. The objective of the research is to investigate the various alternatives available for recycling kerbside glass within a specific trial zone of a local council. The study yields valuable perspectives on the design of waste management systems, research, and the analysis of costs for the production of asphalt and glass.

The inventory analysis performed in the study yielded several significant findings. Notably, the KGRSB model demonstrated a higher recycling rate compared to the KRMB model, resulting in a substantially greater production of glass cullet products, approximately three times more than the KRMB model. However, this increased production correlated with higher costs. Across all four scenarios considered, factors such as energy consumption, material usage, and labour costs emerged as significant contributors during the sorting and production stages, with material cost, labour cost, and the cost of electricity identified as the most prominent cost drivers in the process.

Further evaluation of the functional unit based on annually collected waste over a single life cycle revealed that the KRMB model incurred lower costs than the KGRSB model due to its lower production output, amounting to only one-third of the KGRSB model's production volume. Additionally, it was observed that the cost of glass container production was lower than that of asphalt production, reflecting the disparity in their production volumes, with glass container production constituting 12 % of the KGRSB-A and 6 % of KRMB-A.

An assessment of the functional unit representing 1-ton production over a single life cycle demonstrated that the KGRSB method exhibited superior cost-effient performance, showcasing a 40–50 % reduction in costs compared to the KRMB method. It is worth noting, however, that at the production stage, the cost of the glass container production process is higher than that of asphalt, mainly due to the higher energy consumption required for glass containers.

Finally, a comparison of the asphalt and glass models over a 21-year period reveals that the costs of the KGRSB model are higher than those of the KRMB model, largely due to the greater production and waste consumption of the KGRSB model over the extended timeframe. Similarly, asphalt (open-loop recycling method) is more costly due to its larger production volume.

The presented model uniquely interprets the "end-of-life" phase not as the absolute conclusion of a material's lifecycle but as a preliminary stage where materials reaching the landfill are considered for potential R9 (Re-mining) activities. This assumption of a significantly extended period before re-mining can occur, which falls outside the scope of our current study timeline, reflects a long-term perspective on material recovery aligned with circular economy principles but introduces a notable limitation in terms of immediate practical applicability. Additionally, the cost model for the kerbside waste material looping does not attempt to calculate the absolute costs of the processes involved. Instead, it is designed to benchmark costs across various circular economy activities, similar to how environmental life cycle assessments might not fully capture the absolute environmental impacts. This benchmarking is valuable for comparative analysis but may not accurately detail the cost nuances of individual processes, highlighting another limitation of our approach. Furthermore, the current model only evaluates the cost aspect. It cannot consider the full economic analysis of the kerbside waste material looping process. The current scope of the model, primarily applied to kerbside waste material looping, represents a limitation as it has not yet been tested across various waste streams. While the model offers insights for glass waste upcycling and downcycling scenarios, its robustness and applicability could be further enhanced by extending its application to diverse contexts.

It is suggested for future research there is a need for further investigations, particularly comprehensive cost-benefit analyses of the economic aspects, to determine the financial advantages and potential revenue streams associated with these initiatives. These studies will provide a comprehensive understanding of the economic dividends associated with kerbside material loop efforts. In addition, a promising avenue of research is to combine cost analysis with environmental assessment. This integrated approach helps to look at both economic and environmental aspects at the same time, thus providing a multidimensional perspective. By employing this methodological blend, researchers and policymakers can make informed choices about waste management strategies, illuminating the intricate interdependencies between economic efficiency and environmental sustainability and recycling practices. This research is expected to provide insights into the development of more effective and sustainable waste management models. Furthermore, exploring the social impacts associated with MSW management could further enrich our understanding. This would involve assessing how waste management practices affect community well-being, public health, and local economies, thereby providing a more comprehensive analysis of the social dimensions of sustainability.

CRediT authorship contribution statement

Jingxuan Zhang: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Muhammed Bhuiyan:** Writing – review & editing, Supervision, Software. **Guomin Zhang:** Writing – review & editing, Supervision, Software. **Malindu Sandanayake:** Writing – review & editing, Validation, Formal analysis. **Satheeskumar Navaratnam:** Writing – review & editing.

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

Data will be made available on request.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2024.06.023.

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