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Circular Economy in Polyisocyanurate-based Insulation: Lifecycle Cost and Glycolysis Recycling Modelling

Abstract

Purpose: The purpose of this study is to evaluate the economic impact of the integration of Circular Economy (CE) principles into the recycling processes of polyisocyanurate (PIR)-based building thermal insulation.

Design/methodology/approach: The study focuses on the glycolysis recycling of PIR waste and identifies factors influencing the cost-effectiveness of polyol recovery. An agent-based model was designed for product circularity assessment and Lifecycle Cost Analysis (LCCA). The model was applied and evaluated on a polyurethane (PUR)-based PIR building thermal insulation product. Sensitivity analysis was conducted to identify and assess the sources of uncertainty within the model.

Findings: The results identified that the cost of glycolysis agents and the catalyst contributed to 62% of the cost of the polyol recovery process compared to PIR waste. This study highlights the impact of supplementary materials in polyol recovery. Results also highlight how excessive methylene diphenyl diisocyanate (MDI) significantly influences the cost of recycling PIR building thermal insulation.

Originality: This study provides insights into the economic feasibility and material impacts of integrating CE in PIR insulation recycling.

Practical implications: CE of the least recycled materials such as PIR is as an effective alternative to provide a sustainable economic growth and to protect against natural capital depletion.

Keywords: Circular Economy; Remanufacture; Lifecycle Cost; Agent-based modelling; Polyurethane; Thermal Insulation

1. Introduction

Thermal insulation is broadly regarded as one of the most effective measures for enhancing the energy performance of buildings by reducing heat transfer within building envelopes, leading to lower heating and cooling demand and greater overall energy efficiency (Stephan and Athanassiadis, 2017). It offers substantial advantages for both construction firms and building owners by reducing energy use, lowering associated costs, and minimising environmental

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impacts, making it a highly favourable option across the sector (Abu-Jdayil *et al.*, 2019). PIR and PUR insulation materials offer valuable utility due to their energy efficiency and potential for recyclability (Prałat *et al.*, 2023; Reinerte *et al.*, 2024). This performance is enhanced by the insulation's long lifecycle, which eliminates the need for regular replacements and reduces construction waste (Nasir *et al.*, 2017). These insulation materials are widely used in residential, commercial, and industrial buildings that require strong thermal performance and adherence to fire-safety standards (Schiavoni *et al.*, 2016). Due to its strong thermal performance and adherence to fire-safety standards, the use of PUR-based PIRs has expanded with increasing adoption of high-performance building envelopes and nearly-zero-energy building requirements (Prałat *et al.*, 2023). The insulation can be applied to roofs, external walls, facades, and cold-storage systems (Lakatos *et al.*, 2023). However, these materials, despite their long use, often end up in landfills, resulting in significant waste generated after demolition or major building maintenance. Handling PIR insulation waste poses technical and environmental challenges due to its thermoset polymer structure, which makes it systematically demanding to be reprocessed (Gahlen *et al.*, 2021). Chemical additives, layered facings, and flame retardants complicate separation and treatment processes (Thiounn and Smith, 2020). During disposal, PIR can generate hazardous decomposition products, and limited recycling infrastructure further restricts large-scale recovery. These factors increase the cost and complexity of managing PIR waste within construction supply chains (Geyer *et al.*, 2017). PIR waste management presents challenges in both high-income, and low- and middle-income countries (LMCs), although for different reasons. High-income countries generate larger volumes of PIR waste due to widespread insulation use driven by rigorous energy-efficiency standards (Mohajerani *et al.*, 2020). In contrary, LMCs typically lack adequate recycling infrastructure, formal waste-collection systems, and regulatory frameworks, which increases reliance on landfilling or informal disposal, which consequently makes PIR waste management to be considered as a global issue that manifests differently across economic contexts (Tian *et al.*, 2024). Efforts to manage these insulations include the development of chemical recycling approaches such as glycolysis recycling, which can recover polyols for reutilisation in polymer production (Amran *et al.*, 2021). Moreover, several manufacturers have piloted take-back schemes and recycling programmes to increase material recovery ratios. Policy initiatives in Europe and other countries encourage diversion of insulation waste from landfills through extended producer responsibility, landfill taxes, and more sustainable strategies (European Commission, 2020).

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Circular Economy (CE) helps reduce carbon emissions by optimising material production to conserve energy and resources, and by promoting closed-loop lifecycles in waste management (Adelekan and Sharmina, 2024; Amir *et al.*, 2023; Khajuria *et al.*, 2022). In 2002, approximately 376 million kilograms of PUR and PIR insulation foam were incorporated into new products (Zia *et al.*, 2007). Considering the utilisation of insulation materials in the production process by manufacturers and consumption by customers, the concept of 6-R (Redesign, Reduce, Reuse, Repair, Recycle, and Recover) has been brought into consideration to apply the CE concept (Özkan *et al.*, 2025). From a recycling perspective, PUR and PIR insulations can be processed through various recovery methods, including mechanical and chemical recycling approaches (Gu *et al.*, 2021). Chemical recycling processes, such as glycolysis make it possible to recover high-value polyols that can be incorporated back into the production of new insulation products (Lee and Jung, 2022). Kanchanapiya *et al.* (2021) examined the economic feasibility of recycling PUR-based insulation wastes in Thailand using a single-phase glycolysis recycling and found that the regenerated polyol provides substantial financial advantages and performs correspondingly to polyols obtained from virgin material. Numerous studies examined the energy performance, environmental impacts, and lifecycle assessment of incorporating PUR-based PIRs into buildings; however, research addressing the economic lifecycle dimensions of these products within Sustainable Development (SD) and CE frameworks has remained comparatively limited. Gigasari *et al.* (2023) carried out a cradle-to-gate Lifecycle Assessment (LCA) that focused solely on assessing carbon payback times when optimising insulation materials for various building orientations. In an experimental study by Prałat *et al.* (2023), which examined the thermal performance of an innovative PUR-based PIR insulation, the authors did not address cost analysis or the economic implications of their findings. This gap is likely the result of limited emphasis on economic circularity assessments, such as Lifecycle Cost Analysis (LCCA), within existing research, as well as a general lack of specialised expertise in this area among researchers and industry practitioners (Altaf *et al.*, 2024). To view PIR waste as an asset, and to examine the applicability of CE principles for this material/product, this study aims to conduct an LCCA of the material across its value chain. The findings provide meaningful insights to construction companies, recycling firms, and policymakers in the field.

The paper is organised as follows: Section 2 provides a detailed literature review of CE within the context, focusing on thermal insulation and, in particular, PUR and PIR-based insulations. Section 3 provides a succinct outline of the methods used in this research. Section 4 presents the study results and provides the calculated costs associated with the various scenarios in

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PIR's end-of-life, followed by a critical discussion, embracing nuanced elements from the results and assessing how they compare with the existing research. The paper is concluded in Section 5.

2. Literature Review

2.1 Circular Economy

As a response to the prevailing linear model of take-make-dispose, the Circular Economy (CE) concept has emerged as an effective approach for supporting sustainable economic growth while reducing pressure on natural resources (Osobajo *et al.*, 2022). This approach seeks to preserve and enhance the value of raw materials, natural resources, and products by retaining them within the system for as long as possible (Merli *et al.*, 2018). The development of a CE relies on the interconnected stages of products, processes, and systems (Jayal *et al.*, 2010). A sustainable outcome cannot be achieved unless product design, production process, supply chain efficiency, management practices, and investment assessments are treated as an integrated system (Singh *et al.*, 2026). To minimise waste generation and support long-term sustainability, the 6R concept principles offer a structured approach for achieving a closed-loop system. These principles, reduce, reuse, recycle, recover, redesign, and remanufacture, guide the handling of materials throughout a product's entire lifecycle, ensuring that resources remain in circulation for as long as possible (Jawahir and Bradley, 2016). The underlying principles give rise to six practical business strategies that support CE implementation: regeneration, sharing, optimisation, looping, virtualisation, and exchange (Macarthur Foundation, 2015; Rashidian *et al.*, 2025). The housing sector, which consumes nearly 40% of all manufactured products during construction, accounts for around 35% of global energy use (Leising *et al.*, 2018; Osobajo *et al.*, 2022). Although the CE concept has been widely examined across various industries and academic fields, its application to the economic, energy efficiency, and environmental dimensions of buildings remains underexplored (Leising *et al.*, 2018). Due to its low resource efficiency, the building and construction sector produces close to 100 billion tonnes of construction and demolition waste annually, with roughly a third of this material still being landfilled, which indicates significant challenges for sustainable resource management (Shooshtarian *et al.*, 2024). It is widely recognised that material reuse in construction is difficult, as buildings are typically discarded at the end of their lifespan, as reflected in the United Kingdom's annual production of around 45.8 million tonnes of demolition and construction waste (Akanbi *et al.*, 2018).

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2.2 Thermal Insulation and PUR-based PIRs Materials in Buildings

Thermal insulation is widely recognised as an effective means of improving building energy efficiency, offering economic and environmental benefits for both construction firms and building owners (Lakatos *et al.*, 2023). Due to the rapid growth of energy prices and the need for thermal comfort within residential and commercial buildings, thermal insulation products are gaining more attention (Kowalczyk *et al.*, 2023). The deterioration of insulation in older buildings commonly leads to substantial efficiency losses (Chen and Lai, 2025). Traditional insulation materials such as PUR-based insulations, cellulose, mineral wool, cork, glass wool, and polystyrene are widely used in buildings, but they can be costly and, in some cases, pose risks to the environment and human health (Mud Fadhil *et al.*, 2014). Although the use of thermal insulation in construction has increased in recent years, its production and disposal still involve substantial energy consumption and waste generation, largely due to reliance on non-renewable, fossil-based materials (Wang *et al.*, 2018). As an enhanced form of PUR – PIR – offer superior thermal insulation performance (Reinerte *et al.*, 2024). PIRs are among the most applied thermal insulation materials for residential and commercial thermal improvement due to their anti-flammability structure (Lazo *et al.*, 2023). PIRs are generally considered green materials as they are employed to maximise energy efficiency, reduce energy bills and provide thermal comfort within commercial and residential buildings (Gahlen *et al.*, 2021; Lee and Jung, 2022). PIR is also widely used as the insulating core in factory-made sandwich panels, which typically consist of thin metal facings bonded to a light insulating core, and their overall cost structure is strongly influenced by the economic contribution of the core material (Sonnenschein, 2015). In sandwich metal panels, the materials used in the insulation core typically represent a significantly higher cost than the metal facing layers (Mamalis *et al.*, 2008). The focus on the economic lifecycle aspects of these products within the CE perspectives has been, in comparison, substantially limited. Gigasari et al. (2023) conducted a cradle-to-gate LCA study to investigate carbon payback time in optimising insulation materials. In an experimental study of thermal characteristics of innovative insulation made of PUR-based PIR by (Prałat *et al.*, 2023), no consideration was given to cost analysis and economic implications. The limited focus on cost analysis in such contexts is generally due to the low interest in conducting economic circularity analysis (Altaf *et al.*, 2024).

2.3 Chemical Composition and Structural Characteristics of PUR and PIR

In the form of foam and CASEs (coatings, adhesives, sealants and elastomers), PURs account for almost 8% of total polymer-based materials produced globally (Kemona and Piotrowska, 2020). As an advanced form of PUR, the variant PIR has shown outstanding thermal insulation

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properties (Reinerte *et al.*, 2024). PUR and PIR are both derived from PUR, a plastic material formed through chemical reactions (Kingspan Ltd, 2024). Due to the structural and compositional similarity between these two PUR-derived products, they are named as 'PIR-PUR foam' or vice versa (Qian *et al.*, 2022).

2.4 Sources and Generation of PUR-based Waste

The building insulation foam waste is generally generated throughout the manufacturing, construction and demolition phases (WRAP, 2013). In addition, packaging materials associated with PUR-based PIR insulations also contribute to the overall waste stream (Morashti *et al.*, 2022). Although research specifically examining packaging impacts for these products is limited, broader studies indicate that packaging can represent a significant share of product-related material flows and has notable implications for cost and logistics efficiency (Morashti *et al.*, 2022). Most of the generated PUR foam waste is still being transformed into energy as an alternative source of fuel rather than being recycled into a new value-added product (Kanchanapiya *et al.*, 2021). Zia et al. (2007) introduced four major practices to recover and recycle PURs, including mechanical recycling, advanced chemical and thermochemical recycling, product recycling, and energy recovery.

At the end of their useful life, clean and undamaged PUR boards have the potential to be reused as second-hand products, maintaining the same characteristics of newly manufactured products (IBU-EPD, 2018; Kingspan Ltd, 2019a; Modesti *et al.*, 2018).

2.5 Recycling Technologies for PUR-based Waste

Glycolysis recycling has been the most marketed depolymerisation method of downgrading, chemically breaking and returning dead products to life by recovering their crucial primary components (Heiran *et al.*, 2021). The main goal of recycling PUR waste via glycolysis is to recover the primary polyol, which can be reused as a raw material for producing new PURs or branded as a fuel (Heiran *et al.*, 2021).

Although mechanical recycling of PUR waste is not as sophisticated as chemical recycling, with lower costs, only 1% of the produced waste is recycled mechanically (Kanchanapiya *et al.*, 2021). The glycolysis recycling of PUR waste provides the opportunity to recover polyols, as well as polyols containing isocyanates (Kanchanapiya *et al.*, 2021). Currently, the glycolysis process is performed through two different methods, single-phase and split-phase, depending on the obtained mixture during the degradation process of polyols (Kanchanapiya *et al.*, 2021). One of the most influential cost categories of chemical recycling of PUR waste is the capital cost of purchasing the required agents and catalysts throughout the process (Kanchanapiya *et*

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al., 2021). The potential agents and catalysts convenient for the glycolysis recycling of PUR-based waste are shown in Table .

Table I Agents and catalysts for glycolysis recycling of PUR-based waste (Source: Authors).

Agent Type	**Catalyst Type**	**Reference**
Ethylene Glycol (EG)	Organometallic compounds	(Miguel-Fernández *et al.*, 2022)
Hexamethylene Glycol (HDO)	Sodium Acetate (NaAc)	
Propylene Glycol (PG)	Diethanolamine (DEA)	(Amundarain *et al.*, 2022)
Diethylene Glycol (DEG)	Potassium Acetate (KAc)	
Dipropylene Glycol (DPG)	Potassium Hydroxide (KOH)	
Pentamethylene Glycol (PDO)	Dimethylaminoethanol (DMAE)	
Glycerine	Sodium Hydroxide (NaOH)	(Gu *et al.*, 2023)
Trimethylene Glycol	Lithium Octoate	(Kanchanapiya *et al.*, 2021)
Hexamethylene Glycol (HDO)	Stannous Octoate	
Tetramethylene Glycol (BDO)	Driethylenediamine (DABCO)	
Driethylenediamine (DABCO)	Zinc Acetate (ZnAc2)	
Crude Glycerol	-	
Refined Glycerol	-	

A key factor towards recycling PUR-based products through the glycolysis method, is the impurity level of the obtained polyol, as it has a significant contribution towards the polyol mixture ratio in re-producing PUR-based insulations (Miguel-Fernández *et al.*, 2022). Due to its high level of impurities, various studies have been conducted to investigate the utilisation ratio of 10%, 40%, and 70% of the recovered polyol in the polyol mixture to produce new

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PUR-based thermal insulations (Kemona and Piotrowska, 2020). Although extensive research examines the chemical mechanisms of glycolysis for PUR-based PIR waste, again far less attention has been given to the economic feasibility of polyol recovery, particularly the influence of glycolysis agents, catalysts, material purity, and reverse logistics requirements on overall recycling costs (Kanchanapiya *et al.*, 2021; Miguel-Fernández *et al.*, 2022; Zia *et al.*, 2007).

2.6 Landfilling and End-of-life Management of PUR-based Waste

Landfilling is still commonly considered as the last disposal destination of municipal solid wastes (Vaverková, 2019). Almost 50% of the generated PUR waste is taken through the landfilling process (Kemona and Piotrowska, 2020). Accordingly, the construction industry owns almost 35% of the landfilled waste throughout the world (DEFRA, 2023). Landfilling of PUR products after their primary lifecycle is the most common waste treatment among others (Miguel-Fernández *et al.*, 2022). It has fewer environmental impacts than incineration due to PUR wastes' long lifecycle, less resource and energy consumption, and greenhouse gas emissions (Deng *et al.*, 2021). It is recommended that PURs should not be landfilled permanently; however, landfilling should be taken as a temporary solution to store the waste before taking it back for the recovery process by considering the most suitable technologies (Kemona and Piotrowska, 2020). Transport distance is a major cost driver in the disposal of construction materials, and existing studies illustrated that long waste-haul distances significantly reduce the economic feasibility of landfill treatment sue to fuel, labour, and operational demands (Callao *et al.*, 2021; Kim and Jeong, 2017; Di Maria *et al.*, 2018).

2.7 Product Sustainability Assessment Methods

In line with the principles of LCA, LCCA is used to evaluate the economic sustainability of a product or system by examining capital costs, operational costs, and potential savings across the entire lifecycle (Dwaikat and Ali, 2018). To support clearer decision-making, this method examines the total cost of ownership of the product or system from its initial stage through to end-of-life, covering 5 main phases as: concept and definition, design and development, manufacturing and installation, operation and maintenance, and disposal (Norman, 1990). Significant efforts have been made across multiple sectors, including manufacturing, energy, aerospace, logistics, and construction to develop a structured and detailed LCCA framework since the early twentieth century (Farsi *et al.*, 2020). Data plays a crucial role in identifying the necessary information across a product's lifecycle (Yang *et al.*, 2009). The cost structure is organised into several data input categories, which include linked, unlinked, direct, indirect, variable, fixed, opportunity and sunk costs (Graddy-Reed *et al.*, 2021). A substantial part of

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academic and institutional work on LCCA is grounded in the detailed framework developed by the British Standards Institution. The BSI ISO 15686-5 sets out a structured approach for evaluating the lifecycle costs of buildings and construction materials, covering five key whole-life stages: planning, design, construction, operation and maintenance, and end-of-life (BSI ISO15686-5, 2017). Identifying cost drivers across the full lifecycle of an asset is a central component of LCCA, as it helps stakeholders understand cost patterns and potential savings (NATO, 2009). During the manufacturing stage, LCCA depends on factors such as product lifespan, projected sales volume, expected price variability, and the anticipated total costs linked to the product (Kádárová *et al.*, 2015). Moreover, energy consumption in the manufacturing stage is an important contributor to the overall lifecycle cost profile of products, as material choice directly influences processing energy demand (Ivanova *et al.*, 2018; Rivero-Camacho *et al.*, 2023). Transportation distance is one of the dominant cost factors in transporting construction materials, with longer routes significantly increasing fuel demand and overall logistics costs (Daylan and Ciliz, 2016; Kärhä *et al.*, 2024; Zgonc *et al.*, 2019). The installation stage represents a significant element of the overall lifecycle cost of building insulation systems; however, existing research on PUR-based PIR insulation predominantly concentrates on thermal performance and energy efficiency, with comparatively limited analysis on the economic dimension associated with installation (Vasishta *et al.*, 2023; Wiprächtiger *et al.*, 2020).

2.8 Agent-based Modelling

In recent years, Agent-based Modelling (ABM) has received increasing attention in CE research, attracting interest from academics and industry worldwide as a means of analysing and improving the profitability of economic systems. ABM has become a suitable approach for analysing complex bottom-up economic and market modelling (Bert *et al.*, 2015). ABM is widely applied across various sectors, including housing, agriculture, information technology, marketing, manufacturing, and logistics (Luo *et al.*, 2019). ABM focuses on individual units or agents, each with its own characteristics at different stages of the supply chain or lifecycle, and uses their interactions to shape and regulate the behaviour of the overall system or product (Secchi *et al.*, 2024). Agents are understood to operate with autonomy, acting independently based on the information available to them; heterogeneity, reflecting variations in characteristics such as income, preferences, and behaviour; and activity, meaning their actions influence the wider system (Rizzati and Landoni, 2024). They are goal-directed and proactive, stablishing objectives beyond routine tasks, and reactive and perceptive, able to recognise and

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respond to environmental conditions (Fussone *et al.*, 2025). Agents also operate under bounded rationality, making reasonable decisions despite limited information, as illustrated in emergency-exit choices during a fire (Castle and Crooks, 2006). Furthermore, they are interactive and communicative, exchanging information and detecting inconsistencies, possess mobility that supports dynamic interactions within systems (Drchal *et al.*, 2019), and demonstrate learning and adaptation, adjusting behaviour based on experience to function effectively in changing environments (Li *et al.*, 2019). Within the LCA context, ABM explores how different agent characteristics shape decision-making and, in turn, influence the environmental outcomes of the overall system being analysed (Lan and Yao, 2019). Tong et al. (2023) illustrated that recycling outcomes depend strongly on the waste owner's behavioural tendencies, and their ABM successfully revealed underlying psychological patterns influencing these decisions. Ceschi et al. (2021) applied ABM to a new management policy aimed at nudging recycling behaviour and demonstrated that the model effectively captured how multi-layer agents respond across different variables. Tian et al. (2024) used ABM to design a cross-regional policy design, including a 20% improvement in recycling rates and equivalent emission reductions. In waste-related LCA, where systems involve real-time processes such as collection, sorting, and recycling, ABM supports communication among agents and variables, enabling clearer identification of system interactions and helping reduce emissions, minimise waste generation, and expand recycling opportunities (Kerdlap *et al.*, 2020). ABM is valuable because the overall behaviour of a system emerges from its individual mechanisms, which respond differently depending on their environmental conditions, even when following the same rules, which enables the analysis of these complex and autonomous interactions (Bert *et al.*, 2015).

2.9 Research Gaps & Contributions to Knowledge

Among various insulation materials, PUR and PIR-based insulations are widely used due to their superior thermal performance and fire resistance (Modesti *et al.*, 2018). However, despite their long lifespan, PIR and PUR insulations often end up in landfills after building demolition or renovation, contributing to significant waste accumulation and environmental concerns (Prałat *et al.*, 2023). Although the CE framework has been recognised, its integration into insulation waste management remains underexplored (Ghisellini *et al.*, 2016). Prior studies have investigated the energy efficiency and thermal performance of building insulation materials; however, there are still gaps in assessing their economic circularity and cost-effectiveness within the CE in this context. Several key limitations have been identified in the literature, which are (i) most studies evaluating building insulation focus on thermal

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performance and energy efficiency (Gök *et al.*, 2024). However, there is a lack of research integrating LCCA to analyse the economic feasibility of recycling insulation materials (Nyme Uddin *et al.*, 2022). (ii) There are studies on recycling PUR insulation waste, yet specific investigations into PIR-based insulation circularity and cost-effectiveness are limited (Altaf *et al.*, 2024). (iii) Existing research often lacks a complete cost assessment model covering all lifecycle phases, from production to disposal (Nugroho *et al.*, 2022). (iv) Research on glycolysis recycling of PIR insulation remains sparse, particularly regarding the economic impact of additional chemicals such as methylene diphenyl diisocyanate (MDI) and glycolysis agents on polyol recovery costs (Kemona and Piotrowska, 2020). (v) Although ABM is highly capable of handling complex analytical problems, its application has been concentrated mainly in fields such as electrical engineering, robotics and computer science, and building insulation analysis in the literature has been mostly performed within engineering simulation modelling platforms such as DesignBuilder, TRNSYS, AutoDesk, and EnergyPlus (Bastos Porsani *et al.*, 2023; Gök *et al.*, 2024; Pakka *et al.*, 2012; Suresh *et al.*, 2023).

This study addresses these gaps by evaluating the integration of CE principles into the lifecycle cost and recycling processes of PIR-based building thermal insulation. The key contributions are:

1. Performing a full LCCA–economic assessment of PIR insulation within a CE framework, offering insights into cost-effective recycling strategies,
2. Assessing PIR insulation's circularity through Agent Based Modelling (ABM), which provides a novel methodological contribution to insulation waste management considering non-linearity over lifecycle stages, and
3. Investigating the lifecycle cost implications of glycolysis recycling for PIR waste, identifying the major cost contributors, including catalysts and glycolysis agents.

3. Research Methodology

3.1 Methodological Framework

We have adopted an ABM approach to examine the PIR lifecycle and examine pertinent costs. ABM provides a broad range of advantages, as it allows the comprehensive simulation of agent decision-making, capturing the nuanced behaviours of agents in different circumstances (Wu *et al.*, 2024). Furthermore, ABM consolidates the integration of multiple concepts within one framework, enhancing the model's flexibility, robustness and comprehensiveness in analysing attributes of complex behaviours such as phase transitions, breaking points and perturbations (Wu *et al.*, 2024).

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3.2 Data Collection

This study conducted secondary data collection through an extensive review of literature in scientific databases, governmental guidelines, building thermal insulation manufacturers, approved industry-related institutions, well-recognised online commercial database platforms, and approved industry-related product data sheets. Throughout the data collection process, a wide range of secondary reference materials were collected using suitable field-related keywords to search through the reference materials, including titles, abstracts, and main bodies (Figure 1).

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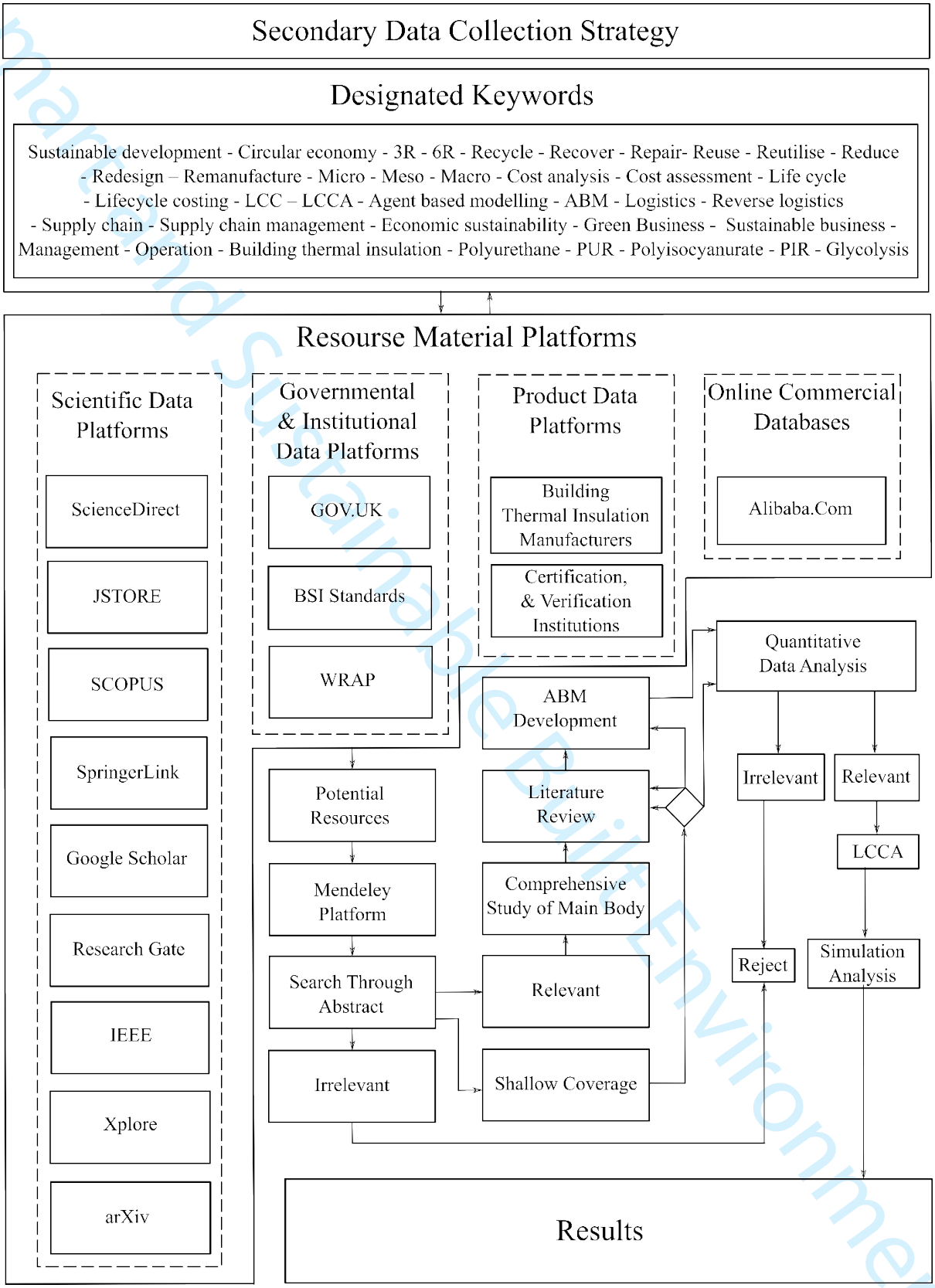


Figure 1. The data collection strategy (Source: Authors).

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3.3 Scope and Assumptions

The scope of the developed model for LCCA would be solely to consider the cost drivers and the benefits drivers are considered as input data. The future cost value was used instead of the net present value. A tactical decision was made to eliminate time from the analytical scope of this research, but to keep it only as an illustrative element for the operational interface of the product's lifecycle within the simulation model. The decision was primarily affected by the nature of the collected data for LCCA. The cost of material extraction and transport to the manufacturer was deemed out of scope. Finally, we used the British Pound (£) as the cost unit in our calculations.

It is also assumed that the unit price for the raw material acquisition in the primary lifecycle stays the same to allow the unit prices to be used within the recycling process. Along with this, a future value formula based on the lifespan of the PIR building thermal insulation, which is 75 years, is applied. Due to a lack of reliable data regarding PIR waste scraps cost, as PIR is a PUR-based product and both can be recycled with the same recycling methods, the cost of PUR scraps was calculated for the glycolysis recycling process. Moreover, it is assumed that PUR scraps are mechanically shredded into granules in the recycling plant. The mixture's recovered polyol ratio is assumed as 10%, as per literature data.

3.4 Agent-based Model Development

A novel single-agent model was developed in AnyLogic software (v. 8.9.4) and tailored to conduct LCCA for this study's proposed product, as illustrated in Figure 2.

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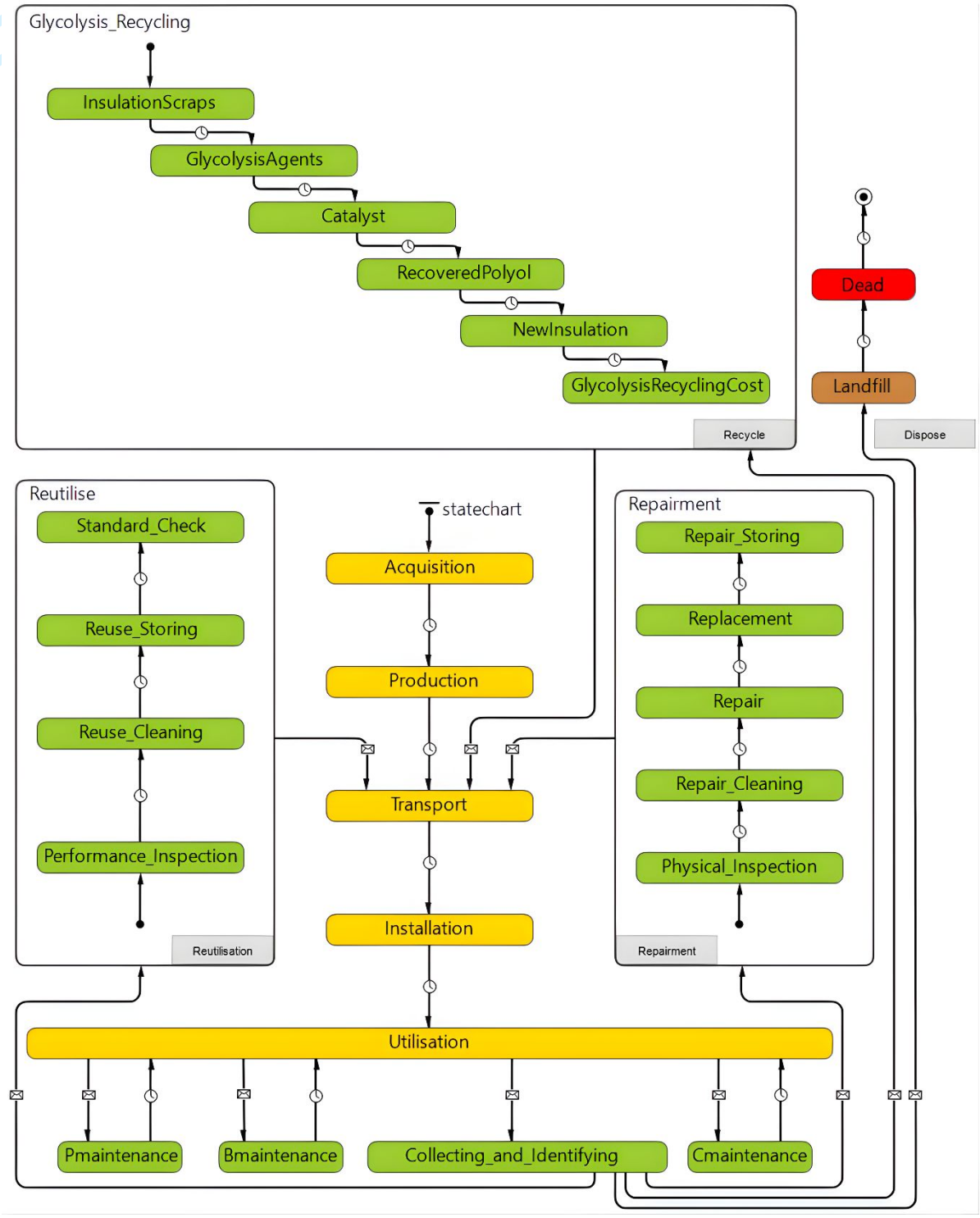


Figure 2. The developed agent-based model (Source: Authors).

The developed ABM has the potential to be tailored to other products with minor adjustments. The model includes the map of the product's entire value chain, from raw materials procurement to green end-of-life and landfill destinations. Figure 3 illustrates the lifecycle of the PUR-based PIR building thermal insulation, and Figure 4 represents the UML state

machine diagram of this model, detailing the applied logic behind the model development in each individual state. The model consists of multiple product lifecycle stages.

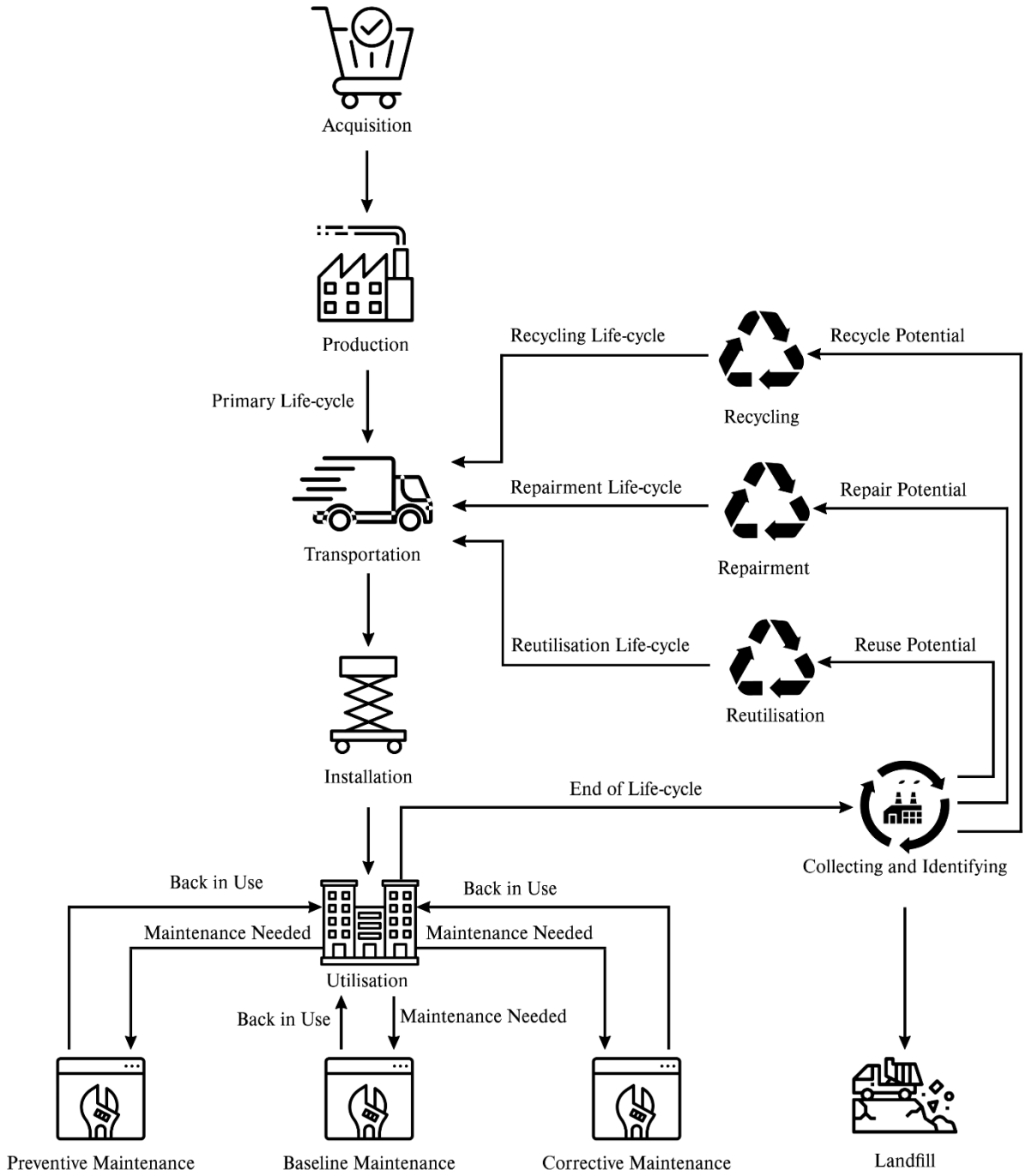


Figure 3. The modelled lifecycle stages of the PUR-based PIR building thermal insulation (Source: Authors).

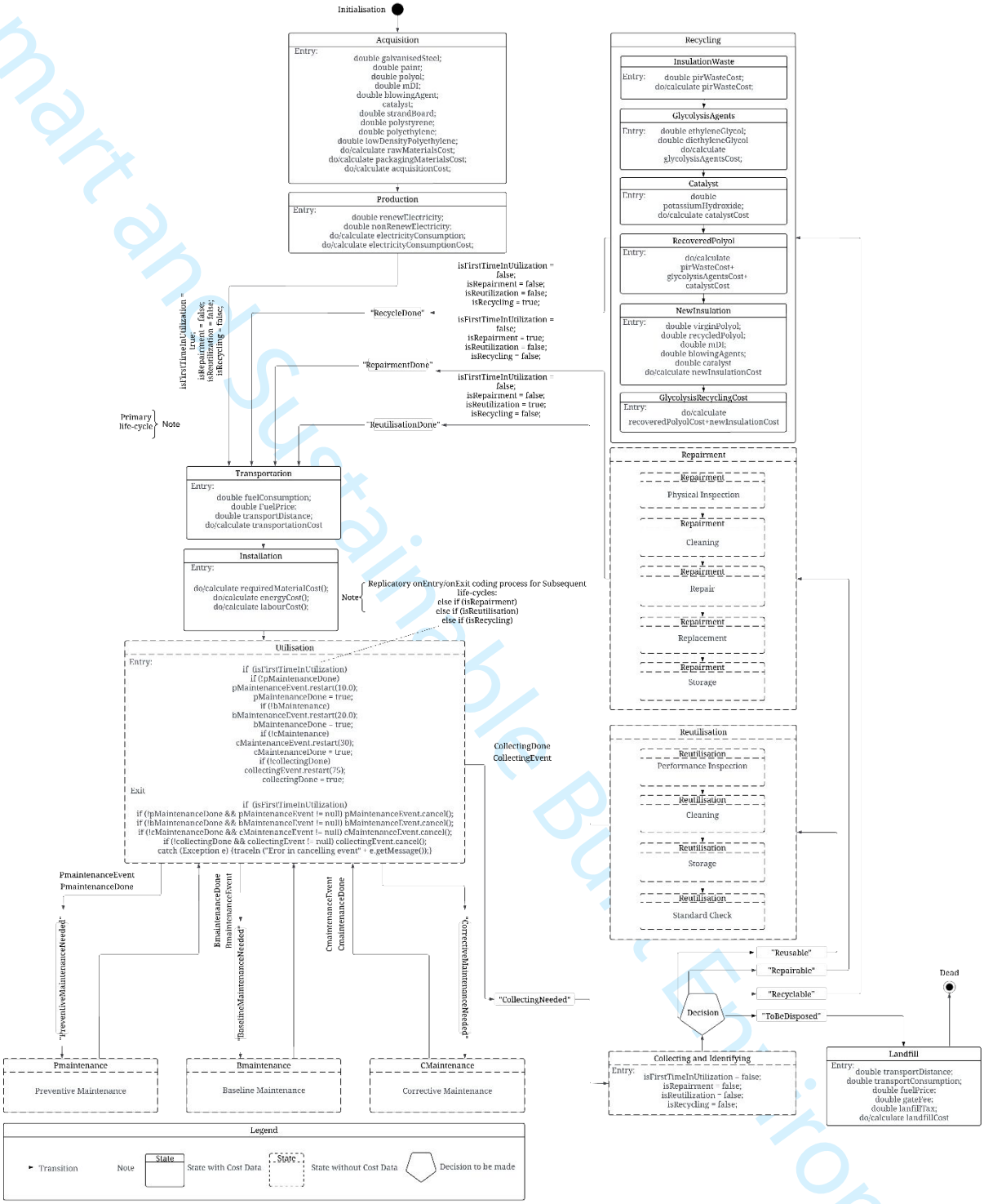


Figure 4. UML state machine diagram of the developed model for PIR building thermal insulation lifecycle (Source: Authors).

The primary lifecycle stage of the model consists of seven stand-alone stages as ‘acquisition’, ‘production’, ‘transport’, ‘installation’, ‘utilisation’, ‘maintenance’, and ‘collecting and identifying’. Once the primary lifecycle ends, four different streams are provided within the model for the product to progress through: ‘after-life reutilisation’, ‘after-life repairment’,

'recycling' and 'landfill'. Three types of transitions are used in the model: transition "Timeout" only for illustration of the product's lifecycle progression, transition by "message" between each state, and transition by "message" by sending it through a designated button, where a decision needs to be made. Therefore, the developed model represents the entire lifecycle of a product under real-world conditions.

3.5 Lifecycle Cost Analysis Equations

Table II illustrates the LCCA formulas that various scholars employ in previous LCCA research projects. Although LCCA is extensively studied in a diverse and wide range of research projects, LCCA equations vary regarding the utilised symbols and equation components. But all the equations are performed in the same way and provide the same results (Altaf *et al.*, 2024; Brealey *et al.*, 2011; Farsi *et al.*, 2020; Shankar Kshirsagar *et al.*, 2010; Shibata *et al.*, 2023; Zhang *et al.*, 2018).

Table II. Proposed Cost Model – LCCA formulations (Source: Authors).

LCCA formulations
$\mathbf{C_R = T_M \times M_P}$ Where, C_R = Composition Ratio; T_M = Total Mass; M_P = Mass Percentage
$\mathbf{LCC = C_A + C_P + C_T + C_I + C\ (Each\ End\text{-}of\text{-}life\ Scenarios = C_{REC}, C_L)}$ where, LCC = Lifecycle Cost; C_A = costs of raw materials acquisitions; C_P = production costs; C_T = transportation costs; C_I = installation costs; C_{REC} = recycling costs; C_L = landfill costs.
$\mathbf{C_A = C_{GE} + C_{PA} + C_{PO} + C_{MDI} + C_{BA} + C_C + C_{SB} + C_{PS} + C_{PF} + C_{LDP}}$ where, C_{GE} = cost of galvanised steel coatings; C_{PA} = cost of coating paint; C_{PO} = cost of virgin polyol; C_{MDI} = cost of methylene diphenyl diisocyanate; C_{BA} = cost of blowing agent; C_C = cost of catalyst; C_{SB} = cost of strand board for packaging; C_{PS} = cost of polystyrene for packaging; C_{PF} = cost of polyethylene film for packaging; C_{LDP} = cost of low-density polyethylene film for packaging.
$\mathbf{C_P = C_{RE} + C_{NRE}}$ where, C_{RE} = cost of renewable electricity; C_{NRE} = cost of non-renewable electricity.
$\mathbf{C_T = ((T_D * F_C) / 100) * F_P}$ where, T_D = transport distance; F_C = fuel consumption per 100/Km; F_P = fuel price.
$\mathbf{C_I} = C_{WBC} + C_E + C_{LAB}$ where, C_{WBC} = cost of sealant; C_E = electricity cost during installation; C_{LAB} = labour costs.

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$C_{REC} = C_{PIRW} + C_{EG} + C_{DG} + C_{PH} + C_P + C_{RP} + C_{MDI} + C_{BA} + C_{CAT}$ where, C_{PIRW} = cost of PIR waste; C_{EG} = cost of ethylene glycol; C_{DG} = cost of diethylene glycol; C_{PH}= cost of potassium hydroxide; C_{CP}= cost of virgin polyol; C_{RP}= cost of recycled polyol; C_{MDI}= cost of methylene diphenyl diisocyanate; C_{BA}= cost of blowing agent; C_{CAT}= cost of catalyst.
$C_L = C_{TLS} + C_{GF} + C_{LT}$ where, C_{TLS}= transport to landfill site; C_{GF}= cost of landfill gate fee /tonne/Kg; C_{GF}= cost of landfill tax /tonne/Kg.
$FV = C_E * (1 + R)^T$ where, FV= future value of each cost element; C_E= cost element; R= inflation rate; T= product's lifecycle period.

3.6 Secondary Data

Following a comprehensive review of various types of Environmental Product Declaration (EPD) documents for different types of building thermal insulations, it was observed that EPD documents are produced in compliance with ISO 14025, TS/14027, 1440, ISO 21930, and EN 15804 standards, and they provide generalised data about a single product or a class of products within a specific sector or industry (EPDIAB, 2024; Gibson, 2022; Kingspan Ltd, 2019a, 2023). The provided data by the EPD was cross-examined with product datasheets (Kingspan Ltd, 2023), and then the closest product specification for 1 **(**m^2) was selected, as presented in Table .

Table III. PIR insulated metal wall panel thermal insulation (Source: Authors); data extracted from (Kingspan Ltd, 2019a). *Click or tap here to enter text.*

Polyisocyanurate (PIR) Insulated Metal Wall Panel		
Property	**Value**	**Unit**
Length (m)	12	m
Width (m)	1	m
Thickness (Core 140)	152.4	mm
Weight	13.5	Kg
R-Value	8.44	$(m^2K)/W$
U-Factor	0.11	$W/(m^2K)$
RSL	75	Year

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In the first stage, the product composition data were collected to identify the required raw materials in the product's production process (Table IV).

Table IIV. Product Composition Data from EPD (Source: Authors), data sourced from (Kingspan Ltd, 2019a).

Product Composition (EPD)		
Material	**Amount (Kg/M²)**	**Percentage of Total Mass (%)**
Galvanised Steel	745.3	64.60 %
Polyisocyanurate	245	21.23 %
Pentane	16	1.39 %
Proprietary Chemicals	147.5	12.78 %
Product Total	1153.8	100%

After collection and examination of the data, the collected values were converted to the product specifications in the datasheet, considering the weight of the product and the composition percentages, using the proportionality formula provided in Table II.

This proportionality calculation was followed with respect to the product's composition provided within the EPD datasheet and has been followed throughout the LCCA for each lifecycle stage section to tailor the collected data based on the chosen product's specifications (Table V).

Table V. Converted ratios for product compositions, unconverted (Source: Authors), data sourced from (Kingspan Ltd, 2019a).

Converted Product Composition		
Material	**Amount (Kg/M²)**	**Percentage of Total Mass (%)**
Steel	8.721	64.60%
Polyisocyanurate	2.862	21.20%
Pentane	0.189	1.40%
Proprietary Chemicals	1.728	12.80%
Product Total	13.5	100%

The same procedure was followed to calculate the material compositions for the product's packaging, as shown in Table VI.

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Table VI. Product packaging compositions (Source: Authors), data sourced from (Kingspan Ltd, 2019b).

Packaging Composition Data From EPD		
Material	**Amount (Kg)**	**Percentage of Total Mass (%)**
Oriented Strand Board	61.9	0.3518
Polystyrene	112	0.6365
Polyethylene Film	2	0.0114
Linear Low-Density Polyethylene	0.058	0.0003
Packaging Total	175.958	100%
Converted Packaging Composition Data Based on EPD		
Material	**Amount (Kg)**	**Percentage of Total Mass (%)**
Oriented Strand Board	4.7491	35.1788
Polystyrene	8.5930	63.6516
Polyethylene Film	0.1534	1.1366
Linear Low-Density Polyethylene	0.0044	0.0330
Packaging Total	13.5	100%

Once the data collection for the composition part was finished, the data regarding the manufacturing stage of the product was collected based on the same methodology which was described in previous stages. To obtain the energy consumption ratios for the product, the ratio of the product to the provided data in EPD was used. The collected data and converted rates are demonstrated in Table VII.

Table VII. Product manufacturing data (Source: Authors).

Manufacturing Data From EPD			
Element	**Amount**	**Cost**	**Reference**

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Renewable primary energy consumption, excluding the renewable primary energy resources used as raw materials - Electricity (MJ)	3,490	*	(Kingspan Ltd, 2019a)
Non-renewable primary energy consumption excluding non-renewable primary energy resources used as raw materials - Electricity (MJ)	70,500	*	
Converted Manufacturing Data Based on EPD			
Element	**Amount**	**Cost**	**Reference**
Renewable primary energy consumption, excluding the renewable primary energy resources used as raw materials - Electricity (MJ)	40.83	*	*
Non-renewable primary energy consumption excluding non-renewable primary energy resources used as raw materials - Electricity (MJ)	824.88	*	*
MJ to kWh Conversion Factor	0.278	*	(Department for Energy Security & Net Zero, 2023a)
Electricity Tariff	*	0.19	(Department for Energy Security & Net Zero, 2023b)
Product Conversion Ratio	0.012	*	*

Similarly, the same process was followed to collect the required data for transporting the product to the development site, which is illustrated in Table VIII.

Table VIII. Product transportation data.

Transportation Data From EPD

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Name	Truck	Unit	Reference
Fuel Type	Diesel	*	(Kingspan Ltd, 2019a)
Litres of Fuel Consumption	39.0625	100 Km	
Vehicle Type	Heavy Duty Diesel	*	
Transport Distance	554	Km	
Weight of Products Transported	1153	Kg/100m^2	
Converted Transportation Data Based on EPD			
Name	**Truck**	**Unit**	**Reference**
Fuel Type	Diesel	*	(Kingspan Ltd, 2019a)
Litres of Fuel Consumption	39.0625	100 Km	
Vehicle Type	Heavy Duty Diesel	*	
Transport Distance	554	Km	
Weight of Transported Product	27	Kg/m^2	
Fuel Price	1.6	(£/L)	(Department for Energy Security and Net Zero - GOV.UK, 2023)

The data for the product lifecycle installation phase was collected and converted, applying the same method applied in previous sections. The data for this stage is illustrated in Table IX.

Table IVIII. Product installation data.

Installation Data From EPD			
Name	**Quantity**	**Unit**	**Reference**
White butyl caulk Steel	15.3	Kg/100m^2	(Kingspan Ltd, 2019a)
Electricity	37.7	kWh/100m^2	
Converted Installation Data Based on EPD			
Name	**Quantity**	**Unit**	**Reference**

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White butyl caulk Steel	0.3583	Kg/m^2	(Kingspan Ltd, 2019a)
Electricity	0.8828	kWh/m^2	
Labour (2 people)	12	4.5 €/m^2	(Nyers *et al.*, 2015)

The data regarding the landfill stage of the product are presented in Table X.

Table IX. Product landfill data.

Landfill			
Name	**Parameters**	**Unit**	**Reference**
Transport	Distance (Km)	50	(Crîstiu *et al.*, 2024)
	Fuel Price (1.56£/Km)	£69.9	(Department for Energy Security and Net Zero - GOV.UK, 2023)
	Weight of Waste (Kg)	4.779	(Kingspan Ltd, 2019a)
Landfill	Landfill Gate Fee	75(£/tonne)	(WRAP, 2023)
	Landfill Tax (£/tonne)	£102.00	(GOV.UK, 2023)

Landfill tax and landfill gate fee are not covered in EPD documents. Therefore, the official and approved rates are provided by (GOV.UK, 2023) and WRAP data were used instead. The distance from the collection and identification to the landfill site was collected from (Crîstiu *et al.*, 2024) paper as 50km as an assumption.

The cost of virgin raw material acquisition to produce PIR building thermal insulation's primary lifecycle and glycolysis recycling was collected on the Alibaba E-Commerce platform ($/tonne), then converted to ($/Kg), which are detailed in Table XI.

Table X. Raw material and Waste acquisition costs

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Material Acquisition Cost		
Material Components	**Price ($/Kg)**	**Reference**
Galvanised Steel Internal Face (0.75mm)	$0.49	(Shandong Guogang Steel Group Co Ltd, 2023)
Galvanised Steel External Face (1mm)	$0.49	
RAL 9016 - Traffic White Paint (0.1mm)	$2.50	(Chengdu Hsinda Polymer Materials Co Ltd, 2023)
Polyol	$2.50	(Zhongshan BASD Chemical Technology Co Ltd, 2024)
MDI	$2.60	(Anhui Sufine Chemical Co Ltd, 2024a)
Blowing Agent: Pentane	$3.00	(Xiamen Juda Chemical & Equipment Co Ltd, 2023)
Additives: (Chlorinated - Phosphorus Based)	$2.18	(Jinan Juheng Chemical Co Ltd, 2023.)
Oriented Strand Board	$12.00	(Linyi Yachen Wood Industry Co Ltd, 2023)
Polystyrene	$1.00	(Shanghai Allwin Advanced Material Co Ltd, 2023)
Polyethylene Film	$1.50	(Henan Talent Trading Co Ltd, 2023)
Linear Low-Density Polyethylene	$12.80	(Shenzhen Shenhongji Packaging Material Co Ltd, 2023)
Polyisocyanurate Foam Waste Excluding the Coatings	$1.91	(FMCGTRADE, 2024)
Ethylene Glycol	$0.95	(Anhui Sufine Chemical Co Ltd, 2024b)
Diethylene Glycol	$0.80	(Shandong Arctic Chemical Co Ltd, 2024)
Potassium Hydroxide - KOH	$1.20	(Shandong Near Chemical Co Ltd, 2024)

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The glycolysis agents' ratios (EG, DEG) and catalyst ratio (KOH) were used as 60/40% of the weight of the utilised waste for glycolysis agents, respectively, and 0.5% for the catalyst from which they were collected (Gu *et al.*, 2021). Furthermore, the ratio of the recovered polyol to the glycolysis polyol mixture from which it was collected was taken as 10/90% (Miguel-Fernández *et al.*, 2022).

4. Results and Discussion

Table XII illustrates the total lifecycle cost, including the cost of each individual lifecycle stage of the PIR building thermal insulation, based on the two defined after-life methodologies of glycolysis recycling and product landfill.

Table XII. PIR building thermal insulation lifecycle cost.

Product Lifecycle Cost Summary		
Lifecycle Stage	**Without Future Cost Value (£)**	**With Future Cost Value (£)**
Raw Material Acquisition	£13.60	*
Packaging Raw Material Acquisition	£21.50	*
Manufacturing	£46.41	*
Transportation	£346.2	*
Installation	£94.92	*
Glycolysis Polyol Recovery Material Acquisition	£6.18	£135.10
Glycolysis New Thermal Insulation Material Acquisition	£9.26	£203.03
Landfill Costs	£31.3	£684.47
End-of-Life Destinations		
Glycolysis Recycling Method	£538.10	£860.79
Landfill Method	£553.98	£1,207.14

The findings of this study provide a unique perspective on the economic circularity of PIR building thermal insulation, particularly through LCCA. The existing research on insulation materials has focused on thermal performance and energy efficiency, with studies relying on engineering simulations (Gök *et al.*, 2024).

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Considering the specifications of the PIR building thermal insulation, which is 12m^2, and its weight, which was obtained as 13.5Kg, the total cost of raw materials acquisition for the product was calculated as £13.60. MDI contributed the most to the total cost of the product, with £4.89 for 2.4Kg, which is slightly higher than the cumulative cost of galvanised steel and paint, with £4.08. Also, the cost of the external galvanised steel layer (1mm thickness) was £1.80, which was higher than the inner layer's cost of £1.35 (0.75mm thickness). This was due to the outer layer's thickness and, subsequently, more weight. The cost of polyol, with 1.5Kg weight, was obtained as £2.92, and it was followed by catalyst with £1.15 for 0.7kg weight. The results indicate that the cost of the raw materials used for the insulation product's core material has contributed 70% of the cost of the PIR insulation. In comparison, the cost of metal facings with paint contributed only 30% of the cost of raw material acquisitions in this section. These results align with (Kirugulige *et al.*, 2005; Mamalis *et al.*, 2008), who observed that in sandwich panels, the insulation core contributes the largest share of material cost compared with metal facings. This highlights the need to select core materials that balance performance with cost, and supports the CE principle of sustainable design, which seeks to maintain product efficiency across all lifecycle stages and enable reuse, repair, and recycling (Mamalis *et al.*, 2008).

The results discovered that the materials acquisition cost for PIR building thermal insulation packaging is 61% of the cost of the materials acquisition stage. The cost of materials acquisition for the product's packaging was calculated as £21.50, slightly lower than twice the amount of raw materials acquired for the product itself. The required packaging weight for the product was obtained as 13.5Kg. Polystyrene had the most contribution to the weight of the packaging with 8.59Kg. However, polystyrene had the lowest contribution to the total cost of packaging, with £0.79. In comparison, the lower-density polyethylene film cost was calculated as £10.08, the highest among the other contributors but with a minimal weight of 0.004Kg. Strand boards contributed to the second cost of the packaging with £9.45 for 4.75 kg of weight. The findings are consistent with research showing that packaging can be a major cost driver within logistics and handling processes (Morashti *et al.*, 2022). The high packaging costs identified in this simulation highlight the need for strategic procurement decisions for PUR-based PIRs, which are lightweight, high-volume, and often require protective facings. This also aligns with CE principles of sustainable product design, where packaging choices should minimise cost and material use across all lifecycle stages while supporting efficient transport, storage, and waste management (García-Arca *et al.*, 2017).

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The electricity consumption cost during manufacturing was calculated as £46.4 using the MJ to kWh conversion factor. The non-renewable electricity consumption was calculated as £44.2, which was significantly higher than the cost of renewable electricity consumption, with only £2.2. The electricity consumption results support earlier findings that manufacturing energy represents a notable indirect cost in PUR-based insulation production (Rivero-Camacho *et al.*, 2023). The small variance between raw material and electricity costs suggests that energy demand is closely tied to material selection, as different formulations require distinct reaction times and temperatures, sometimes necessitating additional additives or catalysts to maintain efficient processing.

The cost of transportation to the building development site was calculated at £346.2. The major contributor to the cost of transportation was identified as a *total* transport distance of 554km, significantly affecting the cost of transport. Focusing on the transportation cost, in the EPD document, the weight of the cargo has already been applied to the truck's fuel consumption ratio per 100 km, which is 39.06 (L/100km). The transportation align with studies showing that transport distance is the primary driver of logistics cost for construction materials (Zgonc *et al.*, 2019). In this analysis, the 554 Km delivery route accounted for the highest cost among the primary lifecycle stages, reflecting the strong sensitivity of transport cost to distance and fuel consumption. This is consistent with evidence that lightweight but high-volume PUR-based PIRs occupy significant cargo space, which reduces loading efficiency and increases the need for additional transport trips, ultimately raising overall cost (Kärhä *et al.*, 2024). The reliance of transport operations on fossil fuels further amplifies this cost sensitivity (Daylan and Ciliz, 2016). Therefore, results highlight the need for further investigation into transportation optimisation for PUR-based PIR insulation products.

The labour cost for two people significantly contributed to the installation cost of £91.80. The cost of required butyl caulk was calculated as £2.95, which was higher than the cost of electricity consumption at £0.17. Thus, the cost of PIR building thermal insulation was obtained as £94.92. This stage accounted for a significant proportion of the primary lifecycle cost, reflecting how installation expenses can vary with labour rates, equipment requirements and project complexity (Vasishta *et al.*, 2023; Wiprächtiger *et al.*, 2020). This is directly connected to the CE principle of optimising processes, which emphasises reducing resource utilisation, labour intensity, and operational inefficiencies throughout the entire lifecycle of the insulation. However, published research on PUR-based PIR insulation focuses largely on performance and energy outcomes, with limited attention to detailed LCCA of the installation process.

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In terms of glycolysis polyol recovery, the total weight of needed materials for this stage was 8.8Kg. PIR waste had the maximum weight of 4.78Kg, followed by EG with 2.87Kg, DEG with 1.15Kg, and KOH with 0.01Kg. The total cost of polyol recovery through the glycolysis process is £6.18, and by considering the future value of each material over 75 years, the glycolysis recycling's polyol recovery process was calculated as £135.10. PIR waste contributed the most to the polyol recovery cost by £2.43 and £53.12. Catalyst had the second cost contribution, which was followed by the cost of EG and DEG, respectively. The cost of the catalyst was calculated as £1.52 before and £33.35 after application of the future cost value, which was slightly higher than the cost of EG and DEG, with £1.21 and £1.02 without the future cost value, and £26.40 and £22.23 after application of the future cost value, respectively. However, based on the recovered polyol's 10% ratio within the polyol mixture, this cost element needed to be deducted from the mixture ratio cost to calculate the required virgin polyol for a new product. By adding the weight of required materials for the new PIR production process to the weight of used materials in the recovery process, the total weight required for the entire recycling process was calculated as 13.6Kg. Consequently, the cost of required materials to produce a new building thermal insulation (excluding the polyol recovery stage) was calculated using the same cost data for the raw material acquisition stage as £9.26 without using future cost value, and £203.03 with applying the future cost value. Therefore, the total cost of glycolysis recycling without the future value was obtained as £15.44, considering the future value of £338.13. The glycolysis results indicate that material composition strongly shapes recycling costs. MDI remains the main cost driver, and higher ratios increase raw material expenditure. MDI contributes 32% due to its extra ratio in the mixture compared with other materials, which is 2.4Kg. MDI is a key component broadly used for chemical reactions in producing PUR-based products, and its ratio should be considered during the production process, as it significantly affects the cost of material procurement. A higher proportion of MDI component to achieve enhanced product capabilities and characteristics in PIR insulations has an impact potential on the initial raw materials acquisition costs of PIR products and, at the same time, transforms the parent variance PUR from a low-cost to an expensive product with consuming more virgin materials. The cost of EG, DEG, and KOH contributed to 20%, 17%, and 25% of the polyol recovery process, respectively, showing their pivotal role in affecting glycolysis recycling's economic feasibility, marked by the allocation of 62% of this process's cost to themselves. It should also be considered that the cumulative weight of these entities, 4.03Kg, is slightly lighter than the weight of the utilised PIR waste, 4.78Kg. This highlights that an increase in the volume of their utilisation ratio

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would be extremely cost-effective. But more importantly, an excessive amount of PIR waste - glycolysis agents, and catalysts - would result in impurity ratios within the obtained polyol product, which would ultimately affect the utilisation ratio of the recycled polyol within the polyol mixture to produce new insulations or additional treatments should be carried out to improve the impurity level of the obtained polyol (Kemona and Piotrowska, 2020; Miguel-Fernández *et al.*, 2022). It should be noted that as the glycolysis process is dependent on temperature; a temperature below 180℃ to reduce energy consumption costs would result in low catalyst activity, and a temperature above 220℃ to accelerate the chemical reaction results in undesired reactions, both of which would eventually lead to significant cost increases. Therefore, recycling profitability is further constrained by reverse logistics costs, particularly when waste purity is low, and by the substantial cost share of glycolysis agents and catalysts, which are considered to be major determinants of feasibility (Kanchanapiya *et al.*, 2021; Zia *et al.*, 2007).

The cost of transport to the landfill site was calculated at £31.03. However, by applying the future cost value over 75 years, the cost significantly increased to £684.47. In the simulation analysis, the glycolysis recycling cost was obtained as £538.10 and £860.79, which was cheaper than the landfill by £553.98 and £1,207.14, respectively. These results indicate that transportation has contributed to 97% of the landfill's total cost, highlighting an additional barrier: the transportation cost of waste to the landfill site due to the distance factor. These findings align with Kanchanapiya et al. (2021), who reported that transport costs for PUR-based PIR waste are considerably high, making distance a critical barrier to landfill feasibility. Transport costs between collection and disposal facilities directly reduce economic viability, particularly for lightweight, high-volume materials such as PUR-based PIR insulations. Longer haul distances require additional fuel, labour and equipment, and adds both economic and ecological burdens. The sharp rise in transport costs when future values are applied reflects expected long-term fuel price fluctuations and inflation, indicating the value of lifecycle-based budgeting tools such as future and net present value for long-term circularity assessment.

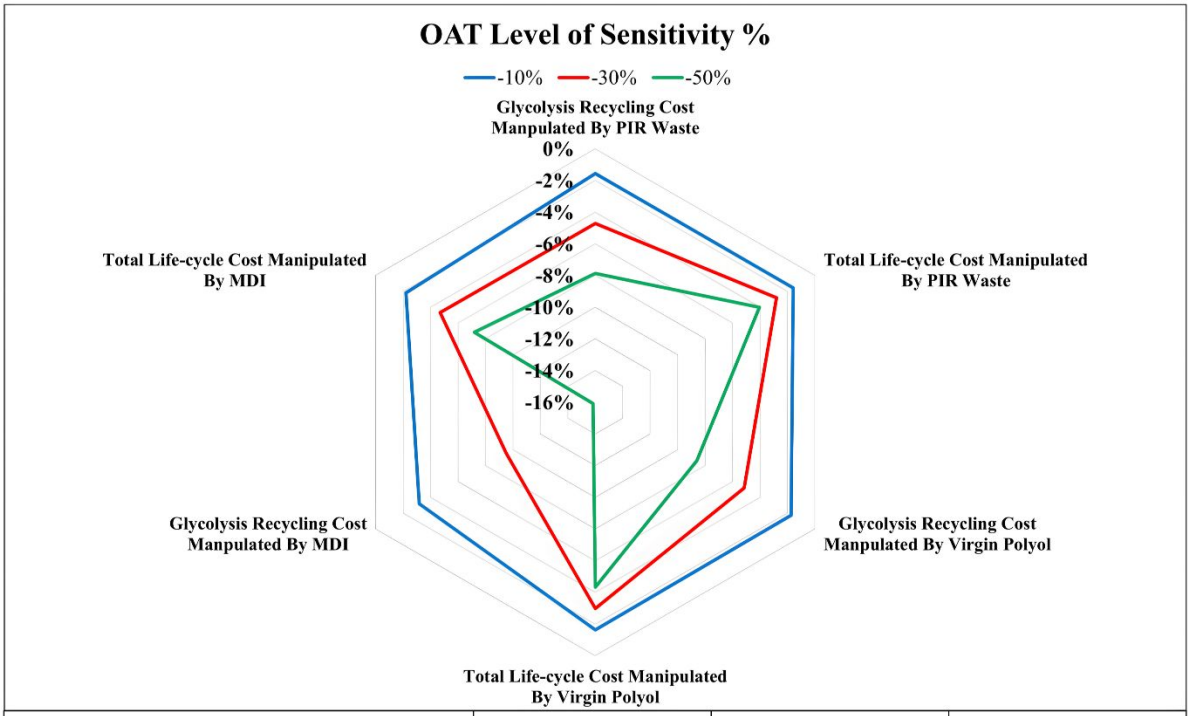
4.1. Model Validation: OAT Sensitivity Analysis

In the first step of the sensitivity analysis, the glycolysis recycling process was identified as the key area likely to significantly affect the total lifecycle cost of PIR insulation, due to its multiple cost components. The entire glycolysis recycling process of PIR insulation consists of two major states: polyol recovery and production of new PIR insulation, along with the applied future cost value for the lifespan of the PIR insulation over 75 years. Three scenarios of reducing the cost of each component by 10, 30 and 50% were developed to explore the range

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of possible output variations. To check the robustness of the model, the cost of PIR foam waste procurement, the cost of MDI procurement, and the cost of virgin polyol procurement were selected as the three input variables. The results of input variable manipulation were observed in the cost of glycolysis recycling and the total lifecycle cost of the product. The logic of defining three different inputs at a time and two outputs was to check the differentiation within both the local and global ranges of the input variables to outputs, along with replication processes with other inputs to increase the confidence of the model to conduct simulation analysis. The results of input cost manipulations to the outputs per percentage and by cost reductions are detailed in Figure 5., respectively.

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Parameters	-10%	-30%	-50%
Glycolysis Recycling Cost Manpulated By PIR Waste	-1.60%	-4.70%	-7.90%
Total Life-cycle Cost Manipulated By PIR Waste	-1.60%	-2.80%	-4.00%
Glycolysis Recycling Cost Manpulated By Virgin Polyol	-1.70%	-5.20%	-8.60%
Total Life-cycle Cost Manipulated By Virgin Polyol	-1.60%	-3.00%	-4.30%
Glycolysis Recycling Cost Manpulated By MDI	-3.20%	-9.50%	-15.80%
Total Life-cycle Cost Manipulated By MDI	-2.20%	-4.70%	-7.20%

Figure 5. OAT Sensitivity Analysis Scenarios by percentage variations (Source: Authors).

Accordingly, MDI had the highest simulation model's input manipulation potential among the others by -3.2, -9.5, and -15.8% by each of the reduction scenarios. Moreover, all the selected inputs have contributed to proportional and predicted changes in the selected outputs, indicating that the developed model is proportionally sensitive to input changes.

5. Conclusions

This study presents a comprehensive economic circularity assessment of PIR-based building thermal insulation, highlighting the cost implications across its lifecycle, from raw material acquisition to end-of-life disposal. The results highlighted the significant role of MDI and glycolysis agents in the economic feasibility of PIR recycling, with MDI contributing 32% of glycolysis costs and glycolysis agents accounting for 62% of polyol recovery expenses. Additionally, packaging costs were identified as a significant financial burden, which demonstrates the need for optimised supply chain strategies. The results indicated that using ineffective and undesirable ratios of raw materials leads to a significant direct and indirect cost increase, higher energy consumption costs, and inefficiency throughout the process. Moreover, the cost of packaging products was higher than the cost of raw materials for the main product, directly and indirectly impacting the product's lifecycle cost through inventory, utility, labour, and transportation. Two glycolysis recycling and landfill methodologies were examined for the end-of-life process of the product. The landfill methodology cost was calculated as higher than the cost of glycolysis recycling due to the transportation cost of waste to the landfill site, and this cost element was excluded in the LCCA of glycolysis recycling according to the data collection limitations. The results identified that the contribution of the additional materials in the recycling process significantly impacts the cost of recycling.

The findings of this study indicate several broader implications beyond the direct cost analysis. The demonstrated cost-effectiveness of glycolysis indicates clear potential as an alternative to landfilling within CE strategies, suggesting that policy measures such as recycling incentives or adjusted landfill charges could support wider adoption of this method. The ABM framework developed here is adaptable and can be applied to other insulation materials or extended to broader CE contexts to analyse economic outcomes under different technological, logistical, and regulatory conditions. The scalability of glycolysis recycling also requires further investigation, particularly regarding infrastructure needs, market potential for recovered polyols, and its integration into existing waste management systems. The results additionally offer practical guidance for both industry and policymakers. Manufacturers may reduce lifecycle and operational costs by optimising raw material ratios and improving packaging practices. Policymakers can use the insights generated by this work to design regulatory measures that encourage recycling uptake, support chemical recycling technologies, and enhance the circularity of construction materials.

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This study presents a novel integration of LCCA within a single ABM framework to analyse the economic circularity of PUR-based PIR insulation. The model, developed in AnyLogic, simulates all major lifecycle stages and cost driver interactions, including recycling, landfill scenarios. This approach addresses a major gap in the existing literature, offering a structured economic circularity assessment for PUR-based PIR insulation and advancing methodological understanding of how material composition and process factors influence lifecycle costs. The model provides a practical decision-support tool for industry and policymakers by enabling detailed evaluation of PUR-based PIR insulation across its entire lifecycle. It supports sustainable material selection, cost-efficient recycling strategies and CE-aligned end-of-life decisions. Although implemented as a single-agent model, the framework is adaptable to other products and contexts, helping organisations reduce investment risks, improve supply chain visibility and strengthen strategic planning within CE applications Future research should incorporate transportation distances and geographic factors into the ABM and LCCA to provide a more realistic representation of real-world conditions and assess the wider economic and environmental viability of alternative end-of-life options.

Limitations include the focus that was placed on the procurement prices for raw materials. Other factors, such as supply chain fluctuations, inflation, and manufacturing costs, could also be included in future research. Future research could integrate a combined economic-environmental LCCA model to provide a holistic sustainability assessment.

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Declaration of generative AI in scientific writing: During the preparation of this work, the corresponding author used OpenAI GPT and Grammarly to check the grammar accuracy of approximately 200 words throughout the main body of the manuscript. After using this tool/service, the author reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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