Sustainable Reverse Supply Chain Optimization: A Case Study in PVC Recycling [*]

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Abstract: This study addresses the optimization of reverse logistics for PVC recycling in Wallonia, focusing on cost minimization and environmental impact reduction. Using a mixed-integer linear programming model, the research integrates transportation, inventory, and processing decisions while incorporating environmental metrics derived from Life Cycle Assessment. The results offer actionable strategies for designing sustainable supply chains, providing a foundation for further exploration to enhance flexibility and applicability in industrial settings.

Keywords: Logistics in Manufacturing, Design of Reverse Logistics Systems, Solid Waste Management, Mixed-Integer Linear Programming, Life Cycle Assessment.

1. INTRODUCTION

The topic of plastic recycling, particularly in relation to polyvinyl chloride (PVC), is highly relevant in the current business and regulatory landscape. Companies face significant challenges in establishing effective recycling technologies and facilities due to high costs, which often makes recycling less attractive compared to alternatives such as landfilling (Iakovou et al., 2024). Nevertheless, European regulations targeting the plastics strategy, which seek to transform the design, production, usage, and recycling of plastic products within the EU, emphasize the critical need to enhance efforts in the plastic recycling sector (European Commission, 2023). These changes necessitate examining effective recycling methods to help companies meet these regulatory requirements by establishing efficient supply chains that optimize reverse waste flows, focusing on reducing both costs and environmental impacts. Indeed, managers in the plastics industry need more insights into sustainable recycling practices to prepare for future regulations and maintain their competitive edge. The increasing pressure from regulations and growing demand for sustainability have made this topic a significant concern for industry practitioners.

Historically, the primary objective of companies has been to minimize supply chain costs or maximize profitability. However, because of rising worldwide environmental consciousness, they are now increasingly accountable for the social and environmental consequences of their operations (Qazvini and Maleki, 2022; Habib et al., 2021).

To enhance decision-making in this domain, our fundamental purpose is guided by two primary objectives: optimizing cost efficiency and mitigating environmental impacts. Specifically, the research question focuses on determining the optimal quantities of materials to transport, process, and store at multiple sites to minimize the total costs and evaluate the environmental impacts over a defined planning horizon. Using a deterministic Mixed Integer Linear Programming (MILP) model, this research integrates transportation, inventory, and processing costs with environmental considerations derived from Life Cycle Assessment (LCA).

This paper is structured as follows: Section 2 provides a literature review, discussing key findings on PVC recycling, optimization models and LCA methodologies. Section 3 describes the problem, and Section 4 presents the problem formulation. Section 5 explains the different scenarios considered in the analysis and Section 6 discusses the outcomes of the model. Finally, Section 7 concludes the paper and suggests directions for future research.

2. LITERATURE REVIEW

This section covers PVC recycling, LCA, and economic and environmental optimization models, providing an overview of key studies and developments in these areas.

2.1 PVC recycling

PVC is a widely used plastic, particularly in the construction sector, where it constitutes around 70% of applications, including pipes, window profiles, and roofing materials (Lewandowski and Skórczewska, 2022). While

its production has steadily increased due to its low cost, durability, and recyclability, this growth has resulted in significant amounts of PVC waste, primarily from construction and demolition activities (Tajik et al., 2024; Ait-Touchente et al., 2023).

Recycling PVC poses several challenges, especially in logistics and waste collection, as the material often contains contaminants, additives, and mixed materials that complicate sorting and processing (Ait-Touchente et al., 2023). Mechanical recycling processes PVC waste by sorting and reprocessing it without altering its chemical structure. This method is most effective for clean and homogeneous PVC waste, enabling multiple recycling cycles while maintaining the material's properties (VinylPlus, 2025). In contrast, advanced recycling techniques, such as dissolution and chemical recycling, are suitable for contaminated or mixed PVC waste. Dissolution isolates PVC while preserving its structural integrity, whereas chemical recycling decomposes it into reusable chemical components (VinylPlus, 2025; Lu et al., 2023). This approach is particularly suited for handling contaminated and mixed PVC waste that is less amenable to mechanical recycling.

However, advanced recycling faces logistical and infrastructural challenges, such as the need for extensive collection networks, significant capital investments, and high operational costs (Tajik et al., 2024). Despite these obstacles, strengthening advanced recycling technologies and improving waste collection systems are critical to overcome these limitations. By addressing these challenges, advanced recycling can play a vital role in creating a more circular PVC economy, reducing environmental impacts, and promoting sustainable waste management (Ait-Touchente et al., 2023).

2.2 Economic and environmental optimization models & Life Cycle Assessment

In today's interconnected world, operating as isolated entities has become increasingly challenging for organizations. With most businesses now being supply chain-oriented, efforts are being made to minimize emissions across supply chains (Ghosh and Mahapatra, 2024). Consequently, organizations must balance profitability with the wider impacts of their operations. Achieving this balance requires optimization of the processing chain by considering multiple factors simultaneously. Therefore, in this section, we provide a concise review of research articles from recent years that have addressed optimization models focusing on economic and environmental factors.

Hariga et al. (2017) present a hybrid model for a cold supply chain, optimizing operational costs and carbon emissions through lot sizing, shipping, and freezer unit allocation. Isaloo and Paydar (2019) focus on supply chain uncertainty, minimizing transportation, operational costs, and emissions using robust optimization methods. Sharifi et al. (2023) optimize a sustainable soybean supply chain, considering profit, job creation, and CO_2 emissions, and use a multi-criteria decision-making method to generate a Pareto frontier for sustainability. Xie et al. (2024) introduce a two-phase optimization model to simultaneously minimize economic costs and carbon emissions in renewable energy projects. Deng et al. (2024) propose a bi-level optimization model to balance carbon reduction policies between local authorities and food waste treatment enterprises.

Most of the studies reviewed focus primarily on carbon emissions, some under carbon reduction policies, but none incorporate the LCA methodology. In this study, we use the LCA methodology to assess the environmental impacts of the processing chain, alongside an evaluation of the total costs. LCA, as defined by ISO 14040 and ISO 14044 (ISO, 2021a,b), is a standardized approach used to evaluate the environmental impacts of a product or service throughout its entire life cycle. In addition to global warming potential, LCA considers a range of other environmental criteria, such as acidification, eutrophication, water use, and resource depletion, offering a more comprehensive environmental profile. This multi-criteria approach helps prevent unintended trade-offs between different impact categories, ensuring that efforts to reduce harm in one area do not lead to greater harm elsewhere (Hauschild and Huijbregts, 2015). With this in mind, the present research adopts LCA, leveraging its accuracy and ability to provide more detailed and holistic environmental insights beyond carbon emissions.

3. PROBLEM DESCRIPTION

This section presents a deterministic MILP model formulated to optimize the reverse logistics network for flexible PVC recycling in Wallonia. The model integrates decisions on optimal quantity allocation, balancing costs and environmental impacts. It accounts for transportation, inventory, and processing costs, alongside environmental considerations related to climate change, fossil resources use, and human toxicity. These indicators were selected as they represent the most impacted categories based on the results of the LCA. The reverse logistics network consists of collection points, a sorting facility, and a recycling center, as depicted in Figure 1. In this system, waste materials are collected from multiple construction, renovation, or demolition sites and processed through sequential steps at the initial partner facility. A part of the processed non-compliant waste is incinerated, while the other part is divided into three categories of crushed PVC waste. These categories are subsequently sent to the second partner for recycling, after which the final product is sold to a third-party buyer. A time horizon is defined, comprising t periods corresponding to the months of the year.
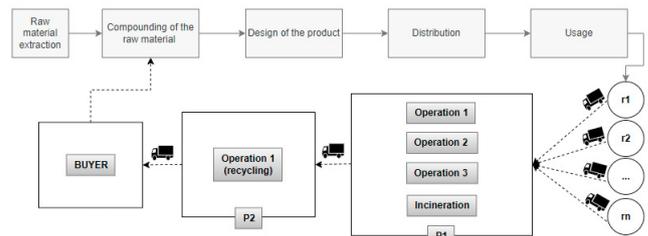

Fig. 1. Proposed reverse processing chain.

The following assumptions are made to clarify the scope of the study:

- The network operates in reverse flow and involves a single product over multiple periods.

- It includes several sources, one sorting center, and one recycling center, all with predetermined locations.
- Transportation is exclusively by road, with homogeneous vehicles that perform a single journey during each time period.

4. PROBLEM FORMULATION

We define four primary sets: the set of sources, denoted by $\mathcal{R}$, where each source is indexed by $r \in \mathcal{R}$; the set of months, represented by $\mathcal{T} = \{1, 2, 3, \ldots, 12\}$, corresponding to the twelve months of the year and indexed by $t \in \mathcal{T}$; the set of PVC categories, $\Phi = \{A, B, C\}$ indexed by $\varphi \in \Phi$; and the set of container type, $v = \{S, D, N\}$, representing the use of a single (S), two (D), or no (N) container(s), and indexed by $v \in \mathcal{V}$. Tables 1 and 2 present the definitions of the parameters and decision variables.

Parameters

$R_{r,t}$	Available raw material (kg) at source r in period t.
P^1	Processing capacity of partner 1 ($P1$).
P^2	Processing capacity of partner 2 ($P2$).
S^1	Storage capacity before processing at $P1$.
$S^{1\varphi}$	Storage capacity of each PVC category, $\varphi \in \Phi$, after processing at $P1$.
$S^{2\varphi}$	Storage capacity of each PVC category, $\varphi \in \Phi$, before processing at $P2$.
S^2	Storage capacity after processing at $P2$.
τ	Transformation factor after processing at $P1$.
T^φ	Rate related to the category of PVC obtained after processing in $P1$.
β	Yield of the final process in $P2$.
γ	Rate of loss during the final process in $P2$.
Γ	Unit cost of the loss during the final process in $P2$.
h^1	Unit storage cost per month of $P1$.
h^2	Unit storage cost per month of $P2$.
α^1	Unit processing cost of $P1$.
α^2	Unit processing cost of $P2$.
$\mathcal{I}$	Unit incineration cost of $P1$.
C_r	Cost for a single container per source r.
D_r	Cost for a double container per source r.
F_r	Initial placement cost of containers at each source r.
$\mathcal{M}_r$	Monthly rental cost per container at source r.
c^1	Cost for a single container at $P1$
c^2	Cost for a single container at $P2$
d^1	Cost for a double container at $P1$
d^2	Cost for a double container at $P2$
p	Selling price per kg.
k^1	Lot size available for processing in $P1$.
k^2	Lot size available for processing in $P2$.
l^A	Proportion of waste category A in $P1$.
l^B	Proportion of waste category B in $P1$.
l^C	Proportion of waste category C in $P1$.

Table 1. List of parameters

The objective is to minimize the costs expressed by:

Minimize:

$$\sum_{r \in R} \sum_{t \in T} \left(F_r \cdot (1 - y_{r,t}^N) + C_r \cdot y_{r,t}^S + D_r \cdot y_{r,t}^D + \mathcal{M}_r \cdot (y_{r,t}^S + 2 \cdot y_{r,t}^D) \right)$$

$$+ \sum_{t \in T} \left(c^1 \cdot z_t^{1S} + d^1 \cdot z_t^{1D} + c^2 \cdot z_t^{2S} + d^2 \cdot z_t^{2D} \right)$$

$$+ h^1 \cdot \sum_{t \in T} \left(s_t^1 + \sum_{\varphi \in \Phi} u_t^{1\varphi} \right) + h^2 \cdot \sum_{t \in T} \left(\sum_{\varphi \in \Phi} s_t^{2\varphi} + u_t^2 \right)$$

Variables

$q_{r,t}^1$	Quantity of material transported from sources to $P1$ during period t.
$q_t^{2\varphi}$	Quantity of each PVC category, $\varphi \in \Phi$, transported from $P1$ to $P2$ during period t.
q_t^3	Quantity of final material transported from $P2$ to the buyer during period t.
x_t^1	Total processed quantity in $P1$ during period t.
$x_t^{2\varphi}$	Total processed quantity of each PVC category, $\varphi \in \Phi$, in $P2$ during period t.
s_t^1	Storage quantity before processing in $P1$ by the end of each period t.
$s_t^{2\varphi}$	Storage quantity of each PVC category, $\varphi \in \Phi$, before processing in $P2$ by the end of each period t.
$u_t^{1\varphi}$	Storage quantity of each PVC category, $\varphi \in \Phi$, after processing in $P1$ by the end of each period t.
u_t^2	Storage quantity of the final material after processing in $P2$ by the end of each period t.
n_t^1	Number of lots to be processed at $P1$ during time t.
$n_t^{2\varphi}$	Number of lots to be processed of each PVC category, $\varphi \in \Phi$, at $P2$ during time t.
ι_t	Quantity of material that is incinerated after processing in $P1$ at time t.
w_t^φ	Quantity of each PVC category, $\varphi \in \Phi$, that is lost during the process in $P2$ at time t.
$y_{r,t}^v$	$= 1$ if the option of container $v \in \mathcal{V}$ is used at source r during period t, 0 otherwise.
z_t^{1v}	$= 1$ if the option of container $v \in \mathcal{V}$ is used at $P1$ during period t, 0 otherwise.
z_t^{2v}	$= 1$ if the option of container $v \in \mathcal{V}$ is used at $P2$ during period t, 0 otherwise.

Table 2. List of decision variables

$$+ \mathcal{I} \sum_{t \in T} \iota_t + \Gamma \sum_{t \in T} \sum_{\varphi \in \Phi} w_t^\varphi + \sum_{t \in T} \left(x_t^1 \cdot \alpha^1 + \sum_{\varphi \in \Phi} x_t^{2\varphi} \cdot \alpha^2 \right)$$
$$- \sum_{t \in T} q_t^3 \cdot p \quad (1)$$

Transportation costs from sources to $P1$ are represented by the first line. These costs parameters are determined based on factors such as distance, travel time and loading and unloading durations. The formulation considers the use of none, one or two containers, the initial placement costs, and the rental costs per container. The second line represents the unit transportation costs from $P1$ to $P2$ and from $P2$ to the final buyer, considering the use of one or two containers. The different costs parameters are derived from transportation cost simulation realized with a simulator developed by the Comité National Routier (CNR) (2024). Subsequently, inventory costs are computed by multiplying the quantity of items in storage by the fixed cost per unit. These costs are incurred by each partner, irrespective of the inventory category or its stage in the processing cycle (either before or after). Processing costs, represented by the fourth line, are calculated as the product of the processing cost per unit incurred by each partner and the quantity processed during each time period t. These costs also include the cost of incineration at $P1$ and the material loss occurring at $P2$. Finally, revenue, denoted by the last term, is calculated by multiplying the unit price of the final product by the quantity of material delivered to the buyer during each time period t, capturing the financial return generated from the sales process.

The model also incorporates three environmental expressions corresponding to the three selected impact cate-

gories. These expressions share a similar structure with the objective function but have been omitted for clarity. Each expression quantifies the environmental impact by multiplying the per-unit impact of transportation or processing by the respective material quantity, thereby ensuring consistency with its designated impact category.

Constraints of the model are listed below:

$$
\begin{aligned}
q_{r,t}^1 &\leq M \cdot (1 - y_{r,t}^N), \\
q_{r,t}^1 &\geq (1 - y_{r,t}^N), \\
q_{r,t}^1 &\leq 26000 + M \cdot (1 - y_{r,t}^S) \qquad \forall r \in \mathcal{R}, t \in \mathcal{T}
\end{aligned} \tag{2}
$$

$$
\begin{aligned}
q_t^{2\varphi} &\leq M \cdot (1 - z_t^{1N}), \\
q_t^{2\varphi} &\geq (1 - z_t^{1N}), \\
q_t^{2\varphi} &\leq 26000 + M \cdot (1 - z_t^{1S}) \qquad \forall t \in \mathcal{T}
\end{aligned} \tag{3}
$$

$$
\begin{aligned}
q_t^3 &\leq M \cdot (1 - z_t^{2N}), \\
q_t^3 &\geq (1 - z_t^{2N}), \\
q_t^3 &\leq 26000 + M \cdot (1 - z_t^{2S}) \qquad \forall t \in \mathcal{T}
\end{aligned} \tag{4}
$$

$$
y_{r,t}^N + y_{r,t}^S + y_{r,t}^D = 1 \qquad \forall r \in \mathcal{R}, t \in \mathcal{T} \tag{5}
$$

$$
z_t^{1N} + z_t^{1S} + z_t^{1D} = 1 \qquad \forall t \in \mathcal{T} \tag{6}
$$

$$
z_t^{2N} + z_t^{2S} + z_t^{2D} = 1 \qquad \forall t \in \mathcal{T} \tag{7}
$$

$$
q_{r,t}^1 \leq R_{r,t} \qquad \forall r \in \mathcal{R}, t \in \mathcal{T} \tag{8}
$$

$$
n_t^1 \cdot k^1 \leq \sum_{r \in \mathcal{R}} q_{r,t}^1 + s_{t-1}^1 \qquad \forall t \in \mathcal{T} \tag{9}
$$

$$
n_t^{2\varphi} \cdot k^2 \leq q_t^{2\varphi} + s_{t-1}^{2\varphi} \qquad \forall t \in \mathcal{T}, \varphi \in \Phi \tag{10}
$$

$$
\begin{aligned}
x_t^1 &\leq \min(n_t^1 \cdot k^1, P^1), \\
x_t^1 &\geq n_t^1 \cdot k^1, \\
x_t^{2\varphi} &\leq \min(n_t^{2\varphi} \cdot k^2, P^2), \\
x_t^{2\varphi} &\geq n_t^{2\varphi} \cdot k^2 \qquad \forall t \in T, \varphi \in \Phi
\end{aligned} \tag{11}
$$

$$
s_t^1 \leq \min(\sum_{r \in \mathcal{R}} q_{r,t}^1 + s_{t-1}^1 - x_t^1, S_1) \qquad \forall t \in \mathcal{T} \tag{12}
$$

$$
s_t^{2\varphi} \leq \min(q_t^{2\varphi} + s_{t-1}^{2\varphi} - x_t^{2\varphi}, S^{2\varphi}) \quad \forall t \in \mathcal{T}, \varphi \in \Phi \tag{13}
$$

$$
\begin{aligned}
u_t^{1\varphi} \leq \min(u_{t-1}^{1\varphi} + (\tau \cdot x_t^1) \cdot T^\varphi \\
- q_t^{2\varphi}, S^{1\varphi}) \quad \forall t \in \mathcal{T}, \varphi \in \Phi
\end{aligned} \tag{14}
$$

$$
u_t^2 \leq \min(u_{t-1}^2 + \beta \cdot x_t^{2\varphi} - q_t^3, S_2) \quad \forall t \in \mathcal{T}, \varphi \in \Phi \tag{15}
$$

$$
\begin{aligned}
q_t^{2A} &\leq (\tau \cdot x_t^1) \cdot l^A + u_t^{1A}, \\
q_t^{2B} &\leq (\tau \cdot x_t^1) \cdot l^B + u_t^{1B}, \\
q_t^{2C} &\leq (\tau \cdot x_t^1) \cdot l^C + u_t^{1C} \qquad \forall t \in \mathcal{T}
\end{aligned} \tag{16}
$$

$$
\iota_t = (1 - \tau) \cdot x_t^1 \qquad \forall t \in \mathcal{T} \tag{17}
$$

$$
w_t^\varphi = \gamma \cdot x_t^{2\varphi} \qquad \forall t \in \mathcal{T}, \varphi \in \Phi \tag{18}
$$

$$
q_t^3 = \sum_{\varphi \in \Phi} \beta \cdot x_t^{2\varphi} + u_t^2 \qquad \forall t \in \mathcal{T} \tag{19}
$$

$$
\begin{aligned}
q_{r,t}^1 &\geq 0, && \forall t \in \mathcal{T}, r \in \mathcal{R} \\
q_t^{2\varphi}, x_t^{2\varphi}, s_t^{2\varphi}, u_t^{1\varphi}, n_t^{2\varphi} &\geq 0, && \forall t \in \mathcal{T}, \varphi \in \Phi \\
q_t^3, x_t^1, s_t^1, u_t^2, n_t^1, \iota_t, w_t^\varphi &\geq 0 && \forall t \in \mathcal{T}
\end{aligned} \tag{20}
$$

$$
\begin{aligned}
y_{r,t}^v &\in \{0,1\}, && \forall t \in \mathcal{T}, r \in \mathcal{R}, v \in \mathcal{V}, \\
z_t^{1v} &\in \{0,1\}, z_t^{2v} \in \{0,1\} && \forall t \in \mathcal{T}, v \in \mathcal{V}
\end{aligned} \tag{21}
$$

The constraints (2), (3) and (4) establish the allowable quantity ranges for each type of container, while (5), (6) and (7) ensure that only one type of container is utilized per period and per site. Based on the information collected from the construction sites, we assume that the quantity does not exceed 52.000 kg, which corresponds to the allowable limit when using two containers. Consequently, we set $M = 52.001$ in the model. This choice ensures that the constraints involving M remain valid by providing a sufficiently large upper bound without being excessively high, thus maintaining numerical stability and logical consistency in the formulation. Constraint (8) limits the quantity transported from each source to the available supply. Equations (9) and (10) define the number of lots available for processing at each plant. The processing constraints for each partner are described by (11), ensuring that the quantity processed is at least a multiple of the lot size but does not exceed the processing capacity. Storage constraints before processing are captured by (12) and (13), which ensure that storage values do not exceed the given capacities while accounting for processed and stored quantities over time. Similarly, constraints (14) and (15) govern storage after processing, ensuring it stays within specified capacity limits while considering processed quantities and previous storage states. Constraints (16) define the quantities that can be transported from $P1$ to $P2$ in each period, considering the transformation rate and the proportion of sorted material across categories. Quantities of initial material incinerated at $P1$ and material losses during the final process at $P2$ are addressed in (17) and (18), respectively. Constraint (19) guarantees that the quantity of the final product delivered to the buyer is equal to the sum of the processed quantity, adjusted by the yield, and the potential stored quantity. Finally, constraints (20) ensure the non-negativity of the variables, while constraints (21) enforce their binary nature.

5. SCENARIOS DEFINITION

The values of the various parameters have been generalized to the greatest possible extent based on the available data. Due to the confidentiality of certain information, some estimations were necessary; however, they were made in a plausible manner based on real data. Specifically, the collected quantities were approximated based on data obtained through interviews. The transportation costs were estimated using the calculation sheet provided by the Comité National Routier (CNR) (2024), while capacity parameters were determined from information supplied by project partners. The storage and processing costs estimates fall within a range specified by the partners but remain imprecise to preserve confidentiality. Although the selling price is assumed to be equal to that of virgin resin, based on the average over the past nine years, using this price in the model yielded no or only insignificant results. This outcome is unsurprising, as an additional cost beyond the virgin resin price is necessary to account for the investment and operating costs required for the recycling unit. Therefore, we decided to double it to obtain meaningful outcomes and facilitate the comparison of different scenarios.

Different instances were created based on real-world conditions by adjusting key model parameters to better understand its limitations. Specifically, each of the following parameters was individually modified to generate eight distinct scenarios:

- *Collection Patterns:* We considered two types of collection: one randomly spread throughout the year and another following a seasonal pattern to account for the impact of construction holidays and weather conditions. In both cases, the total annual collection volume from the four sources remains the same but is distributed differently over time.
- *Batch Sizes:* We analyzed two significantly different batch sizes, with one being ten times greater than the other. This allowed us to assess potential economies of scale. In fact, based on estimates from partner and LCA expert interviews and data, larger batch sizes were found to reduce costs by 25% and environmental impacts by 15%.
- *Recycling Yield:* The composition of incoming waste varies significantly, with PVC content ranging from 30% to 70%, depending on the material type. To account for this variability, we adjusted the recycling process yield to better reflect real-world conditions and evaluate its impact on the logistics chain. Discussions with partners established a 70% yield as a best-case scenario for rigid PVC, reflecting its typical 70% resin content after additive removal. For flexible PVC, yield varies by application. A 50% yield was used as a second reference in our study, as it falls between the 30% and 70% limits and aligns with artificial leather composition. Conversely, a 30% yield more accurately reflects applications such as flooring and roofing.

These modifications allowed to explore different real-world conditions and assess how various parameters influence the model's performance and outcomes.

6. RESULTS

The optimisation steps were performed on a personal laptop computer (Windows 11, 32 GB of RAM) and with CPLEX Studio IDE 22.1.1. Since we must solve a mixed-integer linear program, we have used the classical branch-and-cut CPLEX solver with the default parameters. Concerning the environmental analysis of the chain, the study evaluates LCAs using SimaPro 9.1.1.1 software and the Ecoinvent 3.6 database, employing the ReCiPe 2016 Midpoint (H) method, which addresses 18 midpoint impact categories (Metzmacher, 2025). These midpoint categories measure impacts at the early stages of the cause-effect chain, thereby reducing uncertainties. They can be further aggregated into three endpoint categories: damage to human health, ecosystem diversity, and resource availability. The impact categories evaluated in the model (human toxicity, climate change, and fossil resource use) correspond to each of these endpoints, respectively.

The initial results of the model developed above suggest that achieving the market selling price of the virgin resin at €0.80/kg within the proposed reverse supply chain would be highly challenging. Additionally, the findings indicate a direct correlation between costs and environmental impacts, primarily driven by the energy-intensive nature of the recycling process, which relies on electricity, steam, and fuel consumption. This means that any reduction in costs inherently leads to a decrease in environmental impacts as well.

The analysis of the instances highlights that a high recycling yield (70%), large lot sizes (2000 units), and seasonality lead to the most profitable and environmentally efficient scenario, requiring a minimum selling price of €0.99/kg to remain viable. Moreover, economies of scale significantly reduce both costs and environmental impacts per unit, further reinforcing the advantages of processing larger batches. However, the assumptions and boundaries of this LCA study do not entirely represent the evolving technology, necessitating further LCA studies to refine the results.

7. CONCLUSION

The primary focus of this study is to minimize costs and evaluate environmental impacts through a deterministic MILP framework. By considering transportation, inventory, and processing costs alongside environmental factors using LCA, the model presents a comprehensive approach to reverse logistics networks.

The results regarding costs are relatively optimistic, suggesting that profits can be generated while maintaining a reasonable sales price. The energy-intensive nature of the processes results in a correlation between costs and environmental impact. Uncertainty affects both the quantity and type of waste collected. Further research should explore both single-waste and mixed-waste processing to enhance the model's applicability. Additionally, further refinements of the LCA are required to enable a meaningful comparison between the environmental impacts of recycled PVC and the production of virgin resin. While the focus of this study is on PVC recycling in Wallonia, the model can be adapted to other materials and extended as long as it

adheres to waste transfer regulations and industry-specific regulations.

This integrated framework aims to facilitate more sustainable decision-making within supply chain networks; however, additional refinements are necessary to fully realize its potential. To address its current limitations, several avenues for further research are proposed, including the incorporation of production lot sizing to introduce nonlinearity, thereby offering a more realistic representation of manufacturing processes, and potentially enriching the bi-objective framework by incorporating conflicting objectives. The application of Pareto optimization could resolve these conflicts, enabling a balanced trade-off between production efficiency and environmental impact. Expanding the model to account for uncertainty would address supply chain variability, such as fluctuations in resource availability, process yield, and collection reliability. Methods such as robust optimization, fuzzy programming, or stochastic approaches could enhance decision-making under uncertain conditions. Moreover, incorporating multimodal transportation options would increase the model's flexibility by accounting for trade-offs between various modes of transport. Finally, this study does not consider the distribution of various costs among stakeholders. The development of a business plan would enable a more equitable allocation of costs, and the introduction of more specific cost-benefit constraints for each partner would also influence the model's outcomes. These advancements would significantly enhance the model's applicability and effectiveness in addressing the complexities of modern industrial settings.

ACKNOWLEDGEMENTS

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