Final Report

JIP 2024

6.3.1 Semmtech

Authors:

Wei Fan (5916704)
Giacomo Carachino (6068316)
Suruthi Anushkumar (5958547)

November 1, 2024

Contents

Introduction

The construction industry plays a significant role in the global economy. The construction industry contributes to infrastructure development, job creation, and economic growth. However, almost half of the total waste comes from the construction industry, generating millions of tons of construction and demolition waste every year. These environmental challenges have to be addressed. The concept of circular economy offers a promising solution. It does so by enhancing resource efficiency and reducing waste. The traditional linear model focuses on "take,make and dispose of" .The circular economy extends the lifecycle of materials and promotes sustainability through processes like recycle, reuse and recovery. The environmental impact is minimized and natural resources are also preserved.

In the construction industry, one of the crucial elements of the circular economy is reverse logistics. In the process of reverse logistics, used materials are returned to be repurposed or recycled[2]. In terms of the construction industry, this entails recovering the materials from demolition or reconstruction sites, and instead of sending them to landfills.A demolition site refers to the location where structures such as buildings, bridges or other constructions are being dismantled, deconstructed and demolished.to If the reverse logistics practices are implemented in the construction industry, environmental impact can be reduced.In addition to reducing environmental impact, we can also preserve valuable resources by promoting the recovery of materials like steel, concrete, wood and glass. Through this process, sustainability goals are also aligned by lowering energy consumption, and reducing greenhouse gas emissions which promotes the circular flow of resources.

Urban mining is one such sector that corresponds to these ideas; instead of obtaining raw materials from wild areas, it concentrates on removing precious elements from already existing infrastructures say for example buildings. In order to minimize environmental deterioration and the requirement for extracting virgin materials, urban mining aims to recover resources that are already present in cities, such as metals, polymers, and building materials. Urban mining supports the circular economy by transforming trash into fresh chances for material reuse and recycling by considering buildings and urban areas as resource reservoirs[4]. In addition to reducing the environmental impacts,urban mining industry also creates various employment and business opportunities since the process of dismantling, recycling and recycling are labor intensive. Data is crucial in the urban mining sector. Urban mining firms may increase operational efficiency, save costs, and lessen their environmental effect by utilizing data to manage supply chains, anticipate equipment maintenance, and discover material sources[1]. Additionally, data helps businesses estimate demand for recycled materials, manage emissions and assist compliance with environmental regulations—all of which help to match their efforts with market demands and promote a more sustainable, circular economy.

However, the urban mining sector is challenged by logistical inefficiencies, high prices, and fragmentation, with contractors facing time constraints and data management challenges. Effective recovery and reuse is further hindered by inadequate tracking and a lack of data on materials on destruction.

In order to overcome these barriers, there is an urgent need for proper data management and integration systems. It is important to have effective data collection, tracking and sharing methods to improve the efficiency of urban mining. This can be done by providing detailed information about materials available for recovery to the urban miners. There is a need for digital tools which are easy to use and also increase transparency and interoperability among stakeholders in the construction industry . Transforming the construction industry making it more sustainable and circular[1].

This project proposes visualizing the supply chain process by developing a digital twin model.A digital twin simply means digital model of an actual real wold physical product,system or a process.This digital twin can be used to model,analyze and optimize real-world operations.In context the construction industry this digital twin can be used to view the reverse supply chain chain process, enabling better visualization which can be used to get clear idea about decision -making. Stakeholders can avoid the potential risks, analyze the cost and also evaluate environmental impact. The digital twin will address the data-related challenges.The materials can be tracked,detailed insights about quality,quantity and location are provided this data visibility will allow the urban miners to make informed decisions about material recovery.The digital twin will promote circular economy and contribute to the transition towards sustainability by the circular economy.

This project aims change how the industry is operating making urban mining a more feasible and scalable practice, thereby evaluating the business model to determine how urban mining practice can be economically profitable by lowering cost and mitigating risk.This project is a collaboration between students of Delft University of Technology who come from various backgrounds and the company Semmtech.Semmtech is an IT services and consultancy firm and expert on interoperability.This project is also supported by the National Growth Fund, which is committed to encouraging sustainable economic development via strategic investments.

1 Problem Definition

Despite its promise of sustainable resource recovery, the urban mining sector faces major obstacles that prevent its broad implementation. First of all, the sector is extremely fragmented, making it difficult for stakeholders to collaborate and preventing simplified operations throughout the value chain. Inconsistent material values are another consequence of urban mining's fragmented nature. Urban mining resources vary widely in quality, quantity, and condition, making valuation difficult and often impossible for standardization. This is in contrast with traditional mining, where material quality and availability are typically predictable. It is rare to find accurate and thorough information concerning building materials. Important details on material specifications, including kind, amount, and quality, are sometimes lost after structures are dismantled. Urban miners face difficulties as a result of this lack of data as they are unable to evaluate and recover resources efficiently, which frequently leads to lost reuse chances. The difficulties experienced by urban miners are made worse by logistical inefficiencies. Transporting materials to processing facilities from different demolition sites might result in higher expenses and longer turnaround times, which will have a detrimental effect on the operation's overall sustainability. These problems are made worse by the time constraints placed on demolition contractors, who frequently put speed ahead of thorough material collection, discarding important resources instead of reusing them. Economic considerations are also highly important; a weak business case for urban mining projects is produced by the high expenses of material recovery and processing as well as the unclear market demand for recovered resources. Recovering materials from urban surroundings is labor-intensive and has practical challenges since it calls for specific knowledge and tools that might not be easily accessible. All of these issues make urban mining less scalable and less able to support a circular economy, which emphasizes the need for creative fixes and cooperation from all parties involved in the sector[3].

2 Research questions

Research question:

- What impact can better information management and sharing have on the reverse supply chain of aluminum window frames?
- How much can urban miners operations be streamlined if items destination would be available before demolition?

3 Purpose of the study

The purpose of this study is to play a significant role in the construction industry's continuous shift to more circular and sustainable methods. It specifically looks into how putting in place a strong data management system may help reduce the many dangers that urban miners encounter while working. This study aims to illustrate the possible advantages of implementing an efficient data management system by carefully examining the present issues with data tracking, material value, and logistical inefficiencies within the urban mining industry. Urban miners may increase material recovery rates, improve decision-making processes, and promote improved cooperation among supply chain stakeholders by methodically gathering and integrating precise, real-time data from many sources. In order to help urban miners maximize their operations and more successfully recover precious resources, the project will investigate how good data management may result in increased transparency and efficiency.

Furthermore, the study intends to demonstrate how a thorough data management strategy may aid in standardizing procedures and improving the overall dependability of recovered resources by tackling the problems of uneven material quality and availability. In the end, this research will highlight how important data management is to efficient resource recovery, lowering operational risks, and encouraging sustainable practices in the urban mining industry. By doing this, it will open the door for a more robust and effective construction sector that supports environmental sustainability and is consistent with the circular economy's fundamentals.

4 Stakeholder analysis

Construction companies:

Role: The supply and demand for circular materials is influenced by construction companies, who are both providers of demolished materials and possible buyers of recycled resources.
Interests : obtaining sustainable resources, and using high-quality, reasonably priced building materials, meeting regulatory requirements.
Influence: Their dedication to utilizing recycled materials has the potential to stimulate demand and encourage the implementation of circular methods.
Requirements: Verification of the recovered materials' quality, consistency, and dependability, supported by accurate data to justify integration into new projects.

Urban Miners:

Role: Urban miners play a crucial role in the material recovery process by locating, removing, and processing recyclable materials from buildings that have been destroyed.
Interests: Effective data management to increase profitability, cut expenses, minimise resource waste, and expedite recovery procedures.
Influence: Because their procedures and rates of material recovery have a direct influence on the quantity of recycled materials utilised in the sector, they have a major impact on the success of the circular economy transition.
Requirements: Reliable information on material quality, amount, type, and location is required in order to optimise reuse potential and make well-informed recovery decisions.

Demolition contractors

Role: Demolition contractors play a crucial role in starting the process of recovery by tearing down buildings and making reused materials available.
Interests: Includes cutting operating expenses, completing projects before deadline , and making sure safety and environmental laws are followed.
Influence: The amount and quality of resources accessible for urban mining are influenced by their readiness to embrace methodical deconstruction techniques.
Requirements: A transparent, easy-to-use data management system that enables precise tracking and recording of items that may be recovered, together with instruction on how to treat materials to maintain their integrity.

Semmtech and students from TUD:

Role: Students: Develop the digital twin model and analysis the value the model is going to bring to the construction demolition and construction companies.
Semmtech: Assist and guide the students throughout the project.
Interest: Gain insights about urban mining industry. Contribute to the construction industry's transition to a circular economy.
Influence: Developing a simulation tool to investigate the effects of different parameters on the reverse supply chain can have a great influence on stakeholders and policy makers decisions.
Requirements: Inputs from urban miners about the problems they face.

End users:

Role: The key recipients who will engage with the data and insights of the digital twin model, perhaps utilising it to improve operational performance, maintenance, and energy efficiency.
Interests: Access to up-to-date, comprehensive data on building performance. instruments that facilitate predictive maintenance, lower expenses, and enhance operational efficiency. enhanced safety and risk reduction thanks to precise, current environmental and structural data.
Influence: Certain capabilities in the digital twin concept that offer practical insights into daily operations may be requested by end users. Their input on the model's functioning and usability is crucial for improving it and making sure it satisfies real-world requirements.
Requirements: Data visualisation that is accessible and simple enough for non-technical people to understand. high data dependability and accuracy to guarantee that insights facilitate well-informed decision-making. Compatibility with current procedures and systems to enable smooth user uptake and integration.

Building Owners:

Role: Decision-makers in charge of long-term building investments, such as maintenance, renovation, and environmentally friendly improvements. Relying on digital twin for asset performance and value over time.
Interest: Increased asset value as a result of insights that aid in sustainability and lifetime management initiatives. Clear, thorough information that supports long-term planning, safety, and regulatory compliance. decreased expenses through resource, energy, and maintenance schedule optimization.
Influence: Building owners may have an impact on the model's data scope by giving financial performance and sustainability measures priority. A greater degree of control over development priorities and functionality is frequently the result of their investment in the project.
Requirements: Advanced analytical and reporting capabilities which help in making strategic decisions. Data privacy and security to safeguard private data pertaining to building management and ownership. guarantee of scalability and long-term support to meet upcoming demands and growth.

Materials companies :

Role: They are the providers of used and processed materials used in construction and demolition.
Interest: Insights into demand,cost reduction and usage trends of materials.Opportunities to reduce waste,and finding ways to benefit by recycling and remanufacturing.
Influence: Material tracking, lifecycle data, and recycling metrics are among the components of the model that materials companies may affect.
Requirements: In-depth material monitoring from manufacturing to end-of-life to support circular economy principles. clear information on the state and quality of recovered materials for repurposing and remanufacturing. Predicting material requirements by integration with supply chain data minimizes overproduction and maximizes resource use.

Regulatory bodies:

Role:Standards, rules, and recommendations pertaining to the building and demolition sectors are established and enforced by regulatory authorities. They guarantee adherence to regulations concerning sustainability, data security, health and safety, and environmental effect.
Interest: They are interested in ensuring that the project complies with existing regulations and encourages sustainable practices, especially if it deals with environmental preservation, material reuse, and data interoperability.
Influence: The project must take regulatory requirements into account at every level in order to prevent delays or legal issues.

5 Power Interest grid:

The power - interest grid categorizes the stakeholders for the project based on their level of power and interest in the digital twin development.

High power , High interest (Manage closely:)

Students of TUD: The students are actively involved in creating the digital twin model as major project contributors. Close supervision, frequent updates, and active involvement in the project's development and decision-making processes are all necessary for their function.

High Power, Low Interest (Keep Satisfied):

Regulatory Bodies:Although these organisations can influence the project by imposing compliance requirements, they are not really interested in the day-to-day operations of the project. .

Low Power, High Interest (Keep Informed):

Semmtech: Semmtech's operational involvement in the project's progress is probably reflected in this placement. Semmtech requires frequent updates to make sure they are in line with project progress and results, even though they have little direct control over the project.

Low Power,Low interest(Minimum Effort:)

Building owners,End Users,Construction and demolition companies:These stakeholders are less interested in the specifics of the project's progress and have less control over it. Regular updates, mostly about topics that are important to them, are enough to keep people informed without requiring constant communication.

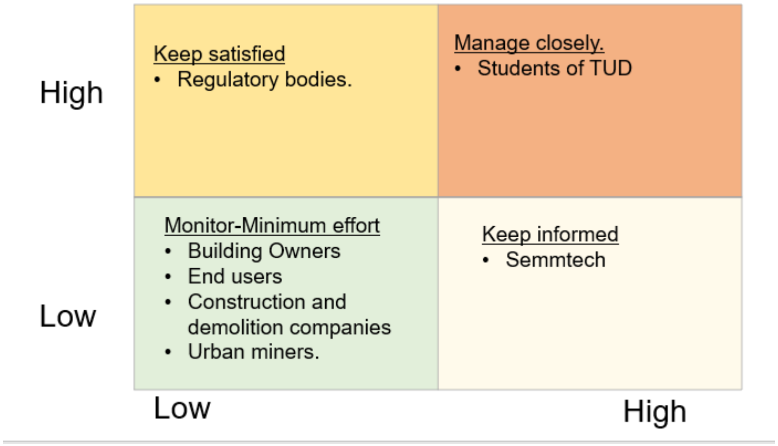

Figure 1: Power Interest grid

6 Sustainability goals

People:
When we think of sustainability goals in people's perspective.The goals is to minimize labour risk by reducing the need for manual inspections through the incorporation of modern materials and technology into building designs.Employee engagement and job satisfaction increase when processes are optimised so that workers may concentrate on important work rather than tedious or ineffective duties. In addition to lessening the impact on the environment, waste reduction encourages a sustainable and accountable work culture.

Profit :
By reducing spending and looking into new sources of income, financial stability may be achieved. Operations can be improved and competitive edge can be achieved in the market by using the concepts of the circular economy. In order to increase profitability while staying committed to environmental goals, doors to strategic alliances and partnerships that may open up new commercial prospects.

Planet:
The three main pillars of our environmental commitment are resource efficiency, waste reduction, and carbon emission reduction.By implementing waste reduction techniques like recycling and reusing into practice to make sure that business practices support a circular economy. The goal is to drastically reduce the carbon footprint which reduces environmental impact.

Ethical issues:
The two main principles of the ethical framework are accountability and transparency. The ultimate objective is to guarantee transparent data ownership , ethical and responsible material and data sourcing. This involves establishing guidelines for data security and privacy and making sure that all applicable legal requirements are met.

7 Project approach

In order to begin this project, the problem was narrowed down and stakeholders and their responsibilities were identified. Extensive market research was carried out to collect the relevant inputs for the model in order to understand the difficulties encountered by urban miners and identify the required solutions. The purpose of key performance indicators (KPIs) is to enable efficient tracking of project results.The KPIs were set. The market analysis includes approaching a variety of experts in the demolition and recycling industries to acquire information from their point of view. Through this interaction, we were able to examine their current supply chains and pinpoint certain issues they have. Areas for improvement were identified by looking at the way data is currently maintained. In addition to enhancing our understanding of the difficulties, this cooperative approach establishes the framework for putting into practice practical solutions that improve data management in the urban mining industry.

For the stimulation, we need to define the input and expected output. Blackbox model was implemented to provide overview of input,output ,Requirements and KPIs.The swin lane was implemented to get an idea of how the process which is to be stimulated looks like. Using linear programming for simulation, we created two modelling strategies in this context that were suited to various circumstances. A business case study was carried out to assess the financial ramifications of our suggested solutions, and an information model was developed to improve connectivity of data and support efficient decision-making. The implementation of successful initiatives that make use of digital twin has been made possible by this cooperative approach, which will ultimately improve sustainability in the building sector.

7.1 Possible Paths

Given this setup, we define a path as the set of processes that a window set undertakes.

Figure 2 is an oriented graph containing all the possible paths a window set can undertake through the system.

There's four different types of processes contained into this graph, store (refering to the window set being stored into the warehouse), remanufacture (refering to the window set passing through the remanufacturing facility), recycle (refering to the window set being sold to the recycling facility) and reuse (refering to the window set being sold to oter buyers).

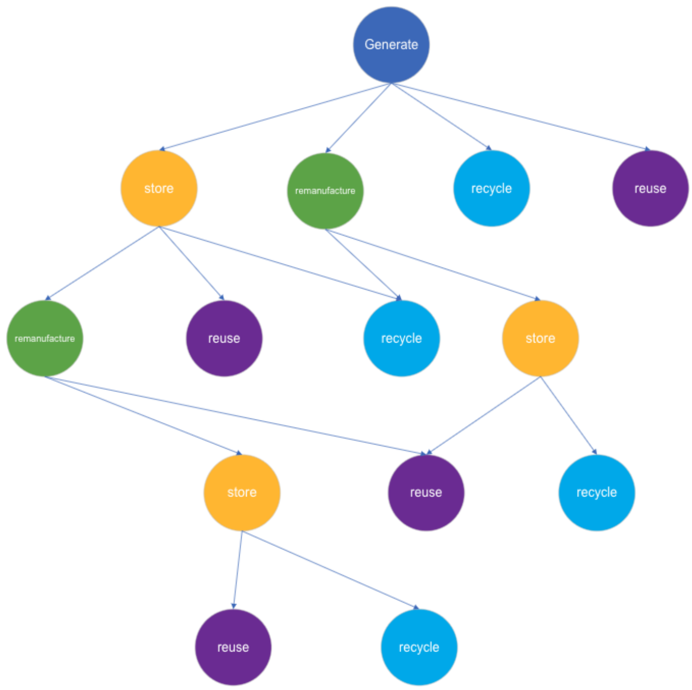

Figure 2: All the possible paths

The Urban Miner is responsible for choosing the best possible feasible path to put each window set through, limited by a set of constraints.

8 Sustainability Assessment

The Sustainability assessments of window remanufacturing systems focus on evaluating their overall environmental impact and finding ways to improve resource efficiency. One of the key areas considered was reducing energy consumption at all stages of transportation, remanufacturing and storage. By tracking energy consumption, we aim to identify areas where improvements can be made to reduce the carbon footprint.
Another important factor is the proportion of reused and recycled windows. Reusing windows has a lower environmental impact than recycling because it requires less energy and emits fewer emissions. Therefore, increasing the reuse rate is one of the main objectives of the system, as it directly contributes to sustainable development by minimizing resource use and greenhouse gas emissions.
Finally, the assessment also considers the waste generated by the process. By focusing on remanufacturing that produces the least amount of waste and ensuring that any waste generated is managed responsibly, we are trying to reduce the overall environmental burden.

Decision Tree Like Model and Simulation

We design a Python simulation model to find out the best choices for each window set obtained from demolition sites. This model evaluates different decision strategies—whether to **reuse** or **recycle** each window set—to maximize total profit while considering sustainability factors. The simulation incorporates various parameters such as transportation costs, remanufacturing costs, storage costs, sale prices, carbon emissions, and resource conservation.

9 Set Up

9.1 Sets

- $\mathcal{I}$: Set of window sets i.
- $\mathcal{S}$: Set of states s: Origin (O), Warehouse (W), Remanufacturing Facility (R), Reusing Facility (RU), and Recycling Facility (RC).
- $\mathcal{T}$: Set of days t, where $t = 0, 1, 2, \ldots, T$.

9.2 Parameters

9.2.1 General Parameters

- N_i: Number of windows in window set i, randomly assigned between 10 and 50.
- D_i: Dimensions of window i (length, width, height) in meters, randomly assigned:
  - Length and width between 0.5 and 2.0 meters.
  - Height between 0.1 and 0.5 meters.
- Age_i: Age of window set i in years, randomly assigned between 1 and 30 years.
- Material_i: Material type of window set i ('Material 1' or 'Material 2').
- Condition_i: Condition of window set i ('Good' or 'Bad').
- t_i^{dem}: Demolition date for window set i, randomly assigned between day 0 and 30.
- t_i^{del}: Delivery date for window set i, randomly assigned between day 20 and 60.
- InfoComplete_i: Information completeness indicator for window set i (True or False).
- C^{inspect}: Inspection cost per window, set to 5 EUR/window.

9.2.2 Cost Parameters

- C^{trans}: Transport cost per km per window (EUR/km/window), set to 0.05 EUR/km/window.
- C^{rem}: Remanufacturing cost per window (EUR), set to 18 EUR/window.
- C^{store}: Daily storage cost per window (EUR/day/window), set to 2 EUR/day/window.
- $P^{\text{reuse factor}}$: Base price factor for reuse, set to 150.
- $P^{\text{recycle factor}}$: Base price factor for recycling, set to 80.
- $t^{\text{rem duration}}$: Remanufacturing duration in days, set to 5 days.

9.2.3 Sustainability Parameters

- E^{trans}: Emission factor for transport (kg CO_2/km/window), set to 0.0002 kg CO_2/km/window.
- E^{rem}: Emission factor for remanufacturing (kg CO_2/window), set to 5 kg CO_2/window.
- E^{rec}: Emission factor for recycling (kg CO_2/window), set to 2 kg CO_2/window.
- P^{carbon}: Carbon price per kg CO_2 (EUR/kg CO_2), set to 0.05 EUR/kg CO_2.
- ρ_1: Density of material 1, set to 2700 kg/m^3.
- ρ_2: Density of material 2, set to 600 kg/m^3.

9.2.4 Capacities

- **Warehouses**:
  - Warehouse 1: Maximum storage capacity: 900 windows, daily storage cost per window: randomly assigned between 1 and 5 EUR.
  - Warehouse 2: Maximum storage capacity: 1000 windows, daily storage cost per window: randomly assigned between 1 and 5 EUR.
- **Remanufacturing Facility**: Daily processing capacity: randomly assigned between 50 and 100 windows/day.

9.3 Decision Variables

- $x_i^{\text{decision}} \in \{\text{Reuse}, \text{Recycle}\}$: Decision for window set i.
- $y_{ist} \in \{0, 1\}$: Binary variable indicating if window set i is in state s at time t.

9.4 Auxiliary Variables

- C_i^{trans}: Total transport cost for window set i (EUR).
- C_i^{rem}: Total remanufacturing cost for window set i (EUR).
- C_i^{store}: Total storage cost for window set i (EUR).
- C_i^{inspect}: Total inspection cost for window set i (EUR).
- R_i^{reuse}: Total revenue from reuse of window set i (EUR).
- R_i^{recycle}: Total revenue from recycling of window set i (EUR).
- E_i^{total}: Total emissions for window set i (kg CO_2).
- C_i^{carbon}: Carbon cost for window set i (EUR).
- S_i^{material}: Resource savings for window set i (kg of material).

10 Model Description

10.1 Objective Function

The adjusted total profit Π is calculated as:

$$\Pi = \sum_{i \in \mathcal{I}} \Big[\big(R_i^{\text{reuse}} \cdot \mathbb{I}(x_i^{\text{decision}} = \text{Reuse}) + R_i^{\text{recycle}} \cdot \mathbb{I}(x_i^{\text{decision}} = \text{Recycle}) \big) - \Big(C_i^{\text{trans}} + C_i^{\text{rem}} + C_i^{\text{store}} + C_i^{\text{inspect}} + C_i^{\text{carbon}} \Big) \Big] \tag{1}$$

where $\mathbb{I}(\cdot)$ is an indicator function that equals 1 if the condition is true, and 0 otherwise. The objective is to **maximize** Π.

10.2 Costs Calculation

10.2.1 Transport Cost

$$C_i^{\text{trans}} = \sum_{\text{movements}} N_i \times D_{\text{move}} \times C^{\text{trans}}$$

where D_{move} is the distance of each movement (km).

10.2.2 Remanufacturing Cost

$$C_i^{\text{rem}} = N_i \times C^{\text{rem}} \times \mathbb{I}(\text{Remanufacturing is performed})$$

10.2.3 Storage Cost

$$C_i^{\text{store}} = N_i \times C^{\text{store}} \times \text{Total Storage Days}$$

10.2.4 Inspection Cost

$$C_i^{\text{inspect}} = N_i \times C^{\text{inspect}} \times \mathbb{I}(\text{Information Incomplete})$$

10.2.5 Carbon Cost

$$C_i^{\text{carbon}} = E_i^{\text{total}} \times P^{\text{carbon}}$$

10.3 Revenue Calculation

10.3.1 Reuse Revenue

$$R_i^{\text{reuse}} = N_i \times P_i^{\text{reuse}}$$

where P_i^{reuse} is the sale price per window for reuse, calculated as:

$$P_i^{\text{reuse}} = \text{Area}_i \times \text{Material Factor}_i \times P^{\text{reuse factor}},$$

where $\text{Area}_i = \text{Length} \times \text{Width}$ and $\text{Material Factor}_i = 1.2$ if $\text{Material}_i = \text{Material}_1$, else 1.0.

10.3.2 Recycling Revenue

$$R_i^{\text{recycle}} = N_i \times P_i^{\text{recycle}},$$

where P_i^{recycle} is the sale price per window for recycling, calculated with a random material factor:

$$P_i^{\text{recycle}} = \text{Area}_i \times \text{Random Material Factor}_i \times P^{\text{recycle factor}},$$

where $\text{Random Material Factor}_i$: Randomly assigned between 0.5 and 1.0 if $\text{Material}_i = \text{Material}_1$, or between 0.3 and 0.8 if $\text{Material}_i = \text{Material}_2$.

10.4 Emissions Calculation

10.4.1 Transport Emissions

$$E_i^{\text{trans}} = \sum_{\text{movements}} N_i \times D_{\text{move}} \times E^{\text{trans}}$$

10.4.2 Remanufacturing Emissions

$$E_i^{\text{rem}} = N_i \times E^{\text{rem}} \times \mathbb{I}(\text{Remanufacturing is performed})$$

10.4.3 Recycling Emissions

$$E_i^{\text{rec}} = N_i \times E^{\text{rec}} \times \mathbb{I}(x_i^{\text{decision}} = \text{Recycle})$$

10.4.4 Total Emissions

$$E_i^{\text{total}} = E_i^{\text{trans}} + E_i^{\text{rem}} + E_i^{\text{rec}}$$

10.5 Resource Savings

When windows are reused, resource savings are calculated as:

$$S_i^{\text{material}} = N_i \times W_i$$

where W_i is the weight of one window in the window set i (kg), calculated based on dimensions and material density.

11 Simulation Algorithm

11.1 Initialization

1. **Facilities Setup**:
   - **Warehouses**: Initialized with locations, capacities, and daily storage costs.
   - **Remanufacturing Facility**: Initialized with location and daily capacity.
   - **Recycling Facility**: Initialized with location.
   - **Reusing Facility(Buyer)**: Initialized with location and delivery date.
2. **Window Sets Generation**:
   - A user-defined number of window sets n are generated with random attributes as specified in the parameters.
3. **Decision Options**:
   - For each window set i:
     - If $\text{Age}_i > 25$, $x_i^{\text{decision}} = \text{Recycle}$.
     - Else, $x_i^{\text{decision}} \in \{\text{Reuse}, \text{Recycle}\}$.

11.2 Decision Combinations

Generate all possible combinations of decisions $\{x_i^{\text{decision}}\}_{i \in \mathcal{I}}$.

11.3 Simulation Loop

The flowchart outline for the simulation process is as Figure 3.

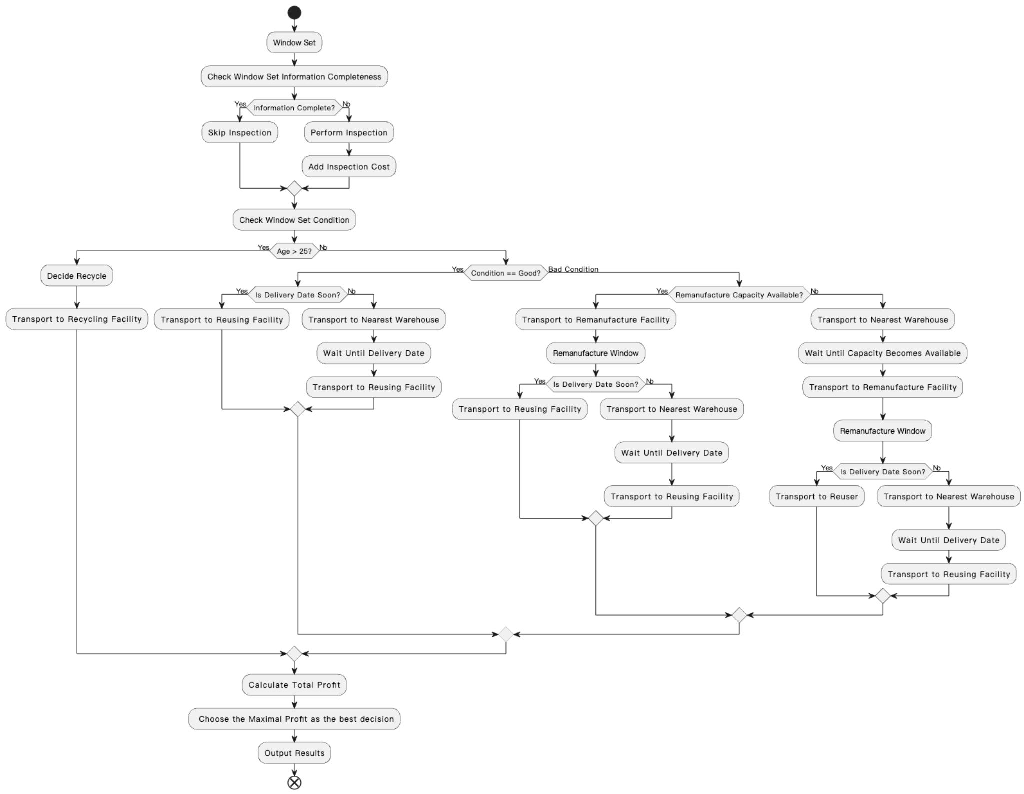

Figure 3: Simulation Flowchart

The simulation loop begins by evaluating each window set's information completeness. If the information is complete, the simulation skips the inspection step. Otherwise, it performs an inspection and adds the inspection cost. Next, the model checks the window set's condition and age. If the window set is older than 25 years, it goes directly to recycling. Otherwise, if it is in good condition, the model assesses if it can be reused. If the delivery date is approaching, the window is transported to the reusing facility; if not, it is moved to the nearest warehouse and waits until the delivery date.

If the window set has a bad condition but remanufacturing capacity is available, it is transported to the remanufacturing facility. If capacity is unavailable, it waits in the nearest warehouse until capacity opens up, then moves to the remanufacturing facility. After remanufacturing, the model checks if the delivery date is soon. If so, it transports the window set to the reuser; if not, it sends it to the nearest warehouse to wait until the delivery date before going to the reuser.

After processing all window sets, the simulation calculates the total Π for each decision path and selects the path that provides the maximum Π. The chosen decision path is recorded, and the simulation outputs the results.

12 Code Execution

12.1 Parameters from the Code

- **Transport Cost per km per window**: $C^{\text{trans}} = 0.05$ EUR/km/window.
- **Remanufacture Cost per window**: $C^{\text{rem}} = 18$ EUR/window.
- **Reuse Sale Price Factor**: $P^{\text{reuse factor}} = 150$.
- **Recycle Sale Price Factor**: $P^{\text{recycle factor}} = 80$.
- **Remanufacturing Duration**: $t^{\text{rem duration}} = 5$ days.
- **Daily Storage Cost per window**: $C^{\text{store}} = 2$ EUR/day/window.
- **Inspection Cost per window**: $C^{\text{inspect}} = 5$ EUR/window.

- **Transport Emission Factor**: $E^{\text{trans per km per window}} = 0.0002$ kg CO_2/km/window.
- **Remanufacturing Emission per window**: $E^{\text{rem per window}} = 5$ kg CO_2/window.
- **Recycling Emission per window**: $E^{\text{rec per window}} = 2$ kg CO_2/window.
- **Carbon Price per kg CO_2**: $P^{\text{carbon}} = 0.05$ EUR/kg CO_2.
- **Density of Material 1**: $\rho_{\text{Material 1}} = 2700$ kg/m^3.
- **Density of Material 2**: $\rho_{\text{Material 2}} = 600$ kg/m^3.

12.2 Output Results

Warehouse Information:

- **Warehouse 1**:
  - **Location**: (73.47, 41.86)
  - **Max Storage**: 900
  - **Daily Cost per Window**: 1.41 EUR
- **Warehouse 2**:
  - **Location**: (222.20, 163.61)
  - **Max Storage**: 1000
  - **Daily Cost per Window**: 3.36 EUR

Remanufacture Facility Information

- **Location**: (9.53, 28.11)
- **Daily Capacity**: 64

Recycling Center Information

- **Location**: (151.61, 7.96)

Reuser (Buyer) Information

- **Location**: (59.65, 194.97)
- **Delivery Date**: Day 54

Window Set Information

We suppose that there are 10 window sets that look like this:

Window Set	Num Windows	Location	Dimensions (m)	Material	Condition
1	36	(66.13, 176.78)	(1.71, 0.51, 0.42)	Material 2	Bad
2	31	(30.66, 113.98)	(1.04, 1.02, 0.21)	Material 1	Bad
3	34	(23.64, 87.95)	(1.44, 1.83, 0.24)	Material 1	Good
4	28	(295.57, 256.60)	(1.80, 1.07, 0.28)	Material 2	Good
5	27	(210.55, 205.06)	(0.61, 1.45, 0.31)	Material 1	Good
6	50	(206.45, 65.88)	(0.99, 1.65, 0.12)	Material 1	Bad
7	23	(273.94, 170.15)	(1.58, 0.82, 0.30)	Material 2	Good
8	45	(161.69, 224.10)	(1.14, 1.38, 0.24)	Material 1	Bad
9	17	(45.85, 47.99)	(1.52, 1.39, 0.25)	Material 2	Bad
10	17	(204.51, 161.09)	(0.90, 1.46, 0.14)	Material 2	Good

Window Set	Age (years)	Info Complete	Demolition Date	Delivery Date
1	7	True	Day 8	Day 37
2	30	True	Day 17	Day 37
3	25	True	Day 1	Day 37
4	7	False	Day 11	Day 37
5	9	False	Day 14	Day 37
6	3	False	Day 12	Day 37
7	8	True	Day 8	Day 37
8	28	True	Day 2	Day 37
9	22	True	Day 17	Day 37
10	24	True	Day 14	Day 37

Since there are 8 window sets that are under 25 years, so the total combinations to evaluate is $2^8 = 256$.

Profit and Environmental Impact Analysis

Optimal Scenario

- **Total Profit**: 49,359.71 EUR
- **Total Emissions**: 239.42 kg CO_2
- **Total Resource Savings**: 128,217.60 kg of material
- **Best Combination of Decisions for window sets 1-10**:

  ('Recycle', 'Recycle', 'Reuse', 'Reuse', 'Reuse', 'Reuse', 'Reuse', 'Recycle', 'Reuse', 'Reuse')

Worst Scenario

- **Total Profit**: 21,694.04 EUR
- **Total Emissions**: 556.08 kg CO_2
- **Total Resource Savings**: 7,970.89 kg of material
- **Worst Combination of Decisions for window sets 1-10**:

  ('Reuse', 'Recycle', 'Recycle', 'Recycle', 'Recycle', 'Recycle', 'Recycle', 'Recycle', 'Recycle', 'Recycle')

Window Sets under Optimal Scenario: Costs, Revenues, and Environmental Impact

WindowSet 1

Decision	Recycle
Total Transport Cost (Recycle)	340.60 EUR
Inspection Cost	0.00 EUR
Total Recycling Price	910.81 EUR
Carbon Cost	3.67 EUR
Expected Net Revenue (Recycle)	1130.14 EUR
Total Emissions	73.36 kg CO_2
Resource Savings	0.00 kg

Daily Locations:

- Day 0 - Day 16: At Original Location
- Day 17 - Day 17: Sent to Recycling Center

WindowSet 2

Decision	Recycle
Total Transport Cost (Recycle)	249.29 EUR
Inspection Cost	0.00 EUR
Total Recycling Price	1348.20 EUR
Carbon Cost	3.15 EUR
Expected Net Revenue (Recycle)	1361.33 EUR
Total Emissions	63.00 kg CO_2
Resource Savings	0.00 kg

Daily Locations:

- Day 0 - Day 16: At Original Location
- Day 17 - Day 17: Sent to Recycling Center

WindowSet 3

Decision	Reuse
Total Transport Cost (Reuse)	376.72 EUR
Total Remanufacture Cost	0.00 EUR
Total Storage Cost	2448.00 EUR
Inspection Cost	0.00 EUR
Total Cost (Reuse)	2824.72 EUR
Total Sale Price (Reuse)	16144.48 EUR
Carbon Cost	0.08 EUR
Expected Net Revenue (Reuse)	13319.68 EUR
Total Emissions	1.51 kg CO_2
Resource Savings	59247.17 kg

Daily Locations:

- Day 0 - Day 0: At Original Location
- Day 1 - Day 36: In Warehouse 1
- Day 37 - Day 37: Delivered to Reuser

WindowSet 4

Decision	Reuse
Total Transport Cost (Reuse)	397.58 EUR
Total Remanufacture Cost	0.00 EUR
Total Storage Cost	1400.00 EUR
Inspection Cost	140.00 EUR
Total Cost (Reuse)	1937.58 EUR
Total Sale Price (Reuse)	8089.40 EUR
Carbon Cost	0.08 EUR
Expected Net Revenue (Reuse)	6151.73 EUR
Total Emissions	1.59 kg CO_2
Resource Savings	9104.26 kg

Daily Locations:

- Day 0 - Day 10: At Original Location
- Day 11 - Day 11: Under Inspection
- Day 12 - Day 36: In Warehouse 2
- Day 37 - Day 37: Delivered to Reuser

WindowSet 5

Decision	Reuse
Total Transport Cost (Reuse)	281.62 EUR
Total Remanufacture Cost	0.00 EUR
Total Storage Cost	1188.00 EUR
Inspection Cost	135.00 EUR
Total Cost (Reuse)	1604.62 EUR
Total Sale Price (Reuse)	4285.54 EUR
Carbon Cost	0.06 EUR
Expected Net Revenue (Reuse)	2680.86 EUR
Total Emissions	1.13 kg CO_2
Resource Savings	20162.78 kg

Daily Locations:

- Day 0 - Day 13: At Original Location
- Day 14 - Day 14: Under Inspection
- Day 15 - Day 36: In Warehouse 2
- Day 37 - Day 37: Delivered to Reuser

WindowSet 6

Decision	Reuse
Total Transport Cost (Reuse)	1049.06 EUR
Total Remanufacture Cost	900.00 EUR
Total Storage Cost	1900.00 EUR
Inspection Cost	250.00 EUR
Total Cost (Reuse)	4099.06 EUR
Total Sale Price (Reuse)	14670.33 EUR
Carbon Cost	0.21 EUR
Expected Net Revenue (Reuse)	10571.05 EUR
Total Emissions	4.20 kg CO_2
Resource Savings	26929.26 kg

Daily Locations:

- Day 0 - Day 11: At Original Location
- Day 12 - Day 12: Under Inspection
- Day 13 - Day 17: In Remanufacture Facility
- Day 18 - Day 36: In Warehouse 1
- Day 37 - Day 37: Delivered to Reuser

WindowSet 7

Decision	Reuse
Total Transport Cost (Reuse)	250.35 EUR
Total Remanufacture Cost	0.00 EUR
Total Storage Cost	1334.00 EUR
Inspection Cost	0.00 EUR
Total Cost (Reuse)	1584.35 EUR
Total Sale Price (Reuse)	4455.20 EUR
Carbon Cost	0.05 EUR
Expected Net Revenue (Reuse)	2870.80 EUR
Total Emissions	1.00 kg CO_2
Resource Savings	5340.76 kg

Daily Locations:

- Day 0 - Day 7: At Original Location

- Day 8 - Day 36: In Warehouse 2
- Day 37 - Day 37: Delivered to Reuser

WindowSet 8

Decision	Recycle
Total Transport Cost (Recycle)	486.85 EUR
Inspection Cost	0.00 EUR
Total Recycling Price	3882.26 EUR
Carbon Cost	4.60 EUR
Expected Net Revenue (Recycle)	4530.99 EUR
Total Emissions	91.95 kg CO_2
Resource Savings	0.00 kg

Daily Locations:

- Day 0 - Day 1: At Original Location
- Day 2 - Day 2: Sent to Recycling Center

WindowSet 9

Decision	Reuse
Total Transport Cost (Reuse)	265.88 EUR
Total Remanufacture Cost	306.00 EUR
Total Storage Cost	510.00 EUR
Inspection Cost	0.00 EUR
Total Cost (Reuse)	1081.88 EUR
Total Sale Price (Reuse)	5408.09 EUR
Carbon Cost	0.05 EUR
Expected Net Revenue (Reuse)	4326.15 EUR
Total Emissions	1.06 kg CO_2
Resource Savings	5492.61 kg

Daily Locations:

- Day 0 - Day 16: At Original Location
- Day 17 - Day 17: In Warehouse 1
- Day 18 - Day 22: In Remanufacture Facility
- Day 23 - Day 36: In Warehouse 1
- Day 37 - Day 37: Delivered to Reuser

WindowSet 10

Decision	Reuse
Total Transport Cost (Reuse)	155.90 EUR
Total Remanufacture Cost	0.00 EUR
Total Storage Cost	782.00 EUR
Inspection Cost	0.00 EUR
Total Cost (Reuse)	937.90 EUR
Total Sale Price (Reuse)	3354.90 EUR
Carbon Cost	0.03 EUR
Expected Net Revenue (Reuse)	2416.97 EUR
Total Emissions	0.62 kg CO_2
Resource Savings	1940.75 kg

Daily Locations:

- Day 0 - Day 13: At Original Location
- Day 14 - Day 36: In Warehouse 2
- Day 37 - Day 37: Delivered to Reuser

12.3 Conclusion, Limitation and Improvements

Conclusion:

Comparing the best and worst scenarios, we could see that:

- **Total Profit**: In the best-case scenario, the total profit is 49,359.71 EUR, which is 27,665.67 EUR (around 127.6%) higher than the worst-case profit of 21,694.04 EUR. This shows that with better information and planning, profit can more than double.
- **Total Emissions**: In the best-case scenario, CO_2 emissions are 239.42 kg, which is 316.66 kg (about 57%) lower than the worst-case emissions of 556.08 kg. This shows that efficient processes and logistics can greatly reduce emissions and help meet environmental goals.
- **Total Resource Savings**: Resource savings in the best-case scenario reach 128,217.60 kg, which is 120,246.71 kg (about 1,508.7%) more than the 7,970.89 kg saved in the worst case. This large increase highlights how better information and planning can help maximize resource reuse and recycling.

In terms of data, there is a significant improvement across these three aspects. The data shown here might look exaggerated because we don't have real data and most parameters are randomly generated by the code, which could make it seem a bit over the top. However, it's enough to show that this model can indeed help urban miners make better decisions.

This model shows several benefits of better information sharing. With more complete data, urban miners can avoid costly inspections, relying on the data instead of checking each window set by hand. This improved information also makes it easier to plan ahead by knowing the condition, material, and specifications of windows before demolition, which can help reduce storage and logistics costs. Accurate information helps schedule remanufacturing better, keeping operations within capacity limits and avoiding delays. Additionally, more complete data supports sustainability, as it increases the chances of reusing windows instead of recycling them, saving resources and lowering emissions.

This window set processing model developed in this study provides a foundational framework for analyzing how complete information affects the profitability and sustainability of urban mining. By focusing on key decision-making factors such as window age, condition, and information availability, the model demonstrates how improved information management can optimize the operational efficiency and financial performance of urban miners.

Limitation:

While the model provides useful insights, it has several limitations that limit its ability to fully represent real-life complexities:

- **Simplified Material Types**: Materials are labeled as "Material 1" and "Material 2," without detailed properties like recyclability or difficulty of remanufacturing, which could impact costs and sustainability.
- **Random Parameters**: Attributes like window location, storage cost, and condition are randomly assigned, which may not reflect real-world patterns accurately.
- **Binary Information Completeness**: The model treats information as either complete or incomplete, missing out on different levels of detail or the cost of managing this information.
- **Fixed Emission Factors and Costs**: Emission and cost values are assumed to be constant, not taking into account changes due to transportation methods, energy sources, or efficiency improvements.
- **No Market Dynamics**: The model uses fixed prices for reused and recycled windows, ignoring changes in demand, price shifts, or competition that could affect profitability.

Improvements:

To make the model more accurate and useful for stakeholders, the following improvements are recommended:

- **Detailed Material Properties**: The model should include more specific information about materials, like recyclability, remanufacturing difficulty, and durability. These details would help in making better processing choices and give a clearer picture of costs, emissions, and profits.

- **Better Information Management**: The model should simulate different levels of information completeness, like partial or full information, to see how this affects decision-making and costs. It should also account for the costs of collecting and managing this information. Additionally, it would be useful to show how different levels of information sharing among stakeholders, like demolition companies, urban miners, and reuse facilities, could affect outcomes.
- **Dynamic Market Conditions**: Adding changes in market demand would help show how these shifts can affect prices and profits for reused and recycled materials. Modeling price variability based on competition or material scarcity would also make the model more realistic.
- **Advanced Logistics Optimization**: The model would be improved by adding route optimization to reduce transportation costs and emissions. It should also consider different types of transportation, like trucks or trains, each with its own costs and emission levels.
- **Environmental Impact Analysis**: To get a more complete view of environmental effects, the model should include metrics like energy use, waste generation, and resource depletion. Extending the model to perform a lifecycle analysis of window sets, from demolition to reuse or recycling, would also make it more thorough.
- **Sensitivity Analysis**: Performing sensitivity analysis on key parameters, such as costs, emissions, and market prices, would help understand their impact on outcomes. This can also help identify which factors most affect profitability and sustainability, making it easier to focus data collection and model improvements on those areas.
- **Policy and Incentive Modeling**: The model should simulate the effects of regulations, subsidies, and taxes on recycling, remanufacturing, and emissions. Testing how different policy changes affect urban miners would also help predict real-world impacts.
- **Stakeholder Collaboration**: It would be helpful to model collaboration between urban miners, demolition companies, remanufacturers, and reuse entities. This could include exploring how agreements or shared platforms improve information flow and efficiency.

These improvements would make the model more realistic and valuable for decision making, helping optimize operations, enhance sustainability, and support policy development in urban mining.

Simulation Optimization Framework

The modeling approach described above provides insights into a decision-making process that an urban miner might use, and its effects on the overall performance of the reverse supply chain. However because of the limitations described in the previous section, we decided to implement an approach to more accurately model both the decision-making process and the operations happening in the reverse supply chain.

To do this we used an approach called Simulation Optimization Framework, which integrates optimization techniques into simulation modeling and analysis.

Specifically we decided to build a Discrete Event Simulation(DES) in which the window frames move through the reverse supply chain. One of the components (the scheduler) acts as an optimal decision-making agent, implemented through a Linear Programming model. Details are discussed in the following sections.

We aim to encode the uncertainty brought into the system by insufficient/imperfect information, in the estimation, done by the urban miner, of both the market value of a window set and when it can be sold.

13 Blackbox Analysis

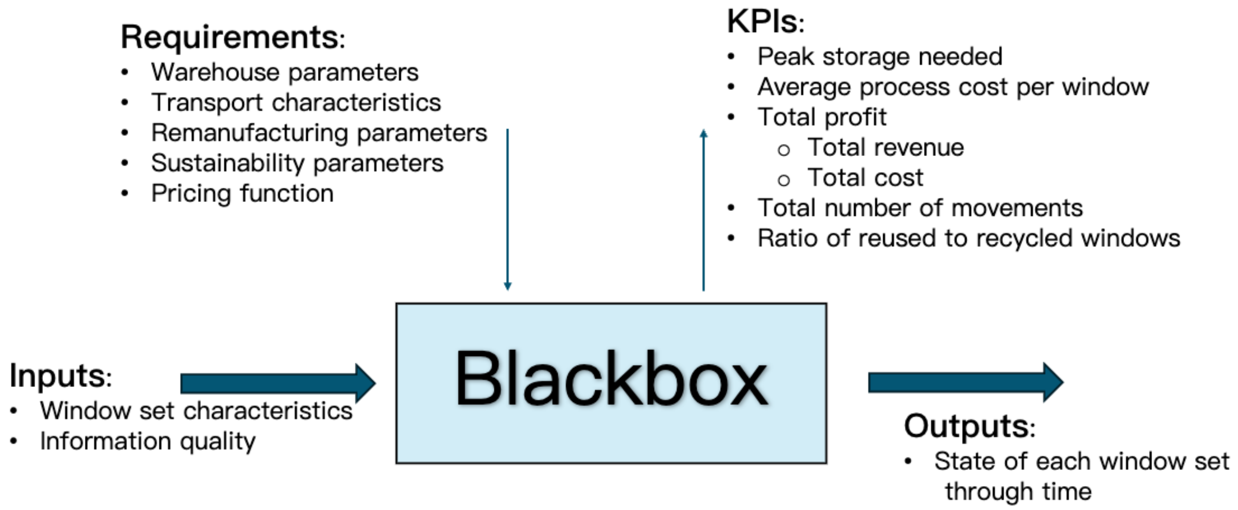

Figure 4: Blackbox Model

This black box model, as shown in Figure 4, outlines the inputs, outputs, and requirements of the window frame remanufacturing and recycling process, providing a clear framework for understanding the interactions within the reverse supply chain.

14 Swimlane Model

Figure 5 is the **Swimlane Diagran** of part of the considered reverse supply chain, used to visualize the process workflow and the interaction between stakeholders.
In the swimlane diagram the **square blocks** represent processes that consume resources (time and/or money),while **romboid blocks** represent processes that, in the simulation, don't consume resources, so they are decisions.

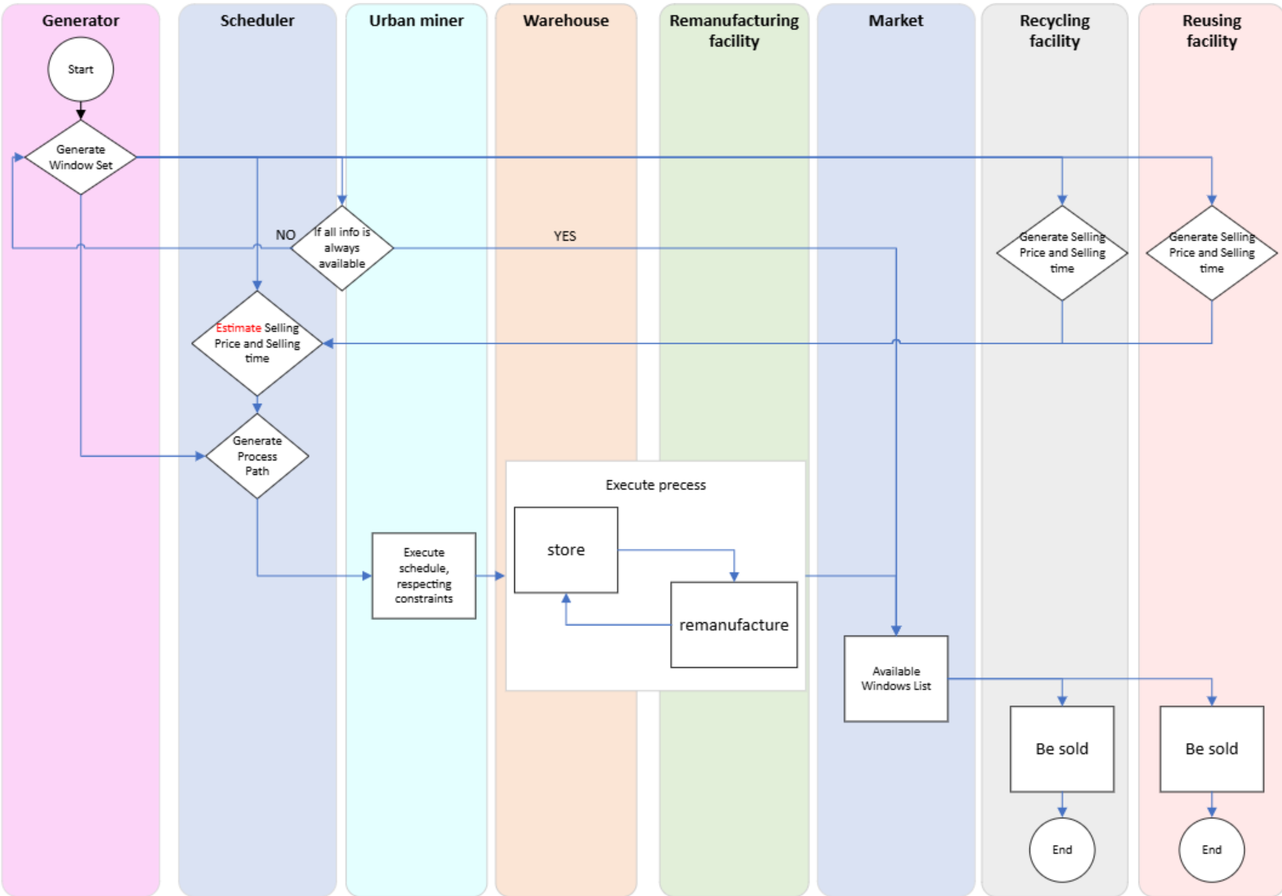

Figure 5: Swimlane diagram

The entire simulation is based on the above Swimlane Diagram.

14.1 Decision Making blocks

Generation of Window Sets In the simulation, window sets are generated by the `WindowSetGenerator` class, which creates a predefined number of window sets with randomized characteristics to simulate real-world variability. For each window set, the following attributes are randomly assigned to ensure diversity:

- **Unique Identifier** (`ID`): Assigned sequentially to each window set.
- **Material**: Randomly chosen from the set `Al1`, `Al2`, `Al3`.
- **Condition**: Randomly selected from `Poor`, `Decent`, `Good`.
- **Number of Windows** (`Num Windows`): A random integer between 5 and 30.
- **Volume**: A random float between 0.2 and 1.0, rounded to two decimal places.
- **Type**: Randomly selected from `Type1`, `Type2`, `Type3`.
- **Sustainability Class**: Randomly chosen from `SC1`, `SC2`, `SC3`, `SC4`.

This generation approach ensures a diverse set of window sets, capturing the complexities and uncertainties inherent in demolition and salvage operations.
We want to highlight that the parameters are intentionally dimentionless, as we think that given the arbitrarity of the way in which they are used, the unit measure or absolute value can be ignored, and it is rather the change in KPIs between configurations that we are going to highlight.

14.2 Selling Price and Time Setting and Estimation

In the model, both the reusing facility and the recycling facility provide information on the selling price and the selling time for window sets. These parameters are critical for the urban miner to make informed decisions about processing and selling window sets.

14.2.1 Selling Price and Selling Time Definitions

- **Selling Price**: The price at which a buyer (reusing or recycling facility) is willing to purchase a window set.
- **Selling Time**: The time at which a buyer is ready to make the purchase.

Transactions can only occur at the specified selling price and at the designated selling time.

14.2.2 Recycling Facility

Selling Price The selling price offered by the recycling facility is a function of the window set's volume, material, and the number of windows. It is calculated using the following relationship:

$$\text{Selling Price Recycle} = (2 \times \text{Volume} + C_{\text{Material}}) \times \text{Num Windows} \tag{2}$$

where C_{Material} is a constant based on the material type:

- $C_{\text{Material}} = 30$ if the material is Al1
- $C_{\text{Material}} = 50$ if the material is Al2
- $C_{\text{Material}} = 60$ if the material is Al3

Selling Time The recycling facility is always willing to accept window sets; therefore, the selling time is effectively immediate and always available.

Urban Miner Estimation The urban miner has perfect information regarding the recycling facility's selling price and selling time. Therefore, the estimated selling price and time are equal to the actual values:

$$\text{Estimated Selling Price Recycle} = \text{Actual Selling Price Recycle} \tag{3}$$

$$\text{Estimated Selling Time Recycle} = \text{Actual Selling Time Recycle} \tag{4}$$

14.2.3 Reusing Facility

Selling Price The selling price offered by the reusing facility is a function of multiple characteristics of the window set, including volume, condition, type, sustainability class, and the number of windows. It is calculated using a polynomial expression:

$$\text{Selling PriceReuse} = \left(2 \times \text{Volume} + C_{\text{Condition}} + C_{\text{Type}} + C_{\text{Sustainability Class}}\right) \times \text{Num Windows} \tag{5}$$

where the constants are defined as:

- $C_{\text{Condition}}$:
  - 60 if condition is "Good"
  - 40 if condition is "Decent"
  - 15 if condition is "Poor"
- C_{Type}:
  - 40 if type is "Type1"
  - 25 if type is "Type2"
  - 15 if type is "Type3"
- $C_{\text{Sustainability Class}}$:

- 15 if class is "SC1"
- 30 if class is "SC2"
- 45 if class is "SC3"
- 50 if class is "SC4"

Selling Time The selling time for the reusing facility is variable and depends on external factors. It is set within a range relative to the demolition date of the window set. In the model, the selling date for reuse is calculated as:

$$\text{Selling Date Reuse} = \text{Demolition Date} + D_{\text{Reuse}} \tag{6}$$

where D_{Reuse} is a random integer sampled from a predefined range (e.g., between $5 -$ Uncertainty and $5 +$ Uncertainty days).

Urban Miner Estimation The urban miner must estimate the selling price and selling time for the reusing facility due to uncertainties. The estimation process is as follows:

Estimated Selling Price The estimated selling price is calculated by multiplying the actual selling price by a random multiplier within a specified range to simulate estimation uncertainty:

$$\text{Estimated Selling Price Reuse} = \text{Actual Selling PriceReuse} \times \delta \tag{7}$$

where δ is a random value sampled uniformly from the range:

$$\delta \in \left[1 - \frac{\text{Estimation Precision}}{2},\ 1 + \frac{\text{Estimation Precision}}{2}\right] \tag{8}$$

The *estimation precision* parameter controls the width of the uncertainty range.

Estimated Selling Time The urban miner estimates the selling time for reuse based on experience and available data. In the model, the estimated selling time is set to:

$$\text{Estimated Selling Time Reuse} = \min\left(\text{Demolition Date} + D_{\text{Estimate}},\ \text{Time Horizon} - 1\right) \tag{9}$$

where D_{Estimate} is a fixed value (e.g., 5 days) representing the average expected delay, and the estimation ensures that the estimated selling time does not exceed the simulation's time horizon, this is done to ensure that the estimated demolition date does not exceed the time horizon, while being the best possible guess.

Estimating the selling price and time for both the recycling and reusing facilities is crucial for the urban miner's decision-making process. By incorporating estimation uncertainties for the reusing facility, we tried to reflect real-world challenges faced by urban miners in forecasting market conditions in order to plan operations.

14.3 Urban Miner decision making

The urban miner observes the window sets generated by the Generator component, he then estimates what the selling time and price could be, and is finally tasked with deciding the optimal path in order to generate the most profit, knowing the current condition of the warehouse and the remanufacturing facility, while complying to all the necessary constraints.

In the simulation we plan on using Linear Programming to achieve this. The output will be the optimal set of actions that that specific window frame should (and would if input information was perfect) undertake.

The urban miner's inability to choose the optimal path is, in this way, only dependent on **the quality of the information that it receives**, which in this simulation is related to how good of an estimation of selling price and time it can make.

The optimality of the urban miner's decision making process is particularly important because of the emphasis of the project on investigating the effect of the quality/and quantity of the data available to all parties in the reverse supply chain. If the decision making of the urban miner were to be suboptimal, the effects on the KPIs would be dampened by the randomness introduced by the arbitrary decision making process. In other words, better/and more information is only better from the urban miners point of view (which operations are being simulated in this project) if they then lead to better decisions, therefore it is essential that better data actually leads to better decisions, the randomness/arbitrariness in the decision making progress needs to be minimized.

15 Discrete Event Simulation

The Discrete Event Simulation (DES) serves as a crucial component in modeling the operational aspects of the window set processing system. It simulates the flow of window sets through various stages, including demolition, transportation, storage, remanufacturing, and sales to reusing or recycling facilities. The DES provides a dynamic and detailed representation of the system's behavior over time, **capturing some of the stochastic nature of events** and enabling the analysis of operational performance under different scenarios.

The DES models the life cycle of window sets from their generation, before demolition, to their final destination, either reuse or recycling. It tracks each window set's state, accumulates costs associated with various processes, and calculates revenues from sales. The simulation aims to provide insights into operational efficiencies, resource utilization, and profitability, considering the uncertainties inherent in the system, such as price estimation precision and selling date uncertainty.

15.1 Assumptions

This model operates under a high number of assumptions, some of them were necessary and dictated by the nature of the simulation, while most of them are a cause of missing data. All the assumptions contribute to the difference between simulated and factual reality.

- **Remanufacturing increases value by some fixed percentage**: the model uses the parameter α as the percentage increase in value of each window set if it is remanufactured.
- **Remanufacturing takes a fixed amount of time and costs a fixed amount per day per window**: remanufacturing process details was really difficult to obtein, really complicated and furthermore beyond the scope of this project, we essentially looked at remanufacturing as something that increases value of the window frame for a cost
- **Reuse market value of the windows is a polynomial function of the window's charachteristics**: all coefficients of the the polynomial are also quite arbitrary.
- **No market dynamics in pricing**
- **The urban miner obtains all the windows for free**: we validated this by talking to people involved in the urban mining industry, but it is still a strong assumption. Only acquisition cost is an inspection cost.
- **A market value exists for all window sets**
- **Transportation happens within the day and costs a fixed amount per unit volume**: we are essentially ignoring the distance between facilities as a parameter. Transportation dynamics are beyond the scope of this project.
- **No operational stochasticity**: remanufacturing, transportation and storing always happen without any problems.

15.2 Simulation Components

The DES comprises several interconnected components, each representing a different aspect of the system. The main components are:

- **Simulation Environment** (`WindowSetSimulation`)
- **Window Set** (`WindowSet`)
- **Window Set Generator** (`WindowSetGenerator`)

- **Scheduler** (`Scheduler`)
- **Urban Miner** (`UrbanMiner`)
- **Warehouse** (`Warehouse`)
- **Remanufacturing Facility** (`RemanufacturingFacility`)

15.3 Component Descriptions

15.3.1 Simulation Environment (`WindowSetSimulation`)

The simulation environment acts as the central hub for the DES. It initializes global parameters, keeps track of all window sets, and records financial metrics such as total revenue, total cost, and total profit. It also calculates and prints Key Performance Indicators (KPIs) at the end of the simulation.
Key responsibilities:

- Setting global parameters, such as the time horizon and cost factors.
- Maintaining a list of all window sets in the system.
- Tracking total revenue and costs accrued during the simulation.
- Calculating KPIs, including profit, average profit per window, peak warehouse usage, total movements, and percentage of window sets reused.

15.3.2 Window Set (`WindowSet`)

Each window set represents a collection of windows with specific characteristics. The `WindowSet` class encapsulates attributes such as material, condition, number of windows, volume, type, sustainability class, and important dates like demolition and selling dates.
Key responsibilities:

- Storing individual window set characteristics.
- Calculating estimated selling prices and times, considering uncertainties.
- Tracking the current state of the window set within the system.
- Accumulating costs incurred during processing (e.g., remanufacturing, storage, transportation, and inspection).

15.3.3 Window Set Generator (`WindowSetGenerator`)

The generator is responsible for creating window sets with random characteristics, simulating the arrival of window sets into the system over time.
Key responsibilities:

- Generating a predefined number of window sets with randomized attributes.
- Calculating actual selling prices for reuse and recycling based on window set characteristics.
- Introducing uncertainties in estimated selling prices and selling dates.

15.3.4 Scheduler (`Scheduler`)

The Scheduler's role is to create an optimal schedule for wach window set to follow. The schedule defines the state in which each window set should be everyday.

It takes as input the estimated selling price to the reusing and recycling facility, the estimated selling date to the reusing facility and the demolition date per window set. It returns the optimal schedule as an output, while taking into account the remanufacturing facility and warehouse capacity.

The Scheduler uses Linear Programming to return the schedule that maximizes profit. The exact model is defined in the section : "Linear Programming Model"

15.3.5 Urban Miner (`Urban Miner`)

The urban miner's role is to manage the movement of window sets through different states based on a predetermined schedule derived from the optimization model implemented in the Scheduler. It handles state transitions, updates costs, and ensures that operational constraints are respected.
Key responsibilities:

- Executing state transitions for window sets according to the schedule.
- Calculating transportation costs for movements between states.
- Updating the current state of window sets and handling special conditions (e.g., awaiting selling dates).
- Tracking the total number of movements for KPI calculations.

15.3.6 Warehouse (`Warehouse`)

The warehouse component simulates the storage facility where window sets are kept before being sold or processed further. It manages capacity, tracks storage costs, and handles the release of window sets when they are ready for sale.
Key responsibilities:

- Receiving window sets for storage.
- Accumulating storage costs on a daily basis.
- Monitoring when window sets are ready to be sent to the reusing facility.
- Tracking peak warehouse usage for KPI calculations.

15.3.7 Remanufacturing Facility (`RemanufacturingFacility`)

The remanufacturing facility processes window sets to enhance their value before sale. It manages processing capacity, tracks remanufacturing costs, and updates the status of window sets upon completion.
Key responsibilities:

- Receiving window sets for remanufacturing.
- Processing window sets over a specified number of days.
- Accumulating remanufacturing costs on a daily basis.
- Updating window sets' processing status upon completion.

15.4 Component Interactions

The DES simulates the flow of window sets through the system by modeling the interactions between components:

1. **Initialization**: The `WindowSetGenerator` creates window sets with random attributes and adds them to the simulation environment.
2. **Scheduling**: The `Urban miner` retrieves the schedule and directs window sets to move between states (e.g., from the origin to the warehouse, remanufacturing facility, or directly to sale).
3. **State Transitions**: Window sets transition between states based on the schedule, with associated costs being accumulated (e.g., transportation cost when moving between locations).
4. **Processing**: Window sets in the remanufacturing facility are processed over several days, accruing remanufacturing costs.
5. **Storage**: Window sets stored in the warehouse accumulate storage costs until they are ready to be sold.
6. **Sale**: Once window sets reach their selling date, they are moved to the reusing or recycling facility, generating revenue.

15.5 Cost and Revenue Tracking

The DES meticulously tracks costs and revenues associated with each window set:

15.5.1 Costs

- **Remanufacturing Cost (`cost_remanufacturing`)**: Calculated daily for window sets in the remanufacturing facility, fixed cost per window per day.
- **Storage Cost (`cost_storage`)**: Accumulated daily for window sets stored in the warehouse, fixed cost per unit volume per day.
- **Transportation Cost (`cost_transport`)**: Incurred each time a window set moves between states, calculated based on volume, number of windows, and a fixed cost per unit volume.
- **Inspection Cost (`inspection_cost`)**: A fixed cost applied once when a window set is introduced into the system.

15.5.2 Revenues

- **Sale to Reusing Facility**: Revenue is generated when a window set is sold to the reusing facility. If remanufacturing is completed, the selling price is increased by a factor of $(1 + \alpha)$ to reflect the added value.
- **Sale to Recycling Facility**: Revenue from sales to the recycling facility is based on the actual selling price without adjustments.

15.6 Key Performance Indicators (KPIs)

At the end of the simulation, several KPIs are calculated to assess the system's performance:

- **Total Revenue**: Sum of revenues from all sales.
- **Total Cost**: Sum of all accumulated costs (remanufacturing, storage, transportation, inspection).
- **Total Profit**: Difference between total revenue and total cost.
- **Average Profit per Window**: Total profit divided by the total number of windows processed.
- **Peak Warehouse Usage**: Maximum storage volume utilized during the simulation.
- **Total Movements**: Total number of state transitions (movements) made by all window sets.
- **Percentage of Window Sets Reused**: Ratio of window sets sold to the reusing facility compared to the total number of window sets, expressed as a percentage.

15.7 Simulation Flow and Execution

The DES operates in a time-stepped manner, advancing one day at a time until the simulation reaches the defined time horizon. The main steps in each simulation day are:

1. **Scheduler Actions**: The scheduler checks for any scheduled movements for the current day and executes them, updating states and accumulating transportation costs.
2. **Warehouse Processing**: The warehouse component updates storage costs and checks if any window sets are ready to be moved to the reusing facility, if yes it sends them there.
3. **Remanufacturing Processing**: The remanufacturing facility processes window sets, increments days in processing, applies remanufacturing costs, and checks for completion.
4. **Reusing facility**: The reusing facility accepts a window set only if its "selling date" has arrived, if not the window set is sent to the warehouse.
5. **State Updates**: Window sets update their processing status, and any completed window sets are moved accordingly.

15.8 Difference between the DES and the Schedule made by the LP

The duality between the Discrete Event Simulation and the Linear Programming Model is the key characteristic of this kind of simulation.
The two have slightly different operations, the key differences are the following:

- The LP considers the warehouse to have a limited capacity and works to never exceed it, while in the DES the peak volume needed in the warehouse is seen as a performance indicator, the higher the needed capacity, the worse the process performance.
- The selling price and time to the reusing facility are not known in the LP, it makes the optimal schedule based on the **estimated** selling price and time to the reusing facility.
- If the selling time to the reusing facility for a specific window set has not arrived, but the current schedule wants to sell the window set (due to a wrong estimation of the selling time), the window set is sent to the warehouse instead, and marked as "waiting for selling date", the warehouse keeps it until the selling date arrives, then the window set is sent to the Reusing facility as initially intended.

16 Linear Programming Model

The following is the Linear Programming Model used by the Scheduler component to calculate the optimal schedule.

16.1 Sets

- I: Set of window sets, indexed by i.
- S: Set of states, defined as {'O', 'W', 'R', 'RU', 'RC'}.
  'O' stands for Origin,
  'W' stands for Warehouse,
  'R' stands for Remanufacturing facility,
  'RU' stands for Reusing Facility,
  'RC' stands for Recycling facility.
- T: Set of time periods, indexed by t.

16.2 Decision Variables

- $f_{i,s_1,s_2,t} \in \{0,1\}$: Binary flow variable, it is 1 if window set i moves from state s_1 to state s_2 at time t, 0 otherwise. Self flows are allowed, so a flow does not always correspond to a movement, but only if $s_1 != s_2$
- $s_{i,s,t} \in \{0,1\}$:Binary State variable, is 1 if window set i is in state s at time t, 0 otherwise.
- $R_i \in \{0,1\}$: Binary variable, is 1 if window set i has completed remanufacturing, 0 otherwise.

16.3 Parameters

- t_{rem}: Required days for remanufacturing to be completed.
- demolition_date$_i$: Demolition date of window set i.
- estimated_selling_time_reuse$_i$: Urban miner's stimation of the earliest selling date for reuse of window set i.
- c_{rem}: Remanufacturing cost per window per day.
- c_{storage}: Storage cost per unit volume per day.
- $c_{\text{transport}}$: Transportation cost per unit volume per movement.
- inspection_cost: Fixed inspection cost per window set.
- C_{rem}: Capacity of remanufacturing facility.
- $V_{\text{warehouse}}$: Capacity of the warehouse.
- num_windows$_i$: Number of windows in window set i.
- volume$_i$: Volume per window in window set i.
- estimated_selling_price_reuse$_i$: Estimated selling price for reusing facility, urban miner's estimation of the actual selling price to the reusing facility.
- actual_selling_price_recycle$_i$: Actual selling price for recycling facility, only a function of the total volume and the material of the window set.
- α: Adjustment factor for reuse price after remanufacturing. Remanufacturing increases the value of a window set by a factor of 1+α.

16.4 Objective Function

The objective function represents the total profit made by the urban miner, the aim of the model is to maximize it.

$$\text{Maximize } Z = \sum_{i \in I} \left[s_{i,\text{RU},T-1} \cdot \text{estimated\_selling\_price\_reuse}_i \cdot (1 + \alpha \cdot R_i) + s_{i,\text{RC},T-1} \cdot \text{actual\_selling\_price\_recycle}_i \right]$$

$$- \left[\sum_{i \in I} \sum_{t \in T} s_{i,\text{R},t} \cdot \text{num\_windows}_i \cdot c_{\text{rem}} + \sum_{i \in I} \sum_{t \in T} s_{i,\text{W},t} \cdot \text{volume}_i \cdot \text{num\_windows}_i \cdot c_{\text{storage}} \right.$$

$$\left. + \sum_{i \in I} \sum_{t \in T} \sum_{s_1 \in S} \sum_{s_2 \in S, s_2 \neq s_1} f_{i,s_1,s_2,t} \cdot \text{volume}_i \cdot \text{num\_windows}_i \cdot c_{\text{transport}} + \sum_{i \in I} \text{inspection\_cost} \right]$$

16.5 Constraints

State Exclusivity Constraint
Each window set has to be in exactly one state each day.

$$\sum_{s \in S} s_{i,s,t} = 1, \quad \forall i \in I,\ \forall t \geq \text{demolition\_date}_i$$

Pre-Demolition Availability Constraint
Window sets are only available after the demolition date.

$$s_{i,s,t} = 0, \quad \forall i \in I,\ \forall t < \text{demolition\_date}_i,\ \forall s \in S$$

Initial State Constraint
The day of demolition the window sets are initialized at the origin.

$$s_{i,\text{O},\text{demolition\_date}_i} = 1, \quad \forall i \in I$$

Flow Conservation Constraints
These two constraints ensure a correct relationship between states and flows.

$$\sum_{s_1 \in S} f_{i,s_1,s_2,t} = s_{i,s_2,t}, \quad \forall i \in I,\ \forall t > \text{demolition\_date}_i,\ \forall s_2 \in S$$

$$s_{i,s_1,t-1} = \sum_{s_2 \in S} f_{i,s_1,s_2,t}, \quad \forall i \in I,\ \forall t > \text{demolition\_date}_i,\ \forall s_1 \in S$$

Flow Exclusivity Constraint
Each window set has to be in exactly one flow each day. Self flows are allowed, so a flow does not correspond to a movement.

$$\sum_{s_1 \in S} \sum_{s_2 \in S} f_{i,s_1,s_2,t} = 1, \quad \forall i \in I,\ \forall t \geq \text{demolition\_date}_i$$

No Backflow to Origin Constraint
No flow to the origin allowed.

$$\sum_{s_1 \in S} f_{i,s_1,\text{O},t} = 0, \quad \forall i \in I,\ \forall t > \text{demolition\_date}_i$$

Terminal State Constraints
No flow from the 'RU' or 'RC' to states other then themselves (only self flows allowed).

$$f_{i,s_1,s_2,t} = 0, \quad \forall i \in I,\ \forall t \geq \text{demolition\_date}_i,\ \forall s_1 \in \{\text{RU}, \text{RC}\},\ \forall s_2 \in S,\ s_2 \neq s_1$$

Selling Date Constraint for Reusing Facility
Window sets can only flow to the 'RU' after their selling date.

$$\sum_{s_1 \in S} f_{i,s_1,\text{RU},t} = 0, \quad \forall i \in I,\ \forall t < \text{estimated\_selling\_time\_reuse}_i$$

Remanufacturing Completion Indicator Constraint
This constraint ensures that R_i is only 1 if the window set i has been in remanufacturing for at least t_rem days.

$$\sum_{t \in T} s_{i,R,t} \geq t_{\text{rem}} \cdot R_i \quad \forall i \in I$$

Remanufacturing Capacity Constraint
Remanufacturing facility capacity cannot be exceeded.

$$\sum_{i \in I} \text{num\_windows}_i \cdot s_{i,\mathsf{R},t} \leq C_{\text{rem}}, \quad \forall t \in T$$

Warehouse Capacity Constraint
Warehouse capacity cannot be exceeded.

$$\sum_{i \in I} \text{volume}_i \cdot \text{num\_windows}_i \cdot s_{i,\mathsf{W},t} \leq V_{\text{warehouse}}, \quad \forall t \in T$$

17 Experiments and Results

A set of brief validation experiments were performed before the proper experiments, to check the proper functioning of the model.

Parameters used
It is important to underline the arbitrarity of all the parameters used in this simulation.
Of course all parameters used in this simulation greatly influence the result, but we believe that what matters most is relative change in KPIs rather then their absolute value, because of this all KPIs and parameter are left unitless.
If correct parameters were measured and input into the simulation, we believe it would yield sufficiently descriptive results about the system with such parameters.

The window sets considered for the experiment of this model are shown in the Appendix:Window Set Data.

Instead of discussing the individual values of the characteristics of the window sets considered, we think it is more usefull to think of their relative interaction. In other words, we think that the parameters chosen are sufficiently descriptive to answer the research question, because they are such that the optimal destination per window set varies like this:

- for 6 out of 30 window sets the material value is higher then the reusing value, without remanufacturing.
- for 24 out of 30 window sets the reusing value is higher then their material value alone.
- of those 24 window sets 13 should be remanufactured before being sold.

In general we can say that, for the moment, the situation is not so clear, there is actually contention between possible paths, some window sets have higher value material value then market value, but most don't, and remanufacturing is worth the cost for about half of these.
In other words we created a distribution of characteristics such that the operations undertaken by the urban miner are important, we want to investigate the effect of data quality on this.

17.0.1 Experiment - Scenario 1: Perfect Information

In the first scenario, the urban miner operates under perfect information conditions, with precise estimations of selling prices and selling times for the reusing facility. The parameters used are:

- **Price Estimation Precision**: 0 (perfect accuracy)
- **Selling Date Uncertainty**: 0 days (exact selling date known)
- **Inspection Cost**: 0 per window set

Results

- **Total Revenue**: $57,999.52$
- **Total Cost**: $9,377.29$
  - Remanufacturing Cost: $6,975.00$
  - Storage Cost: 213.84
  - Transportation Cost: $2,188.45$
  - Inspection Cost: 0
- **Average Profit per Window**: 108.77
- **Peak Warehouse Usage**: 59.84
- **Total Movements**: 55
- **Percentage of Window Sets Reused**: 80.00%

17.0.2 Experiment - Scenario 2: Imperfect Information

In the second scenario, the urban miner faces uncertainties in estimating selling prices and selling times. The parameters are:

- **Price Estimation Precision**: 1, the price estimation range if 50% in either directions.
- **Selling Date Uncertainty**: 7 days, the urban miner's estimation can be off by a week at most.
- **Inspection Cost**: 150 per window set

Results

- **Total Revenue**: $62,850.41$
- **Total Cost**: $14,329.83$
  - Remanufacturing Cost: $6,660.00$
  - Storage Cost: 348.03
  - Transportation Cost: $2,821.80$
  - Inspection Cost: $4,500.00$
- **Average Profit per Window**: 90.19
- **Peak Warehouse Usage**: 75.42
- **Total Movements**: 60
- **Percentage of Window Sets Reused**: 56.67%

17.1 Analysis and Discussion

17.1.1 Impact on KPIs

Comparing the two scenarios, we can specifically observe that:

- the average profit per window increases from 90.19 int he imperfect situation to 108.77 in the perfect situation, registering an increase of 17%. A significant amount.
- the percentage of window sets increases from 56.67% to 80.00%, registering a 23,33% increase. A significant amount. The urban miner, uncertain about the selling prices and times in the imperfect information scenario, opts to recycle more window sets to mitigate the risk of holding inventory or incurring additional costs. This shows that even without a market value increase, data sharing and integration can have a significant impact on circularity.
- The cost plummets from $14,329.83$ in the imperfect to $9,377.29$ in the perfect situation, decreasing by 34.6%, a significant amount. Operations can be streamlined, resulting in lower costs.

This indicates that perfect information allows for better cost management and decision-making, leading to higher profitability even with lower revenues.

17.1.2 Effect on Operational Decisions

Reuse vs. Recycling Decisions In the perfect information scenario, 80% of window sets are reused, whereas in the imperfect information scenario, this percentage drops to 56.67%. The urban miner, uncertain about the selling prices and times in the imperfect information scenario, opts to recycle more window sets to mitigate the risk of holding inventory or incurring additional costs.

Remanufacturing and Storage Costs The remanufacturing cost is slightly lower in the imperfect information scenario ($6,660.00$) compared to the perfect information scenario ($6,975.00$), possibly due to fewer window sets being remanufactured. However, the storage cost is higher in the imperfect information scenario (348.03 vs. 213.84), indicating that uncertainties lead to longer storage times and increased costs.
The results demonstrate that high-quality data management and complete information sharing within the supply chain can significantly benefit the urban miner:

- **Pre-Sale Opportunities**: With complete information, window sets can be sold before they are harvested, eliminating market uncertainties related to selling prices and times.
- **Inventory Reduction**: Pre-selling window sets reduces the need for storage, lowering storage costs and minimizing inventory holding risks.
- **Streamlined Operations**: Clear communication and data sharing facilitate smoother transitions between demolition, processing, and sale, enhancing overall efficiency.
- **Market Responsiveness**: Access to real-time data allows the urban miner to respond swiftly to market demands, adjusting operations accordingly.

The experiments underscore the significant impact of data quality on the urban miner's profitability and operational efficiency. Perfect information enables the urban miner to make optimal decisions regarding the processing and sale of window sets, maximizing profit while minimizing costs and risks. Conversely, imperfect information leads to increased uncertainty, prompting more conservative strategies that may result in lower profitability and higher operational costs.
Investing in high-quality data management systems and fostering complete information sharing within the supply chain can mitigate market uncertainties. By doing so, the urban miner can pre-sell window sets, reduce inventory levels, and optimize resource allocation, ultimately enhancing competitiveness and sustainability in the market.

18 Limitations and Future improvements

This model runs under a set of assumptions, the most important of which are described inn Section 15.1 "Assumptions", which i will report here, since all assumpptions are also limitations of the model as far as in they don't exactly correspond with reality.

- **Remanufacturing increases value by some fixed percentage**: the model uses the parameter α as the percentage increase in value of each window set if it is remanufactured.
- **Remanufacturing takes a fixed amount of time and costs a fixed amount per day per window**: remanufacturing process details was really difficult to obtein, really complicated and furthermore beyond the scope of this project, we essentially looked at remanufacturing as something that increases value of the window frame for a cost
- **Reuse market value of the windows is a polynomial function of the window's charachteristics**: all coefficients of the the polynomial are also quite arbitrary.
- **No market dynamics in pricing**
- **The urban miner obtains all the windows for free**: we validated this by talking to people involved in the urban mining industry, but it is still a strong assumption. Only acquisition cost is an inspection cost.
- **A market value exists for all window sets**
- **Transportation happens within the day and costs a fixed amount per unit volume**: we are essentially ignoring the distance between facilities as a parameter. Transportation dynamics are beyond the scope of this project.
- **No operational stochasticity**: remanufacturing, transportation and storing always happen without any problems.
- **Fixed Costs**: Costs such as transportation, storage, remanufacturing, and inspection are considered fixed per unit. In reality, these costs may vary due to factors like fluctuating fuel prices, labor costs, and economies of scale.
- **Capacity Constraints**: While capacities for the warehouse and remanufacturing facility are defined, the model does not account for potential bottlenecks or delays caused by capacity limits being reached.

All of the above cntribute to the difference between this model and reality.

Furthermore an incredible limitation of this model is the current lack of accurate data for parameter setting.

Sections of the model like Window set generation, Price Setting Price Estimation, Capacities, Cost parameters and Remanufacturing process dynamics could be greatly improved in their accuracy with regards to reality if real life data were to be integrated with this model.

For example the generation of the window sets can be done using real distribution of windows characteristics and real demolition dates of real buildings.

For these reasons we regard this model as a proof of concept of a method of investigating the impact of information quality and management on urban miners' operations.

Future improvements could tackle some of the limitations of the model, to try to bring it closer to reality, either through inputting real life data, relaxing some of the assumptions or defining a better modeling structure.

19 Market research

Purpose: The market research aims to Gain insight into the market environment that can help develop strategies for improving resource efficiency and sustainability in urban mining operations.

Scope: With a focus on how these factors affect the project's goals, the study examines important market drivers, industry trends, obstacles, important players, and possibilities unique to urban mining.

Methodology
A combination of industry reports, literature studies, and stakeholder interviews with recycling and demolition firms were used to perform the market study. Sources of Data: Information was acquired from scholarly works, trade journals, market research studies, and the opinions of experts involved in urban mining operations.

Findings Industry Overview: The practice of recovering raw minerals from garbage, structures, and old goods in urban settings is known as "urban mining." Urban mining has become more popular as a sustainable resource recovery method as the world's population and urbanization rise. By removing valuable minerals from waste streams, such as metals, plastics, and concrete, it lessens the environmental damage caused by conventional mining methods.

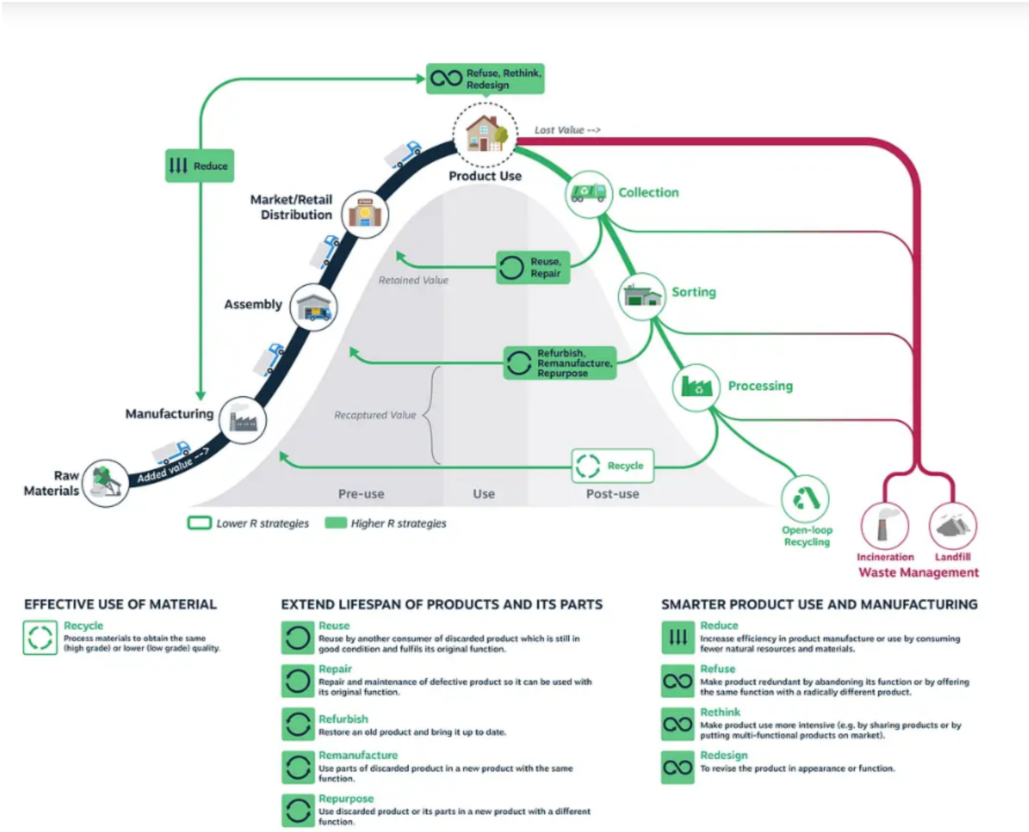

Figure 6: Supply chain of Urban Mining industry[4]

Urban mining in Europe

Due to stringent waste management laws and a strong dedication to sustainability, urban mining has become a crucial building concept in Europe. Member states have been encouraged to implement urban mining programs as a result of the European Union's aggressive waste reduction and circular economy goals. With an emphasis on recycling building materials, some European nations have created thorough frameworks for urban mining. For example, the European Commission's Circular Economy Action Plan highlights the significance of minimising environmental consequences, encouraging resource reuse, and recovering materials from building and demolition waste. With an emphasis on recycling building materials, some European nations have created thorough frameworks for urban mining. For example, the European Commission's Circular Economy Action Plan highlights the significance of minimising environmental consequences, encouraging resource reuse, and recovering materials from building and demolition waste. In Europe, countries like Germany, Sweden, and the Netherlands are leading the way in urban mining initiatives. To improve material recovery procedures, they have put in place cutting-edge recycling facilities and encouraged cooperation between waste management organisations, building companies, and research institutes. Furthermore, creative projects and pilot programs around Europe demonstrate how urban mining has the potential to transform the building sector. These initiatives frequently concentrate on creating effective methods for recovering materials, informing interested parties, and showcasing the financial and ecological advantages of urban mining. Because of stringent waste management laws and a strong dedication to sustainability, urban mining has become a crucial building concept in Europe. Member states have been urged to embrace urban mining as a result of the European Union's aggressive waste reduction and circular economy goals.

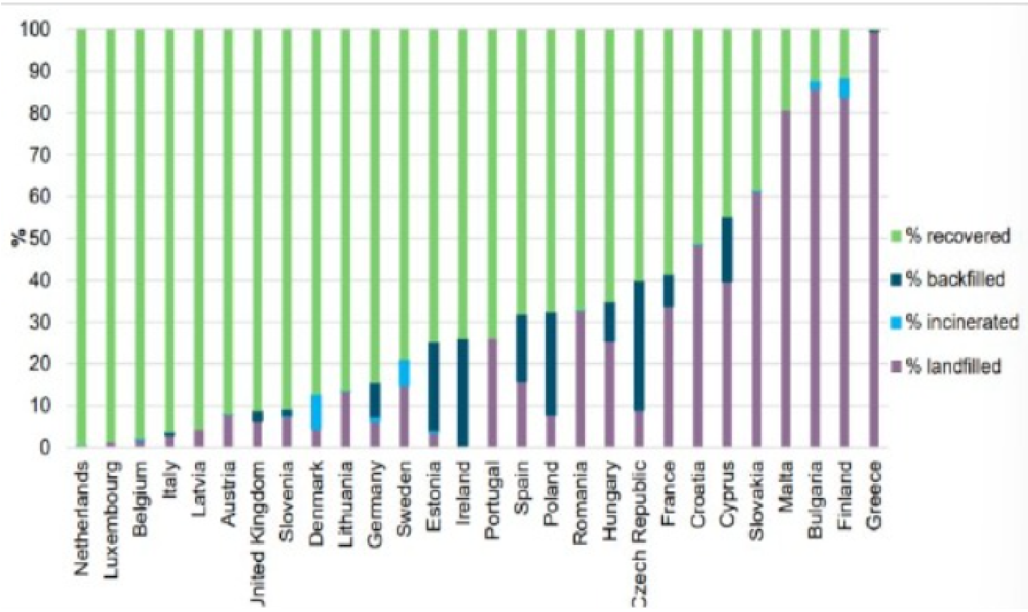

Figure 7: Urban Mining Industry Overview: Percentage of Collected Waste[5]

The figure gives an overview of Urban mining Industry by displaying the percentages of garbage that are collected, backfilled, burnt, or landfilled in each nation, this bar chart demonstrates the waste management practices used by various European nations. The meaning of each category in relation to waste management is broken down as follows:

Percentage Recovered (green): Denotes trash that has been transformed into energy or valuable resources through recycling, reuse, or other means.
Percentage Backfilled (blue): Defines trash that is utilised to fill up areas, such quarries or abandoned mines.
Incinerated (dark blue): Denotes garbage that has been burnt in incinerators, frequently to produce electricity.
Percentage Landfilled (purple): Denotes garbage that is dumped in landfills, which is often the least eco-friendly choice.

A number of important variables contributed to the Netherlands' 100 percent recovery rate:

Advanced Waste Management Policies:
To reduce landfill usage, the Netherlands has strict laws. To promote recycling and resource recovery, the nation has enacted laws and implemented incentives.

Investment in Recycling Infrastructure:
To effectively process and recover resources from garbage, the Netherlands has made significant investments in recycling facilities, sorting technology, and urban mining businesses.

Commitment to the Circular Economy:
The Netherlands is dedicated to the circular economy concept, which views trash as a resource. In order to establish a closed-loop system that reduces waste and increases resource efficiency, this strategy places a strong emphasis on material reuse and recycling.

Public Awareness and Participation:
People in the Netherlands are extremely conscious of the environment, and they actively participate in recycling and garbage separation initiatives, which increases recovery rates.Concrete, metals, wood and other building materials are recycled as part of urban mining techniques in the Netherlands. This lessens the carbon footprint connected to conventional mining and building methods in addition to aiding in the preservation of natural resources. Through a number of laws and incentives designed to encourage circular building methods, the government backs these initiatives.

Market Drivers and Challenges:

Drivers:
Resource Scarcity: As the demand for raw resources rises, new sources are needed.
Environmental Regulations: Urban mining techniques are encouraged by stricter waste management laws.
Initiatives for the Circular Economy: The emphasis on sustainability encourages the recovery and reuse of materials.
Technological Developments: Recycling technology advancements improve operational effectiveness.
Problems with Data Management: Ineffective data management reduces operational efficacy.
Economic Viability: Profitability is impacted by changes in recoverable material prices.
Public Perception: Acceptance may be hampered by misconceptions about the environmental effects of urban mining.

Key Players:
Demolition and recycling companies: essential for tearing down buildings and retrieving resources.
Waste Managment Companies: Waste recovery operations should incorporate urban mining methods.
Technology providers: Provide data analytics and process optimisation solutions.
Government Agencies and NGOs:Encourage environmentally friendly behaviour and lend support to urban mining projects.

Opportunities and Trends:
Digital Transformation: Urban mining procedures may be made more efficient by integrating technology such as digital twins.
Cooperation Across Sectors: Public-private partnerships have the potential to stimulate resource recovery and innovation.
Sustainability Initiatives: As sustainability gains more attention, there are opportunities for urban mining to support corporate social responsibility (CSR) objectives.

Analysis:
Implications: According to the results, there are a lot of chances to improve sustainability in this project. Digital twin may be combined to increase stakeholder participation, optimize operations, and enhance resource management.
Comparison: The findings are consistent with the body of research on urban mining, which highlights the necessity of better data management and technology integration to address industrial obstacles.

Conclusion:
In conclusion, the market research emphasizes the need for data management tools.It is essential to make use of technology and stakeholder cooperation, important drivers and obstacles have been highlighted.

20 Value preposition

The value proposition of the project is to build a digital twin model to promote data interoperability, remanufacturing, and reverse logistics in order to shift the construction industry's supply chain towards a circular economy. Digital twin model enables stakeholders to:

- Optimize the material reuse and reverse supply chain process.
- Minimize environmental impact.
- Increase profitability and efficiency.

- Support regulatory requirements.

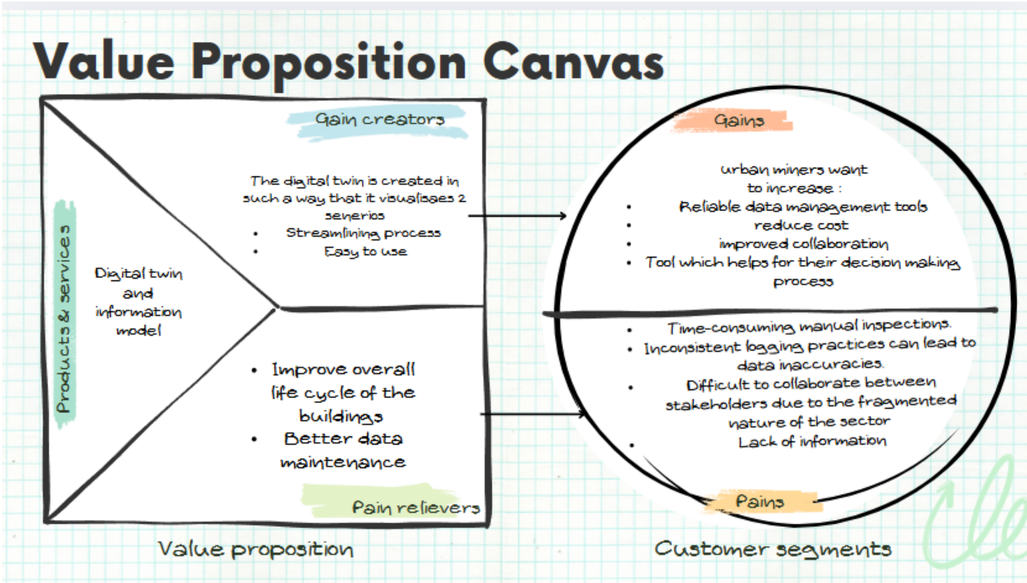

Figure 8: Value Preposition canvas

The figure above gives a illustration of a Value Proposition for Urban Miners Using Semmtech's Digital Twin: Pain : Recovery attempts are hindered by urban miners' inability to value and coordinate resources, data inconsistency, and inefficient logistics. Solution: To simplify urban mining procedures, digital twin offers strong data management, logistical optimization, and improved collaboration Unique Benefits: Standardized material values, improved stakeholder engagement, and real-time data insights guarantee quicker and more precise resource recovery. Outcome: A scalable model is developed that promotes a circular economy, lower expenses, increase recovery rates, and make wiser decisions.

21 Business canvas model

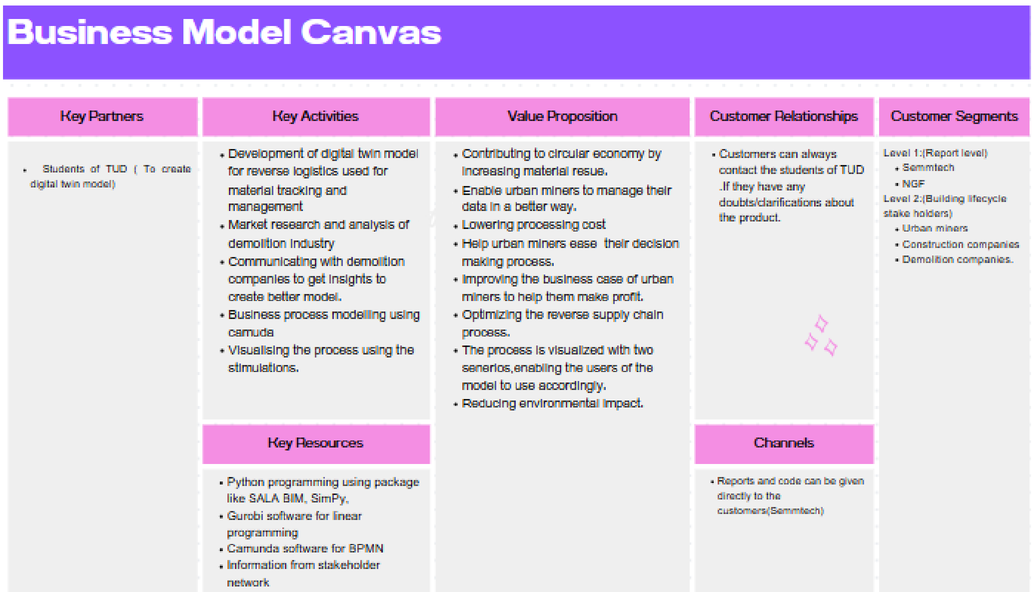

Figure 9: Business canvas model

Key partners: The digital twin model are by the students. Researching, evaluating, and implementing into practice a solution centred on material monitoring and management in urban mining is part of their job.

Key activities:

- The primary objective is to develop a digital twin for reverse logistics, which will aid urban miners in efficiently tracking and managing resources.
- Investigating the recycling requirements and material flow in the demolition sectorthrough market research.
- Decision tree model which helps in making decisions by mapping out possible outcomes based on various choices .
- correctly representing the logistics operations with the use of BPMN (Business Process Model and Notation).
- Putting the reverse supply chain into a clear visual representation using simulation tools.

Key resources:

- Python programming (SALABIM): simulating procedures and managing data associated with urban mining through the use of Python and certain libraries.
- Gurobi Linear Programming Software: used for optimisation, assisting the group in resolving challenging supply chain issues.
- Camunda for BPMN: The team may develop visual workflows using this business process modelling software.
- Data from the Stakeholder Network: using industry stakeholders' perspectives to develop a useful and pertinent model.
- Python for decision tree.

Value proposition:

- Sustainability: By promoting material reuse and reducing environmental effect, the concept promotes the circular economy.
- Effective Data Management: Makes it possible for urban mining firms to better handle and examine their data.
- Cost Reduction: Reduce processing expenses via resource and logistical optimization.
- Better Decision-Making: Offers data-driven insights to urban miners to enhance their business results.
- Reverse supply chain optimization supports operational efficiency and strategic planning by streamlining procedures and visualizing them via scenarios.

Chanels:
The customer will get the deliverables (a project report and a digital twin file) for future usage.

Customer segments:

Level 1: Report-Level Customers -Internal Stakeholders

- These are the main consumers of the project report and the knowledge gained from the investigation of the digital twin. They want to know about project developments, strategic insights, and suggestions for urban mining procedures.
- Requirements include possible enhancements for sustainable urban mining, decision-making assistance, and actionable insights.
- Procedures: Project documentation, data analysis, and reporting.

Level 2: Building Lifecycle Stakeholders (Digital Twin Users)

These are external stakeholders who will directly interact with the digital twin model and benefit from its data-driven insights for material management and lifecycle planning.

Customer Segment: Stakeholders involved in the building lifecycle, such as:

- Architects: For design and sustainability compliance.
- Demolition Contractors: For efficient material recovery and reusability assessment.
- Urban Miners: For data on material specifications, availability, and valuation.
- Transporters: For logistics planning based on material requirements.
- Warehousing and Storage Providers: For organizing and storing reclaimed materials.
- Recyclers and Buyers: For accessing high-quality material data for resale or reuse.

So they will be the final users of the digital twin product.

22 Business plan

This project is just there in the form of report. But this project can be taken to another help by using the digital twin model.
An outline plan of how digital twin can be used to create provide is given:

Sources of Income:

- Subscription Fees: Depending on the features utilized (e.g., simple tracking vs. complete lifecycle analytics), membership to the digital twin platform can be purchased on a monthly or annual basis.
- Data monetization: Charge for analytics reports, real-time insights, and comprehensive material data that are useful to recyclers and demolition contractors.
- Consulting and Support Services: Extra money made by offering advice on optimizing urban mining and helping users of digital twins get started.

Cost Structure:

- Development Costs: Upfront expenses for creating the platform, integrating sensors, and acquiring data analysis software.
- Maintenance and Upgrades: Constant expenses for data storage, system upkeep, and sporadic program updates.
- Marketing and Sales: Expenses related to acquiring new customers, integrating them, and providing continuing customer service.

23 Business process modeling using Camunda

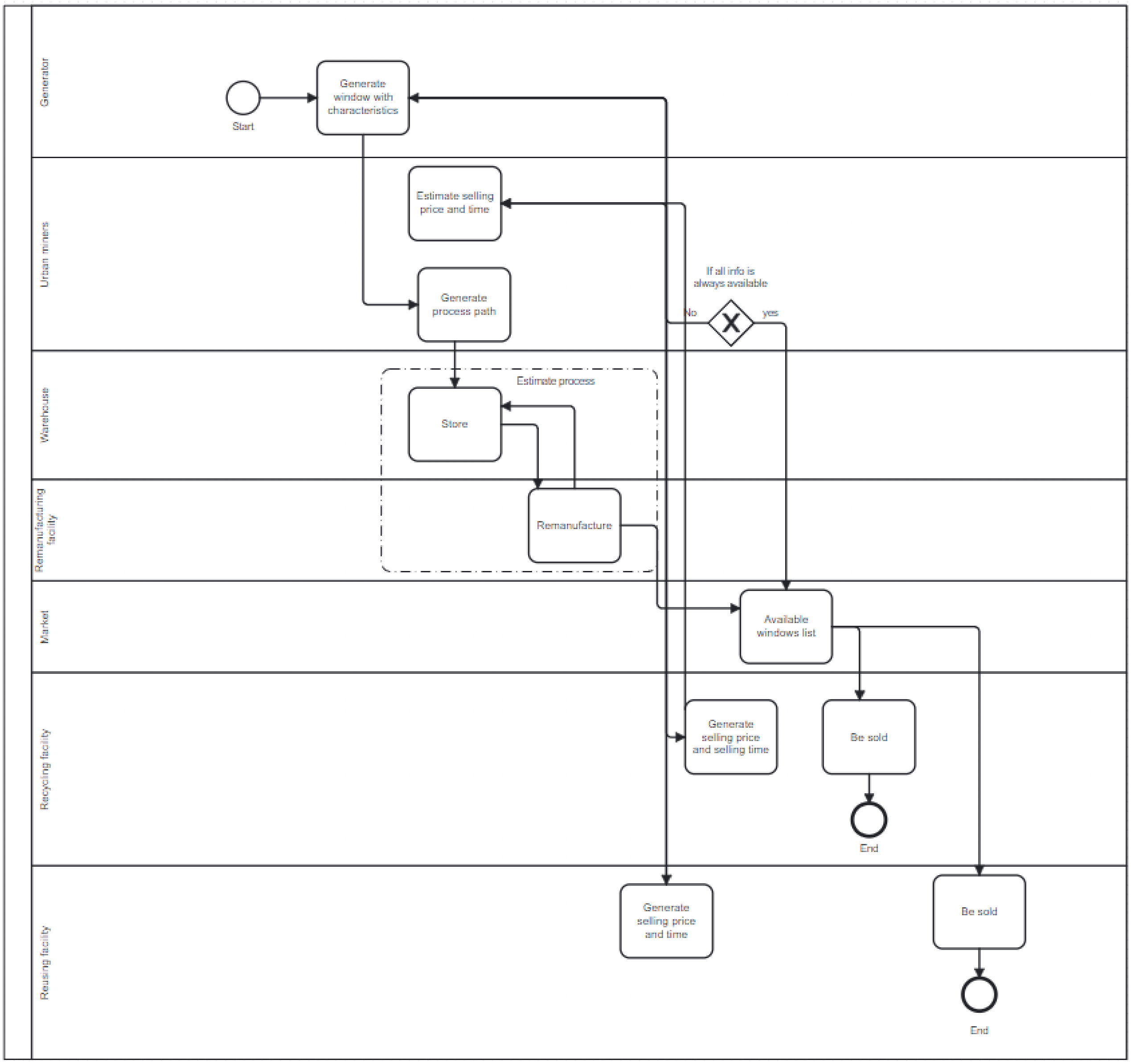

Figure 10: Business process modelling using Camunda

The process for creating, processing, and marketing windows with particular attributes is shown in this BPMN (Business Process Model and Notation) diagram. There are five primary players in the process, and each is represented in a different swimlane:

Generator:

- Initiates the process by generating a window with specific characteristics.

Urban Mines:

- Calculates the estimated time and selling price for the generated window.
- Creates a process path for the workflow's subsequent phases.

Warehouse:

- Verifies that the required information is available. If not, actions for remanufacturing or storing the window are part of the process flow.

- Specifies the available windows following any storage or remanufacturing that may be required.

Market:

- Repeats the price and time prediction for selling after receiving the list of available windows.
- The procedure is completed by designating the window as "sold."

Receiving entity:

- When the window is marked as sold, the workflow is finished.

Loops and Decision Points:

- **Decision Gateway:** Checks that all necessary data is accessible. If "yes," the list of available windows is displayed. If the answer is "no," a storage or remanufacturing phase is initiated.
- **Loops of Feedback:** Allows for storage and, if required, reprocessing between the remanufacturing and warehousing operations.

The procedure seeks to guarantee that windows are appropriately produced, stored, priced, and ultimately sold to effectively satisfy market demands.

24 Conclusion

The construction industry faces significant challenges in transitioning toward a circular economy, hindered by data discrepancies, decentralized processes, and complex logistics that impede efficient material reuse. Addressing these obstacles is crucial for reducing waste, minimizing environmental impact, and promoting sustainable practices within the sector.

This project contributes to overcoming these challenges by developing a digital twin model that investigates the importance of data sharing, management and availability throughout all steps of the reverse supply chain. By implementing a Simulation Optimization Framework, the model provides stakeholders with a clear view of possible future.

A key component of the project is the use of Business Process Model and Notation (BPMN), implemented with Camunda, to map and analyze the urban mining processes. This facilitates improved understanding and communication among stakeholders—including suppliers, resellers, contractors, and demolition companies—fostering collaboration and alignment toward sustainable practices.

Central to the digital twin is the Discrete Event Simulation (DES) model, which simulates the operational dynamics of window set processing from demolition to resale. The DES model highlights the critical importance of data quality in the urban mining supply chain. By comparing scenarios with perfect and imperfect information, the results demonstrate that high-quality data enables the urban miner to make informed decisions, maximize profitability, and increase the percentage of window sets reused. Specifically, with perfect information, the urban miner achieved an increase in the average profit per window frame of 17% and a reuse rate of 80%, whereas uncertainties led to more conservative strategies and a reduced reuse rate of 56.67%.

These findings underscore that effective data management and complete information sharing are essential for the success of circular economy initiatives in the construction industry. High-quality data allows for window sets to be sold before they are harvested, eliminating market uncertainties and enhancing decision-making accuracy.

In conclusion, this project advances the industry's transition toward circularity by addressing key barriers related to data quality and process transparency. By promoting better data interoperability and stakeholder collaboration, the project aims to inform stakeholders and policy makers, demonstrating how digital solutions can drive both environmental and economic value.

References

[1] Gunarathne, N., de Alwis, A., and Alahakoon, Y. (2020). Challenges facing sustainable urban mining in the e-waste recycling industry in sri lanka. *Journal of Cleaner Production*, 251:119641.

[2] Hosseini, M. R., Rameezdeen, R., Chileshe, N., and Lehmann, S. (2015). Reverse logistics in the construction industry. *Waste Management & Research*, 33(6):499–514.

[3] Industries, P. (2021). Urban mining – challenges and solutions. Accessed: 2024-10-31.

[4] Metabolic (2024). From buildings to resources: The role of urban mining in circular cities. Accessed: 2024-10-31.

[5] Montemayor Leos, J. (2020). Façade reverse logistics: Achieving circularity by application of reverse logistics strategies for curtain walls & window wall façade constructions.

A Window Set Data

ID	Material	Condition	Num	Vol	Type	SC	Dem. Date	SD Reuse	SP Reuse	SP Recycle
WindowSet_1	Al2	Poor	7	0.67	Type1	SC1	19	24	499.38	359.38
WindowSet_2	Al3	Good	6	0.83	Type1	SC2	19	24	789.96	369.96
WindowSet_3	Al3	Good	13	0.83	Type3	SC4	16	21	1646.58	801.58
WindowSet_4	Al3	Good	11	0.75	Type3	SC2	17	22	1171.50	676.50
WindowSet_5	Al1	Decent	18	0.98	Type2	SC2	15	20	1745.28	575.28
WindowSet_6	Al2	Good	6	0.48	Type3	SC1	14	19	545.76	305.76
WindowSet_7	Al1	Poor	22	0.82	Type2	SC1	2	7	1246.08	696.08
WindowSet_8	Al1	Good	8	0.32	Type1	SC1	13	18	925.12	245.12
WindowSet_9	Al1	Poor	11	0.42	Type1	SC3	14	19	1109.24	339.24
WindowSet_10	Al2	Poor	18	0.47	Type2	SC1	7	12	1006.92	916.92
WindowSet_11	Al2	Good	21	0.24	Type3	SC2	2	7	2215.08	1060.08
WindowSet_12	Al1	Good	15	0.72	Type3	SC4	7	12	1896.60	471.60
WindowSet_13	Al1	Poor	27	0.27	Type1	SC4	8	13	2849.58	824.58
WindowSet_14	Al2	Decent	9	0.71	Type1	SC4	20	25	1182.78	462.78
WindowSet_15	Al2	Decent	13	0.87	Type1	SC1	19	24	1257.62	672.62
WindowSet_16	Al1	Good	7	0.88	Type2	SC4	10	15	957.32	222.32
WindowSet_17	Al2	Decent	9	0.43	Type2	SC4	11	16	1042.74	457.74
WindowSet_18	Al3	Good	5	0.69	Type2	SC3	11	16	656.90	306.90
WindowSet_19	Al3	Decent	20	0.51	Type2	SC3	2	7	2220.40	1220.40
WindowSet_20	Al3	Poor	25	0.43	Type3	SC1	6	11	1146.50	1521.50
WindowSet_21	Al1	Good	9	0.33	Type2	SC3	2	7	1175.94	275.94
WindowSet_22	Al3	Good	14	0.61	Type2	SC3	10	15	1837.08	857.08
WindowSet_23	Al2	Good	26	0.31	Type2	SC3	1	6	3396.12	1316.12
WindowSet_24	Al1	Poor	24	0.50	Type2	SC1	12	17	1344.00	744.00
WindowSet_25	Al1	Good	11	0.45	Type3	SC3	11	16	1329.90	339.90
WindowSet_26	Al1	Poor	24	0.22	Type1	SC2	2	7	2050.56	730.56
WindowSet_27	Al2	Poor	27	0.68	Type1	SC4	15	20	2871.72	1386.72
WindowSet_28	Al3	Poor	12	0.46	Type3	SC3	14	19	911.04	731.04
WindowSet_29	Al1	Poor	10	0.69	Type2	SC4	19	24	913.80	313.80
WindowSet_30	Al1	Poor	19	0.86	Type2	SC3	17	22	1647.68	602.68

B Python code

The related code is available on GitHUb: JIP-6.3.1-Code.