CIRCULAR FOAM

Model of the waste logistics for appliances and for construction waste

Deliverable 7.4

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Date: 27 August 2025

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 10103685

I Technical References

Project Acronym	**CIRCULAR FOAM**
Project Title	Systemic expansion of regional CIRCULAR Ecosystems of End-of-Life FOAM
Grant Agreement Number	101036854
Project Coordinator	Dorota Pawlucka, Covestro Deutschland AG dorota.pawlucka@covestro.com
Project Duration	October 2021 – September 2025 (48 months)

Deliverable No.	D7.4
Dissemination Level[1]	PU
Lead Beneficiary	WUEV
Issue Date	M35

[1]PU-public, CO-confidential, only for members of the consortium (including the Commission Services), EU-SEC-classified information: SECRET UE (Commission Decision 200/444/EC)

II History of changes

Version	Date	Short description of changes
V1.0	20.08.2024	First Draft by WUEB
V2.0	24.09.2024	Second draft after Revision by WUEB

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101036854

III Executive Summary

This study presents a cohesive set of models aimed at optimizing PUR foam waste management across diverse European regions, each characterized by unique logistical and operational challenges. By employing advanced methodologies such as optimization, stochastic programming, and dynamic forecasting, the research seeks to enhance waste management efficiency and sustainability. The overarching goal of these models is to address region-specific needs while maintaining a common objective: maximizing efficiency, reducing logistics costs and minimizing environmental impact. The application of optimization techniques across well-established infrastructure settings enables the maximization of recycling efficiency. Meanwhile, stochastic programming and dynamic forecasting serve as tools to manage uncertainty and variability in waste availability, particularly in regions with emerging waste management systems and those located at greater distances from processing facilities.

Key findings highlight that due to the high costs associated with establishing and operating chemical processing facilities, it is economically feasible to maintain a single processing plant. In remote regions, costs are significantly impacted by the method of consolidation and compression of PUR foam. Moreover, obtaining foam from demolition waste from individual homes is particularly cost-intensive, and the material gathered from such sources often lacks sufficient quality for effective processing.

The results of the study show a reduction in operational costs and improved adaptability to dynamic waste patterns, providing strategic insights into infrastructure development and logistical planning. The models offer scalable and flexible solutions, ensuring robustness against future changes in waste generation and processing technologies. This integrated approach underscores the importance of customizing waste management strategies to fit regional contexts while maintaining a unified framework, enhancing the potential for achieving sustainable, economically viable solutions across and within Europe.

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IV Disclaimer

This deliverable reflects only the view of the authors. The Agency and the European Commission are not responsible for any use that may be made of the information it contains.

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1. Introduction

The construction of large halls in urban areas is a significant trend influenced by factors such as urbanization, population growth, and economic development. Urban expansion leads to a demand for large-scale infrastructure projects, including halls and other facilities to meet various needs Lokhande et al. (2020). The rise in population density and economic activities drives the expansion of urban built-up areas, resulting in the development of new structures and public facilities that require substantial land resources (Han & Li, 2020). The construction of large halls in urban areas is often part of broader urbanization processes involving landscape transformation and land utilization for various purposes (Zhang et al., 2021). Accelerated urbanization results in increased construction activities, including the development of new dwellings and urban infrastructure to cater to a growing population (Wilke et al., 2019). This rapid urbanization alters land use patterns, with farmland and forest areas converted into construction land to accommodate urban growth (Liu & Abdullah, 2023). The environmental impact of urban construction, including large hall construction, is a critical consideration. Studies emphasize the need to balance urban development with environmental conservation to preserve ecosystem service values amidst urban land expansion (Zhang et al., 2021). The construction of large urban regions and the expansion of urban areas can alter land use patterns, impacting ecological processes and landscape dynamics (Rogov & Rozenblat, 2019). Moreover, the construction of large halls in urban areas contributes to material consumption and carbon emissions associated with infrastructure development (Wang et al., 2020). Urban expansion-related construction activities require significant resources and energy, leading to environmental consequences like greenhouse gas emissions. Sustainable urban planning and development strategies are crucial to mitigate the environmental footprint of large-scale construction projects in urban areas (Yu et al., 2020).

2. PUR Foam insulated panels in construction

Foam board insulation is a commonly used material in construction for its thermal insulation properties. It is typically made from materials like polyisocyanurate (polyiso), polyurethane foam, or polystyrene. These foam boards are lightweight and easy to install, making them popular for insulating walls, roofs, and floors in buildings. Polyisocyanurate (polyiso) foam boards offer high thermal resistance and are commonly used in roofing and wall insulation due to their effectiveness in reducing heat transfer Auad et al. (2007). Polyurethane foam boards are known for their versatility and can be used in various applications, including thermal insulation in construction (König et al., 2008). Expanded polystyrene (EPS) foam boards are lightweight and provide good thermal insulation properties, making them suitable for building insulation (Yan et al., 2019). Foam board insulation plays a crucial role in improving energy efficiency, reducing heating and cooling costs, and enhancing indoor comfort in buildings. By selecting the appropriate foam board insulation material based on factors like thermal conductivity, fire resistance, and environmental impact, construction professionals can create well-insulated and sustainable structures.

Polyurethane foam insulation boards are a type of insulation material commonly used in construction for their excellent thermal insulation properties. These boards are typically made from polyurethane foam, a versatile material known for its low thermal conductivity, high compressive strength, and excellent adhesion properties (Park et al., 2021). Polyurethane foam insulation boards are widely adopted in various industrial fields due to their high compressive strength, low thermal conductivity,

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and excellent impact resistance (Park et al., 2021). Polyurethane foam insulation boards are utilized in a range of applications, including insulating refrigerators, freezers, piping, tanks, shipbuilding, and LNG cargos (Kim et al., 2010). These boards play a crucial role in enhancing energy efficiency, reducing heating and cooling costs, and providing thermal comfort in buildings. Additionally, polyurethane foam insulation boards are valued for their lightweight nature, ease of installation, and durability, making them a popular choice for insulation in construction projects (Kim et al., 2010). By incorporating polyurethane foam insulation boards into building structures, construction professionals can create well-insulated and energy-efficient spaces that meet thermal performance requirements and contribute to sustainable building practices.

3. Approaches, Methods and Objectives

Assessing the environmental impact of insulation boards waste is crucial for sustainable waste management practices in the construction industry. By evaluating the potential waste generation and disposal of insulation boards, construction projects can identify opportunities to reduce environmental harm, promote recycling, and enhance overall sustainability. Understanding the lifecycle of insulation boards waste helps in implementing strategies to minimize waste, reduce carbon footprint, and optimize resource utilization, contributing to a more environmentally friendly and efficient construction sector.

Developing a comprehensive model for the logistics of PUR foam waste collection at the European level is challenging due to varying supply levels and sources across different regions. In Western Europe (e.g., the Netherlands), historical data on PUR foam waste can largely be utilized, whereas in Central Europe (e.g., Poland), buildings using technology utilized PUR foam were constructed significantly later and are not yet subject to demolition. Additionally, depending on the distance to processing facilities (chemical recycling), there may be varying requirements for consolidation points or methods of preparing the waste for transport. Consequently, the work has been divided into two parts. The first addresses the acquisition and transport of PUR waste from residential buildings in areas close to the processing facilities (Amsterdam Region - Netherlands), while the second, the acquisition of foam from the demolition of halls and industrial buildings in regions remote from the processing facilities (GZM - Poland).

TABLE 1: REGIONAL DIFFERENCES IN PUR FOAM WASTE MODELLING ACROSS EUROPE

Model	Region	Source of PUR Foam Waste	Availability of Historical Data	Processing Facility Proximity
Distributed Source	Netherlands	Primarily residential	Low	Close
Remote Distance Planning	Poland	Industrial demolition and households	Low	Distant

The Table 1 compares strategies across three regions: the Netherlands, and Poland. Each region's approach is tailored to its specific circumstances regarding PUR foam waste management. The Netherlands employs the "Distributed Source " approach, which handles primarily residential waste sources. The availability of low-level historical data aids in formulating strategic plans, and the processing facilities' proximity allows for reduced transportation costs. This model aims to optimize logistics and improve waste management efficiency. In Poland, the "Remote Distance Planning" model takes a future-oriented stance, dealing with limited current waste due to newer construction and preparing for increased industrial demolition waste. The challenge here lies in the low availability of historical data

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and the significant distance to processing facilities. Therefore, the focus is on developing infrastructure and planning to manage future waste effectively, considering these logistical challenges. Overall, the table highlights how each region's approach to PUR foam waste management is shaped by its specific advantages and constraints, striving to balance logistical challenges with environmental and operational goals.

TABLE 2: APPROACHES FOR PUR FOAM WASTE MODELLING IN EUROPE

Model	Methodology Used	Goal
Distributed Source	Stochastic programming	Minimizing collecting costs
Remote Distance Planning	Dynamic Optimization with Forecasting Availability	Minimizing logistics cost and reducing environmental impact through a dynamic approach.

The table 2 outlines the methodologies and goals associated with different models of PUR foam waste management in Europe, highlighting how each is tailored to the specific challenges of its region. The "Distributed Source" model applies stochastic programming to minimize collecting costs, effectively managing uncertainty in collection processes. The "Remote Distance Planning" model employs dynamic optimization with forecasting availability to minimize logistics costs and reduce environmental impact through a dynamic approach. Each model, with its distinct methodology and objective, provides strategic insights into enhancing PUR foam waste management practices across different regional contexts.

These models are designed to enable the modeling of any future PUR foam waste management systems, serving as a valuable point of interest for policymakers. For example, the model developed for Poland can provide crucial insights for the German model regarding the availability and costs of acquiring PUR waste, which can be instrumental in assessing economies of scale for planned processing facilities. By understanding the dynamics and variables in each region, policymakers can make informed decisions, optimizing waste management strategies and enhancing efficiency across Europe. To achieve this objective, we will develop a decision model that takes into account various factors such as the projected volume of foam available, the capacity of recycling facilities, transportation logistics, and environmental considerations. The model will consider different scenarios and policy options to identify the most efficient approach for collecting and managing polyurethane foam waste in the region in long time horizon.

Moreover, it's important to note that the decision model developed through this research is designed to be versatile and applicable to other regions as well. Its universal nature allows for customization and adaptation to different areas facing similar challenges in PUR waste management. This means that policymakers and waste management authorities in various regions can utilize the model as a valuable tool to assess the optimal strategies for polyurethane foam waste collection and management in their specific contexts. By sharing the model and its findings, we can foster knowledge exchange and collaboration, contributing to sustainable waste management practices beyond the scope of the analyzed regions.

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4. Model for distributed source with stochastic parameters

In this section, we present a model that examines regional processes in the value chain. It was designed with regions in mind which have a very high density of buildings from which waste can be extracted, and applied to the Amsterdam region as one of our pilot regions. The model has been designed to be able to cope with a limited prior knowledge on the exact waste quantities and qualities: Based on assumptions and available estimates, it is possible to compile a set of scenarios, against which the model can hedge, leading to an informed decision. The expected financial and environmental cost of this 'best' decision are the objectives that the model aims to minimize. An important feature of the model is that it takes into account that any private company that needs to dispose waste will do so in the most economically attractive way: Treatment facilities need to be located such that it is economically sensible for these parties to dispose their waste there.

4.1 A stochastic model: Optimizing over multiple scenarios at once

One of the important challenges related to developing models for the regional waste flows is that relevant strategic decisions have to be made without having exact knowledge on some important indicators. Most importantly, more optimistic and pessimistic scenarios on waste quantities and the quality or yield of the waste that is available should be taken into account.

Evaluating the regional logistics could be done using a scenario analysis: Different scenarios for the waste can be simulated and the costs and environmental effects of a certain locational configuration can be observed. We are however interested in the performance of the system under the optimal regional location configuration. That is, optimal with regard to all possible future realizations of the uncertain demand parameters. To allow this, we make use of stochastic programming. In the following paragraphs, we will list some preliminaries to introduce the stochastic programming paradigm:

The general form of a stochastic program is as follows (Birge & Louveaux, 2011):

$$\mathit{minimize}\ \boldsymbol{c}^{\boldsymbol{T}}\boldsymbol{x} + \mathbb{E}[Q(\boldsymbol{x},\boldsymbol{\xi})]$$

$$\mathit{subject\ to}$$

$$A\boldsymbol{x} = \boldsymbol{b}$$

$$\boldsymbol{x} \geq \boldsymbol{0}$$

Where $Q(x,\xi) = \min\{\boldsymbol{q}^{\boldsymbol{T}}\boldsymbol{y} : W\boldsymbol{y} = \boldsymbol{h} - T\boldsymbol{x}, \boldsymbol{y} \geq \boldsymbol{0}\}$ is called the second-stage value function.

This formulation indicates the following structure:

- We have to take some first-stage here-and-now decisions ($\boldsymbol{x}$) now, and there are some decisions ($\boldsymbol{y}$), which we may take later in a second stage.
- The feasibility of the first-stage decisions is defined by a set of linear constraints. There may also be integer restrictions on $\boldsymbol{x}$ in some cases.
- The objective is to minimize the cost incurred by the first-stage decision and the expected cost of the second-stage value function $Q(\boldsymbol{x},\boldsymbol{\xi})$, which depends on the first-stage decision $\boldsymbol{x}$ and some uncertain parameters $\boldsymbol{\xi}$.
- The second-stage value function is usually a Linear Program (LP), whose cost function and constraints are parameterized by $\boldsymbol{q}, \boldsymbol{h}$ and T, all of which may depend on $\boldsymbol{\xi}$. In some cases, there may be integer restrictions on the second-stage variables $\boldsymbol{y}$.

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It is common to take $\boldsymbol{\xi} \in \boldsymbol{\Xi}$, where $\boldsymbol{\Xi}$ is a set of scenarios that describes the uncertainty. It can be constructed empirically or through sampling. In this case, we have a finite number of scenarios, where each scenario has its associated probability p_s, and we can solve a model bearing this structure using the Large-Scale Deterministic Equivalent (LSDE). This LSDE contains a copy of $\boldsymbol{y}$ for each scenario s, and integrates the first-stage and second-stage problem into a large single program. This may be an LP or a mixed-integer linear program (MILP), depending on whether there are integer restrictions on $\boldsymbol{x}$ or $\boldsymbol{y}$. When we present our model, the formulation we present and solve is this LSDE formulation.

4.2 PUR Waste Scenarios: Data pipeline for Amsterdam

In order to generate scenarios corresponding to different future realities of the future demolition waste, we use publicly available data sets that contain information relevant to our pilot region. Figure 1 depicts the process of collecting and processing data can provide us with a scenario set which can be used as model input.

The first step (top of Figure 1) is to collect data from 3 main public sources:

- **Basisadministratie Adressen en Gebouwen (BAG)** *(https://bagviewer.kadaster.nl/, Area of availability: Netherlands)* – A national database administering all building objects and addresses in the Netherlands, including geometry features and some building characteristics such as function and year of construction
- **Actueel Hoogtebestand Nederland (AHN)** *(https://www.ahn.nl/, Area of availability: Netherlands)* – National height database, that includes height measurements in built environments.
- **Nationale EnergieAtlas: Bezitsverhouding woningen per postcode** *(https://www.nationaleenergieatlas.nl/, Area of availability: Netherlands) – Contains data of ownership composition for each postal code, indicating for example the share of buildings owned by social housing corporations)*

In step 2 (center of Figure 1), we extract and determine the following information from these sources:

FOR EACH BUILDING:

- **Which of 5 categories it belongs to:** Buildings are classified as **single home residential** *(All buildings with 1 residential unit),* **small multi-home residential** *(2-8 residential units),* **medium size multi-home residential** *(9-40 residential units),* **large multi-home residential** *(41+ residential units),* or **utility building** *(Building without residential function)*
- **Information about the geometry of the building:** Using height estimates from the AHN database and the geometry feature from the BAG, we can estimate the surface area of building roofs and walls, as well as the slopes of roofs. Sometimes it is hard to estimate the surface height around a building, leading to small anomalies in building height. This also led to the presence of negative heights in the data. We assume that each building is at least 2 meters heigh, and thus set building heights in our data set that were lower than 2m, to the minimum of 2m.

FOR EACH POSTAL CODE:

- **What percentage of buildings is owned and maintained by social housing corporations** this is relevant because renovation or demolition of these buildings will likely happen at the same time, leading to job sites with a large enough volume to bypass an intermediary collection or sorting center.

In step 3 (bottom of Figure 1), the obtained data is linked to a dashboard, where the following parameters can be set and adjusted:

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- Percentage of buildings that contain PUR/PIR based insulation materials in **walls:** *For each type of building and construction period, an estimate of the probability that it contains PUR/PIR based insulation in its walls can be provided.*
- Percentage of buildings that contain PUR/PIR based insulation materials in **roofs:** *For each type of building and construction period, an estimate of the probability that it contains PUR/PIR based insulation in its roof can be provided.*
- Expected **thickness** of insulation panels: *Can be set separately for flat roofs, sloped roofs and walls*. *This is used to convert surface areas into waste volumes*
- **Surface correction factors**: *Multipliers used when converting wall or roof surface area to waste volume. For example, one might set the correction factor for walls lower than 1, for example because of space used by windows.*
- **Minimum bypass volume**: *This indicates the volume threshold for which PIR/PUR insulation waste can be directly transported from a job site to a treatment facility: For big job sites, it should be possible to separately transport the materials, without needing an intermediary recycling and rough sorting agent. This could occur for example, when it is possible to fill an entire truck with just foam waste. Changing this parameter will impact the spread of expected waste volumes: A higher minimum bypass volume will lead to more waste concentrated at regional waste collection hubs.*

Given all these parameters, and the linked data, expectations of waste volumes for the planning horizon can be computed, and scenarios can be generated to form an input of the stochastic programming model.

4.3 Monte Carlo scenario generation

In order to generate the initial scenarios, we initially fix the following parameters:

TABLE 3. GENERAL PARAMETERS FOR INSULATION VOLUME ESTIMATION

Parameter	Value
Insulation panel thickness flat roof	160 *mm*
Insulation panel thickness roof with slope	185 *mm*
Insulation panel thickness walls	160 *mm*
Job-site threshold for bypassing intermediary collection/rough-sorting facility	40 m^3 of PIR/PUR waste
Discount factor roof insulation	1.0
Discount factor wall insulation	0.8

Other parameters that need to be fixed for scenario generation are the probabilities that different buildings contain PIR/PUR-based insulation, to be found in Table 3. These initial probabilities are example inputs to the scenario generation method, based on the assumptions that PIR/PUR can be found more in roofs than in walls, and that for buildings with brick façades, other methods of insulation are more common. Furthermore, we assume that if the walls are insulated using PUR/PIR material, the roof contains the same insulation material (but not vice versa).

TABLE 4. INITIAL ESTIMATE CONFIGURATION OF PROBABILITIES OF CONTAINING PIR/PUR-BASED INSULATION PER BUILDING TYPE AND YEAR

Building type	*Period of construction*	*Wall/Roof*	Probability of containing PIR/PUR

Single home residential, small multi-home residential or medium multi-home residential	***1975-2024***	*Wall*	0.01
		Roof	0.05
Large multi-home residential	***1975-2024***	*Wall*	0.08
		Roof	0.15
Utility buildings	***1975-2024***	*Wall*	0.3
		Roof	0.4

Finally, the composition of the obtained insulation waste from renovation and demolition needs to be estimated, as some of the transported material will not be fit for recycling. The yield of the material will differ from building to building, and the distribution of the percentage of recyclable material likely depends on the period of construction. In more recent years, likely more PIR insulation will have been used, for which a future recycling process may become available at a later point in time. Table 5 provides an initial setting that corresponds to these assumptions.

TABLE 5. RECYCLABLE MATERIAL % PROBABILITY DISTRIBUTION PER CONSTRUCTION PERIOD

Period of construction	**Distribution of recyclable material %**
1975-1984	Uniform on [0.45, 0.75]
1985-2004	Uniform on [0.6, 0.75]
2005-2014	With probability of 0.5: Uniform on [0.7,0.9]; With probability of 0.5: 0
2015-2024	With probability of 0.25: Uniform on [0.75,0.95]; With probability of 0.75: 0

These parameters are fairly rough estimates, meant as an initial input to demonstrate the working and dynamics of this model. The authors would like to stress that upon obtaining further insights, for example based on expert opinions, they can easily be adjusted and the model can be re-optimized for a set of scenarios corresponding to this more detailed parameter configuration.

In order to generate the scenarios, we perform a Monte Carlo simulation where we sample from the standard random uniform distribution: We sample four values $u_{1bs}, u_{2bs}, u_{3bs}, u_{4bs}$ per building b and scenario s, and we draw one additional value u_{5s} for each scenario:

- If u_{1bs} is smaller than the relevant probability value in Table X, building b is assumed to contain PUR/PIR insulation in its walls or roof, respectively, in scenario s.
  Example: if $u_{1bs} = 0.02$ for a single home, in scenario s this building will contain PUR/PIR insulation in its roof (0.02 ≤ 0.05) but not in its walls (0.02 > 0.01)
- If u_{2bs} is smaller than the percentage of buildings owned by social housing corporations in the postcode area where building b is located, this building will count as a social housing corporation-owned building in scenario s.
- If u_{3bs} is smaller than the probability that <u>no</u> material can be recycled, the total amount of PIR/PUR material that needs to be collected from building b will not be recyclable in scenario b.
- If the preceding is not the case for building b in scenario s, we let L and H be the boundaries for the relevant uniform distribution form Table X that applies to building b. The percentage of recyclable material at building b in this scenario can now be derived as follows:
  $L + (H - L)(\rho u_{5s} + (1-\rho)u_{4bs})$. The parameter ρ, which takes a value between 0 and 1, regulates the variation of the percentages within and across scenarios. A low value means high variation within scenarios, and little difference in the distribution of sampled values across scenarios. Conversely, a high value of ρ indicates that these percentages will differ across scenarios, but there will be less variation within the scenarios. We initially set ρ to **0.5**.
  Example: In scenario s, let $u_{5s} = 0.85$. For a particular building b, $u_{3bs} = 0.6$, and $u_{4bs} = 0.2$. Assume $\rho = 0.5$. $u_{3bs} > 0.5$, indicating that the recyclable material percentage for building b in this scenario will not be 0. Proceeding, we obtain 0.7+0.2(0.5*0.85 + 0.5*0.2) = 0.805. Thus,*

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in this scenario 80.5% of the material obtained from building b is recyclable and the remaining 19.5% is not. Note that the relatively high value for u_{5s} means that the recyclability percentages of buildings in this scenario will be relatively high compared to other scenarios.

Using this procedure, amounts of recyclable and unrecyclable waste are generated for every building in each scenario. To determine where this waste is collected from, the job-site threshold from Table X and whether or not a building is owned by a social housing corporation are crucial. For every building that does not produce enough material on its own to exceed the job-site threshold, the insulation waste is not collected separately. If a building is owned by a social housing corporation, waste will be pooled and collected for every postal code. If not, the assumption is that it is first sent to the nearest rough-sorting facility and the waste will be collected from there.

NB: This procedure assumes that the amount of PIR/PUR waste in each building, and its yield in terms of material recyclability is independent. Even though this assumption does not strictly hold in reality, because the model will be solved on an aggregated level, the assumption will have little effect on the eventual scenarios.

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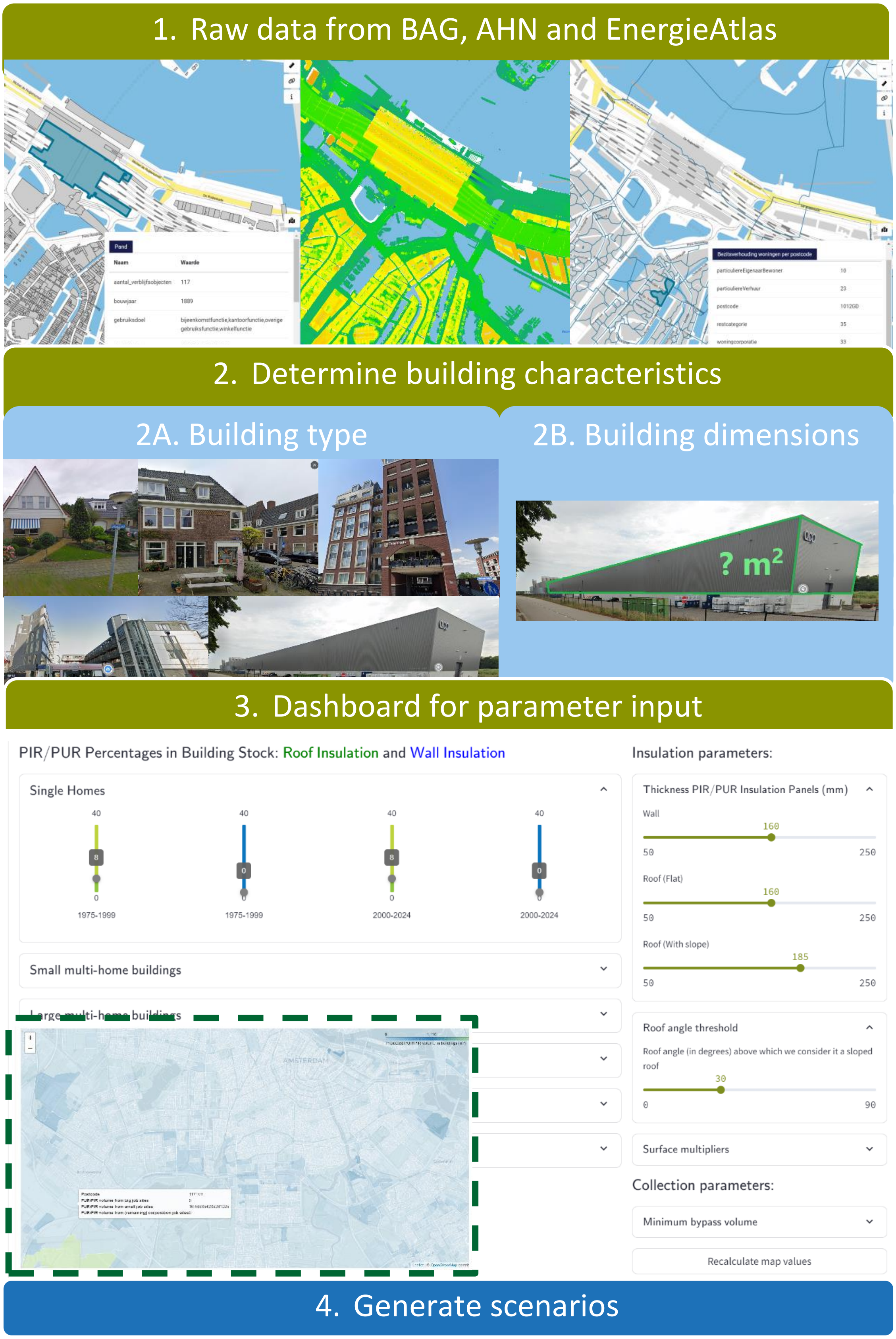
FIGURE 1. DATA PIPELINE USED FOR AMSTERDAM SCENARIOS: USED SOURCES AND INFORMATION



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4.4 Stochastic model: Sets, variables, parameters, assumptions

Before going over the objective and constraints of this model, we will first introduce its notation by defining the relevant sets, parameters and variables.

Table 6 outlines the set of nodes of the network. All nodes together form the set N, which can be divided into different subsets, each subset consisting of its own type of nodes. In Table 6, the set of nodes that can be considered **sources** is highlighted in **blue**, the set of **intermediary nodes** is highlighted in **orange**, and the sets of **sink nodes** of the model are highlighted in **green**. Furthermore, we define sets Q containing the possible quality grades and S, the set of input scenarios for the waste volume.

Between the different subsets of nodes, different sets of links exist over which waste can be transported. The complete set of allowed links, Z, is defined as the union of cartesian products of different subsets of nodes.

TABLE 6. SETS USED IN THE AMSTERDAM MODEL: NETWORK NODES, QUALITY GRADES, SCENARIOS

Sets	
$i, j \in N$	Nodes of the network
$c \in C \subset N$	Set of rough-sorting collection facilities
$v \in V \subset N$	Set of incineration plants where incineration of PIR/PUR could take place
$r \in R \subset N$	Set of locations where mechanical treatment and fine-sorting can take place
$o \in O \subset N$	Set of transfer points, where matarial that is suitable for recycling can be transferred to chemical treatment facilities (Domestic and abroad).
$q \in Q$	Set of different quality ranks for the material. In our case study, we use the set {1,2} where 1 is material suitable for recycling and 2 is material unsuitable for recycling
$s \in S$	Set of scenarios

TABLE 7. TRANSPORTATION LINKS THAT ARE ALLOWED IN THE AMSTERDAM MODEL

Transportation links	
$C \times V$	Between rough-sorting collection facilities and incineration plants
$C \times R$	Between rough-sorting collection facilities and fine-sorting / mechanical treatment installations
$R \times V$	Between fine-sorting / mechanical treatment installations and incineration plants
$R \times O$	Between fine-sorting / mechanical treatment installations and transfer points
Z	Set of all transportation links $:= (C \times V) \cup (C \times R) \cup (R \times V) \cup (R \times O)$

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Between the different subsets of nodes, different sets of links exist over which waste can be transported. The complete set of allowed links, Z, is defined as the union of cartesian products of different subsets of nodes.

Table 8 explains the decision variables in the stochastic program. The model has two sets of **first-stage decision variables** (highlighted in **purple**) and two sets of **second-stage decision variables** (highlighted in **pink**).

Finally, the parameters of the model are summed up in five small groups in Table X:

- w_1 and w_2 regulate how much emphasis the model puts on both of the two objectives: Financial and environmental.
- Some general parameters of the model are M, K, and D_{cqs}. The latter stems from the scenario generation procedure described earlier.
- Parameters relating to financial cost can be divided in two categories: The **yellow** variables reflect **costs covered by parties involved in the system**: These may be public parties (such as government) or companies that collaborate to process the material as a part of the circular value chain. The variables highlighted in **brown** reflect **costs incurred by private parties** that need to dispose of their waste. These costs (partially) drive where and how agents decide to dispose of their waste.
- Parameters e and v_{jq} are related to the emissions caused by transportation and different ways of processing.
- p_s denotes the probability that scenario s will occur in the future.

TABLE 8. AMSTERDAM MODEL VARIABLES

Variables	
X_{ijqs}	Total amount of material of quality q that is transported between locations i and j in scenario s.
y_r	Decision whether to set up an encapsulated environment at location r.
z_r	Decision how many treatment units (set of machines) are set up at location r.
b_{is}	Indicator binary variable of unused (free) capacity at location i in scenario s.

TABLE 9. AMSTERDAM MODEL PARAMETERS

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Parameters	
w_1	Weight for financial component of cost function.
w_2	Weight for emissions component of cost function.
M	A very big constant.
K	Annual treatment capacity of a single unit (set of machines) a treatment and fine-sorting site.
D_{cqs}	Annual waste volume for quaility q at collection site c in scenario s.
a	Cost of transporting 1 m^3 of material over 1 kilometer.
g_{jq}	Public party cost of processing 1 m^3 of material of quality q at node j.
c_r	Annualized cost of establishing an encapsulated environment at location r and annual cost of operating a facility there.
ζ	Annual cost of operating a single unit (set of machines) for fine-sorting and shredding.
π_j	(Private) cost for a collection party to process their waste at location j.
e	Emission generated by transporting 1 m^3 of material over 1 kilometer.
v_{jq}	Emission generated by treating 1 m^3 of material at location j.
p_s	Probability of scenario s occuring.

LIST OF RELEVANT MODELING ASSUMPTIONS:

- While on-site separation of recyclable and non-recyclable materials is impossible, and the materials need to be transported together, the quality composition can be determined on-site on inspection *(The model assumes that quality composition is roughly known before choosing where to transport the waste; This is not going to be the case exactly, but the assumption is not unrealistic if those parties handling the waste on-site are able to make a reasonable judgement on this, especially since we aggregate the collection sites into squares of 5 km by 5 km)*
- The model planning horizon currently spans the period in which each building in the area of interest will have undergone demolition or renovation. The length of this period in years should correspond to the depreciation time of the sorting and treatment installation, and is roughly estimated to be **25 years**.
- All demolition waste that (possibly) contains PUR/PIR has to be dealt with, either by transportation to an incineration plant or by supplying it to parties that sort and process it to prepare for further recycling.
- Establishing an environment in which pre-sorting and treatment can take place is costly and incurs a setup cost. Treatment capacity is modular and can be acquired in incremental steps of K.
- The cost objective does not correspond to the cost of one single party: It should be viewed in the light of trying to set up an economically solid value chain, in which the possible additionally incurred cost for establishing these logistics and facilities could instead be bridged by a subsidizing mechanism or extra investments. All costs that should be allocated to any beneficiary of establishing this value chain, be it government or a market player, together make up the cost objective.

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- Relevant costs and emissions can be described by a single scalar factor that is valid throughout the planning horizon. These values are known when strategic decisions need to be made for locating treatment facilities.
- Any party responsible for delivering waste from demolition and renovation sites will dispose it in the most economic way. That is, they will choose the option that is cheapest for them, not necessarily what is 'best' with respect to the optimal circular value chain.
- Incineration remains allowed throughout the planning horizon; Current incineration locations will remain open.
- The model contains transfer nodes as artificial sinks which can model the costs and yields of further transportation and downstream processing.
- The model does not take into account (extreme) seasonal or yearly deviations in waste flows, as the flows and capacities are annual averages over the total planning horizon.

4.5 Stochastic model: Objective and constraints

OBJECTIVE:

In the stochastic model, we aim to **minimize** the following objective:

$$w_1 * \left(\sum_{s\in S} \sum_{q\in Q} \sum_{(i,j)\in Z} p_s\left[ad_{ij} + g_{jq}\right] X_{ijqs} + \sum_{r\in R} c_r y_r + \sum_{r\in R} \zeta z_r \right)$$

$$+ w_2 * \left(\sum_{s\in S} \sum_{q\in Q} \sum_{(i,j)\in Z} p_s\left[ed_{ij} + v_j\right] X_{ijqs} \right)$$

As mentioned earlier, this is a multi-objective formulation. The first part models financial cost. It consists of the expected cost incurred by transporting waste, processing waste at incinerators or treatment facilities, and the cost of setting up (a) treatment location(s) and acquiring the equipment necessary to fine-sort and process the materials. The second part models expected emissions of transporting and processing waste.

This objective is minimized subject to the following constraints:

CONSTRAINT 1 – ALL WASTE SHOULD BE DEALT WITH:

$$\sum_{j\in V\cup R} X_{cjqs} = D_{cqs} \; \forall c \in C; \; \forall\, q \in Q; \;\; \forall s \in S$$

This constraint ensures that the outflow of material at any collection location c should match the corresponding waste volume at that location in each scenario.

CONSTRAINT 2 – NO QUALITY SEPARATION BEFORE TREATMENT:

$$\frac{X_{cjqs}}{D_{cqs}} = \frac{X_{cjq's}}{D_{cq's}} \; \forall\, c \in C; \forall j \in V \cup R; \forall s \in S; \forall q, q' \in Q$$

This constraint ensures that the composition of the outflows of waste from a collection site is equal to the original composition at that site. It ensures that it is not possible to send all high-quality material to a treatment facility and all low-quality material to incineration; Separation of these flows can only happen <u>after treatment.</u>

CONSTRAINT 3 – CONSERVATION OF FLOW AT TREATMENT FACILITIES:

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$$\sum_{j \in V \cup O} X_{rjqs} = \sum_{c \in C} X_{crqs} \, \forall \, r \in R; \forall q \in Q; \forall s \in S$$

This constraint ensures that any waste that enters a treatment facility will leave the treatment facility, either to be sent onward to incineration or to an artificial transfer sink for downstream processing.

CONSTRAINT 4 – CAPACITY CONSTRAINT AT TREATMENT FACILITIES:

$$\sum_{c \in C} \sum_{q \in Q} X_{crqs} \leq K z_r \, \forall \, r \in R; \forall s \in S$$

This constraint ensures that treatment facilities can process all the waste that is sent towards them.

CONSTRAINT 5 – EQUIPMENT CAN ONLY BE INSTALLED AT ESTABLISHED TREATMENT LOCATION:

$$z_r \leq M y_r \, \forall \, r \in R$$

This constraint ensures equipment (and corresponding capacity) is cannot be placed at location r if no facility is set up there.

CONSTRAINT 6 – STACKELBERG CONSTRAINT:

$$\left[\left(ad_{cj'} + \pi_{j'} \right) - \left(ad_{cj} + \pi_j \right) \right] \sum_{q \in Q} X_{cjqs} \geq M \left(b_{j's} - 1 \right) \forall \, c \in C; \forall j, j' \in V \cup R; \forall s \in S$$

This constraint models the assumption that external agents who want to dispose of their waste do so in the most economical way. It builds on a formulation by (Yao, Yi, Wang, Zhen, & Liu, 2022). It works as follows:

- The left-hand side of the constraint is negative if and only if both of the following are true:
    - Any amount of waste is transported from location c to location j
    - From location c, it is cheaper to transport and process the waste to location j' than to location j.
- The right-hand side of the constraint is 0 if there is idle capacity at location j'. The constraint is relaxed otherwise: If there is no idle capacity at location j' the right-hand side will equal $-M$.

This modelling trick ensures that it is not possible to produce a solution where an agent chooses to dispose of their waste at facility j if there exists a facility j' which has idle capacity, and which is a more economical option for this agent.

CONSTRAINT 7 – AVAILABILITY INDICATOR CONSTRAINT:

$$M b_{rs} \geq z_r - \frac{\sum_{c \in C} \sum_{q \in Q} X_{crqs}}{K} \quad \forall \, r \in R; \forall s \in S$$

This constraint ensures that indicator variable b_{rs} must be equal to 1 if there is any idle capacity at treatment facility r.

CONSTRAINTS 8-12 – DOMAIN SPECIFICATION FOR DECISION VARIABLES:

$$X_{ijqs} \geq 0 \, \forall (i,j) \in Z; \forall \, q \in Q; \forall \, s \in S$$

$$b_{rs} \in \{0,1\} \, \forall \, r \in R; \forall s \in S$$

$$b_{is} = 1 \, \forall \, i \in V \cup O; \forall s \in S$$

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$y_r \in \{0,1\} \; \forall \, r \in R$

$z_r \; \in \; \mathbb{Z}_0^+ \; \forall \, r \in R$

These constraints specify the domains of the decision variables: X_{ijqs} should not be negative, b_{rs} is a 0-1 indicator variable that should be equal to 1 for uncapacitated nodes (incinerators and artificial transfer nodes), y_r is a binary variable and z_r is a non-negative integer.

4.6 Model inputs and input size reduction

Figure 2 shows the area around Amsterdam for which we have collected data and experimentally tested the stochastic model. The data collection and processing process needs to take place step by step, because determining the height for each building is a memory-intensive process. Each of the red rectangles shows one zone for which we have collected and processed data through our pipeline process. The model has been applied to the region consisting of all red rectangles together.

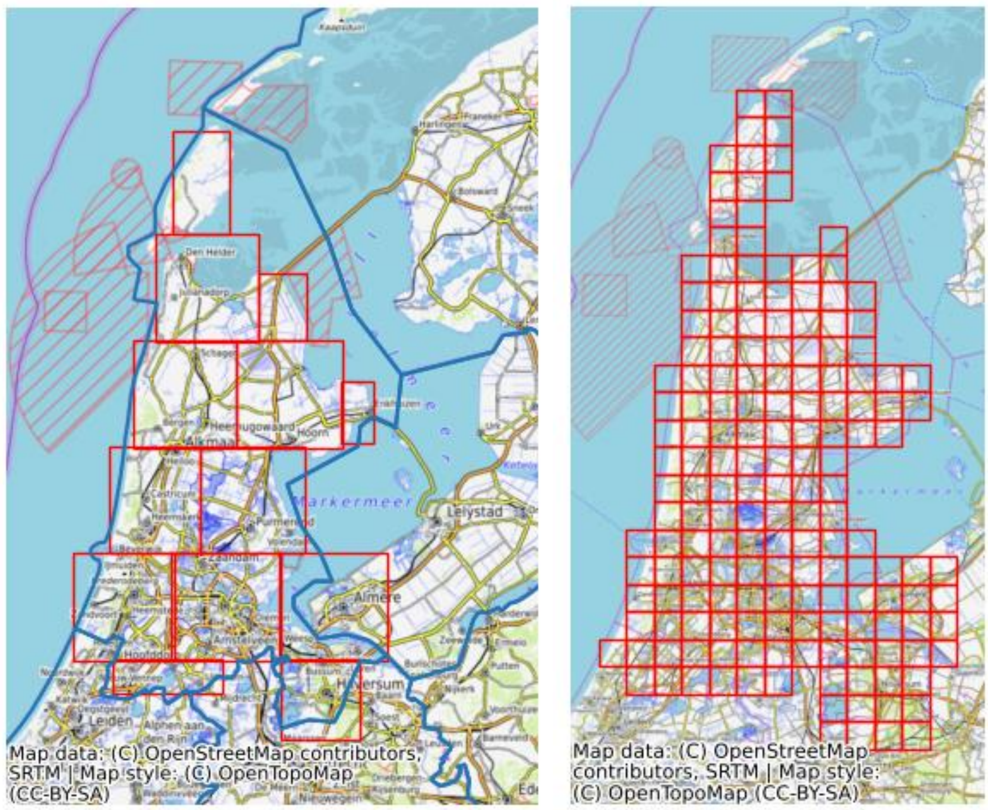
For the potential collection locations, we queried the IBIS Bedrijventerreinen dataset containing all industrial zones in the Netherlands (https://data.overheid.nl/dataset/ibis-bedrijventerreinen). We selected locations where there is still some available area to give out, and for which the environmental zoning classification is 4 or higher (so that waste treatment activities will be allowed). We have identified 42 suitable locations in the pilot region. There are two existing incinerators in the region, one in Alkmaar and one in Amsterdam.

In order to compute the transportation distances from the sites from which waste can be transported to the potential facility locations and incinerators, we made use of the distance matrix API provided by https://openrouteservice.org and OpenStreetMap data.

After data collection, 1000 equiprobable scenarios were generated using the Monte Carlo sampling method described in Section 5.3. Because of the complexity of the model, which has integer variables in both the first and second stages, it can only be solved for a small number of scenarios and a coarse geographic resolution.

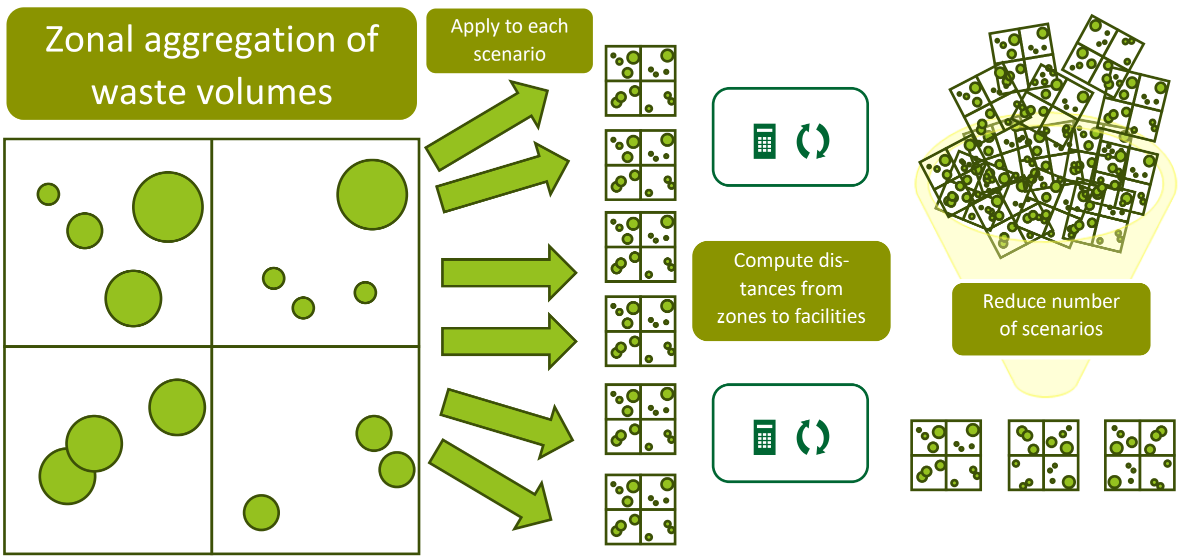
Because of this, we have to aggregate the waste collection sites into larger geographic zones. The model remains tractable if these zones are squares of 5km by 5km. This aggregation results in 168 square geographical zones in our pilot region, as shown in Figure 2. For each scenario and aggregated zone, its distance to the potential facility locations and incinerators is computed as the weighted average of the distances from each of the waste sites within the zone. The values for the annual waste volumes are now obtained by dividing the total waste quantities by 25.

FIGURE 2. AMSTERDAM PILOT REGION TO WHICH THE STOCHASTIC MODEL WAS APPLIED; LEFT: ZONES FOR DATA EXTRACTION; RIGHT: AGGREGATION ZONES USED AS COLLECTION ZONE FOR MODEL INPUT.



We also reduce the sampled scenarios: Retrieving a limited set of representative scenarios and passing these as input to the model, allows us to leverage the benefits of the stochastic programming paradigm, while also preserving model tractability. Our original scenario set is reduced from 1000 sampled scenarios to 12 representative scenarios. For this, we applied the Fast Forward Selection procedure (Heitsch & Römisch, 2003). A schematic overview of reducing the model input to improve tractability is shown in Figure 3.

FIGURE 3. PROCESS OF PROBLEM SIZE REDUCTION PRIOR TO SOLVING MODEL



For the demonstration of the model, we use the following initial (mock) values for the model parameters:

- The annualized base costs for establishing a treatment facility, c_r, are equal to €65.000 for every location. The costs
- The transportation costs α are estimated at €0,055 per kilometer per m^3
- The additional handling costs per m^3 of material are equal at treatment and incineration facilities and amount to €0,10 per m^3.
- We assume that the handling cost an external agent pays for treatment is equal to the cost they pay for incineration.
- The downstream process (all processes that happen after material leaves the region at artificial sink nodes) is assumed to run break-even: The profit/loss of sending a m^3 of recyclable material through a sink node is €0. We remark that this can be seen as a flexible model input: The break-even case merely serves as an example. The cost of sending a m^3 of unrecyclable material through a sink node is set to a very high number, to ensure that this does not occur in the model.
- For now, sink nodes are directly attached to the recovery and treatment locations, assuming a direct transportation link further downstream.
- The modular treatment capacity step K is 50.000 m^3 per year. The cost associated with this capacity is €24.000 per year.
- Regarding emissions, we fix $e = 15{,}2$ g CO_2 as estimate for the emissions of transporting 1 m^3 of waste over 1 kilometer. Processing emissions for fine-sorting/treatment and incineration are set to 30 and 22.000 g per m^3 of waste, respectively. The downstream processing emission linked to the artificial sink node is set to 17.000 g per m^3 of waste.

When setting the parameters, the authors have strived to give an as realistic indication as possible. Some parameter estimates are based on Dutch databases[1], and might differ in other countries. Also, to the knowledge of the authors, some parameters cannot yet be conclusively pinpointed at this time. The authors stress that before deploying the model to draw policy conclusions, a thorough sensitivity analysis, or a more accurate parameter estimation is imperative.

4.7 Model implementation

The scenario generation and data pipeline were implemented using Python, and the model itself has been implemented in Julia, using the Stochastic Programs library (Biel & Johansson, 2022). The model was solved using the commercial solver GUROBI (version 9.5), but the implementation allows for solving the model using another (non-commercial) solver. Constraint 6 is defined for every the cartesian product of sets $C \times (V \cup R) \times (V \cup R) \times S$, resulting in a very large model if all these constraints are added simultaneously. Because of this, we instead opt to add the relevant constraints one-by-one as lazy constraint using solver callbacks. Furthermore, to speed up the solution process, we add the following valid inequality:

1. These include the report "Bottom-up berekening CO2 vrachtwagens en trekkers" by CBS (assuming the weight of a fully loaded truck weighs 9,3 tons with a power of 367 kW) , "Kostenkengetallen voor het goederenvervoer", a publication by the ministry of infrastructure and water management (adjusted for inflation), and the IBIS bedrijventerreinen dataset (https://data.overheid.nl/dataset/ibis-bedrijventerreinen)

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VALID INEQUALITY 1:

$$X_{crqs} \leq y_r D_{cqs} \; \forall c \in C; \forall r \in R; \; \forall q \in Q; \;\; \forall s \in S$$

Finally, since the aggregated distances deviate slightly for each of the 12 reduced scenarios, and the model requires deterministic distances (i.e. independent of the scenarios), we use the weighted averages (by scenario probability) over the 12 scenarios.

4.8 Model analysis and preliminary results

We apply the model using the 12 scenarios resulting from the reduction. Some summarizing characteristics and the corresponding probabilities of these scenarios can be found in Table 10. Fixing w_1 and varying w_2, we retrieved a set of optimal solutions for the scenarios and parameters specified.

TABLE 10. SUMMARIZING CHARACTERISTICS OF SCENARIOS OBTAINED BY SCENARIO REDUCTION

s	Total waste volume (m^3)	Recyclable material % (overall)	Probability p_s
1	178.630	52,6%	9,2%
2	184.962	51,9%	5,7%
3	169.939	53,4%	13,5%
4	181.107	55,4%	8,0%
5	173.812	51,9%	12,4%
6	181.497	52,0%	10,8%
7	180.713	49,2%	5,1%
8	183.272	50,4%	9,1%
9	180.899	51,8%	6,6%
10	176.644	53,3%	11,1%
11	185.993	49,2%	5,3%
12	186.719	54,7%	3,2%

Figure 4 shows a Pareto front of non-dominated solutions, and Figure 5 shows the respective solutions and the service areas of the treatment facilities and the incinerator for one of the scenarios (Scenario 6 from table 10).

FIGURE 4. SET OF NON-DOMINATED SOLUTIONS OF THE STOCHASTIC MODEL. LEFT: BREAKDOWN OF EXPECTED REGIONAL SYSTEM COST, RIGHT: BREAKDOWN OF EXPECTED EMISSIONS

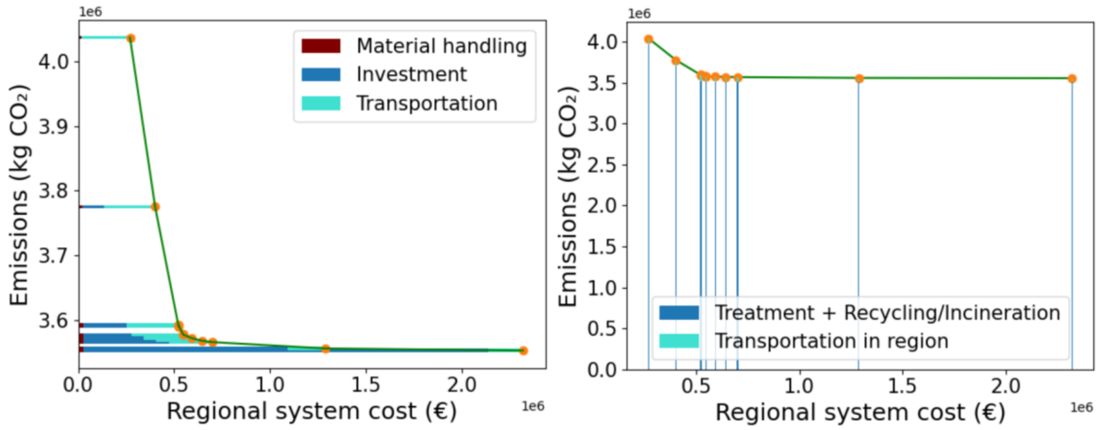

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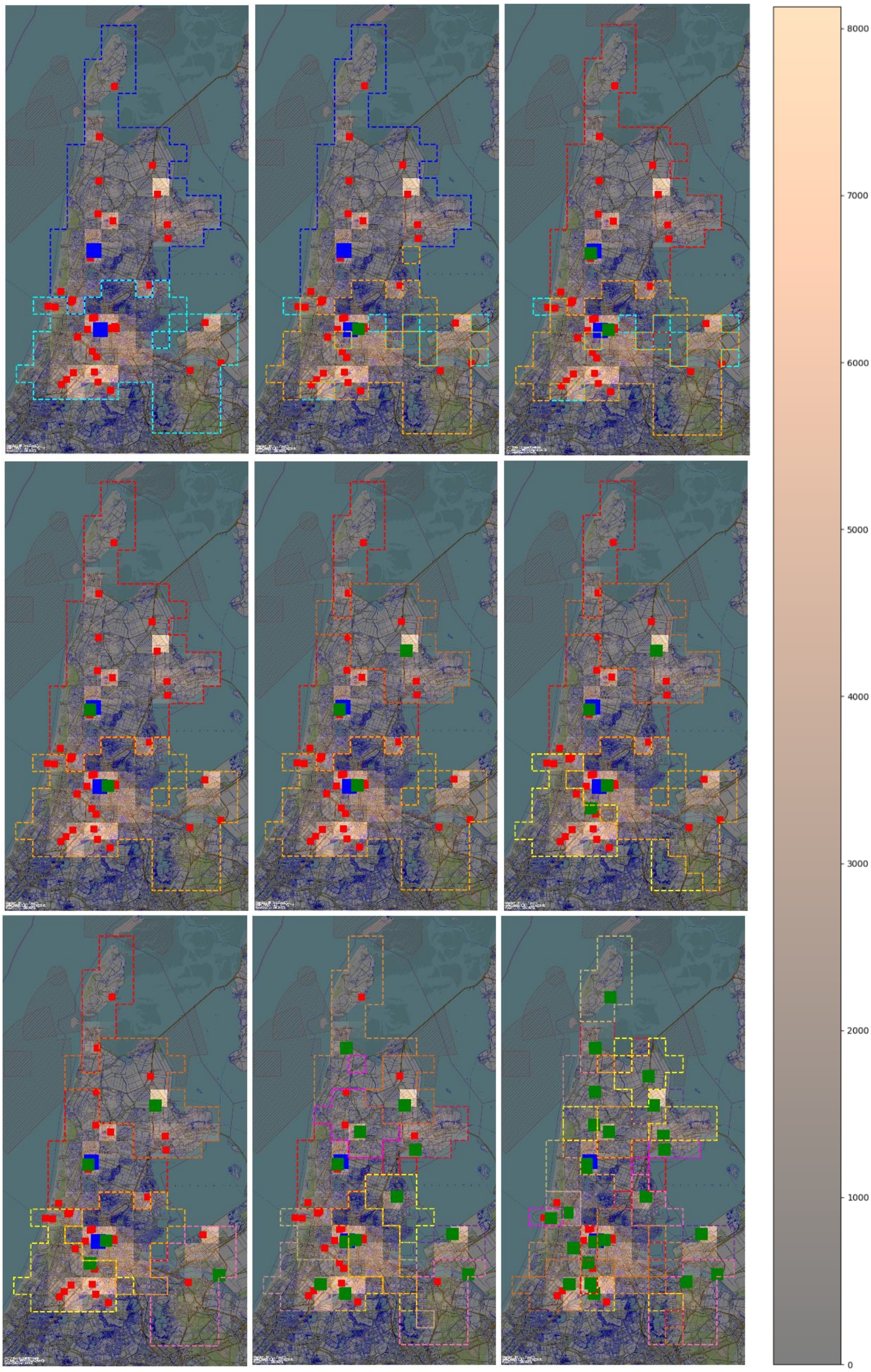
FIGURE 5. SERVICE AREAS OF INCINERATORS AND OPEN TREATMENT FACILITIES FOR PARETO-EFFICIENT SOLUTIONS: FROM LEFT TO RIGHT, TOP TO BOTTOM, THE SOLUTIONS GET MORE COSTLY AND THE EMISSIONS DECREASE. BRIGHTNESS INDICATES TOTAL WASTE VOLUME IN EACH SQUARE (SEE COLOR BAR LEGEND).



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Inspection of Figures 4 and 5 gives the following insights in the dynamics of the system defined by the input parameters described in Section 5.6:

- A relatively small (annualized) investment can lead to a significant reduction in emissions. This reduction is achieved by replacing the emission-heavy incineration process by treatment and (partial) recycling. When giving emissions more importance in the objective function, the model will attend different solutions (see the top row of Figure 5) until no waste is sent directly to incineration anymore.
- As Figure 5 shows, the share of regional transportation in the total emissions is very small in this setting. After reducing all potential emissions from directly sending waste to incinerators, the only way to improve the emission is to reduce these (marginal) regional transportation emissions. This can only be done by opening more facility locations, which comes at a high cost. This behavior explains the kink in the Pareto frontier in Figure 4.
- The Stackelberg constraint, which models economic opportunism of the parties disposing the waste, together with the configuration that these parties are charged the same amount for incineration and treatment, leads to facilities being opened at the same locations as the existing incinerator. This eliminates any monetary incentives these parties may have to prefer sending waste directly to the incinerator. If these inputs are changed, and incineration will be charged more, for example, there will be different dynamics in this regard.
- Even though 200,000 capacity is enough to handle all the waste at treatment plants, and both treatment plants are located near the incinerators, still it is not possible to recover all the waste purchasing 4 incremental capacity steps of 50.000. This is due to the Stackelberg constraint: For a certain waste zone, if the nearest of the treatment facility is full, but the other has some idle capacity, it would be good (emission-wise) for the system to send it there. However, a commercial party will want to disposed of the waste as cheap as possible, and will opt for incineration, which is the nearest alternative.
- We see a pattern emerging where the additional locations that are opened in some of the more emission-friendly pareto-optimal solutions are located close to areas with a relatively high amount of waste. A scenario set with more variation across scenarios would produce less predictable dynamics.

4.9 Possible model extensions

One of the assets of this stochastic model is that it can be easily adapted for different types of inputs. It is relatively easy, for example, to feed the model with a more detailed waste composition (rather than the broad categories 'recyclable' and 'unrecyclable'), by extending the set Q and modifying the generation process. The same holds for applying the model to a larger or different region. Also, the artificial sink nodes can be used to model different configurations for the logistics towards chemical processing, and different financial yields for chemical recycling. Some more involved extensions require substantial reworking of the model, or the development of additional solving techniques. We will now briefly address three of these possible model extensions: Extending stage structure and adding temporal dimension, improved zonal aggregation, and multimodal transportation flows.

Temporal dimension and stage structures

Some of the more restrictive assumptions of the current model are related to time: The model requires waste volumes to be evenly spread throughout the planning horizon and requires parameters to be represented by a single constant for the same period. In order to go about making less restrictive assumptions, a temporal dimension could be added to the model. Unfortunately, this does introduce extra complexity, so this possible addition will be a careful balancing act. The structure of a two-stage model with a temporal dimension is depicted in Figure 6.

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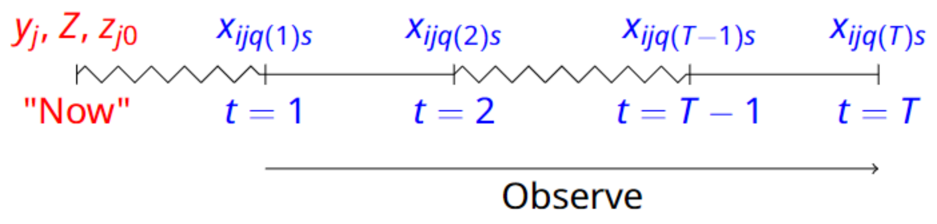
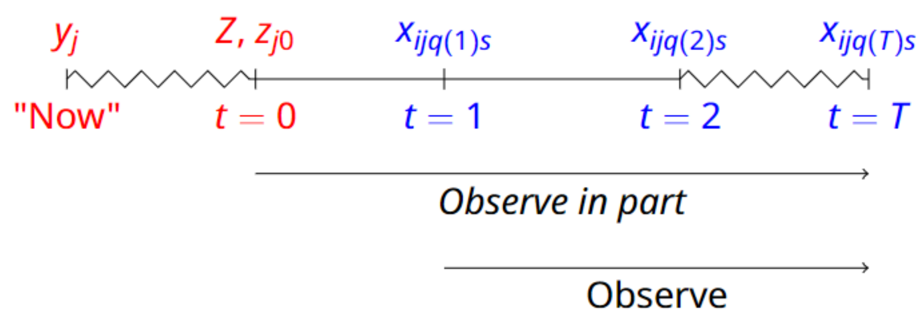
FIGURE 6. POSSIBLE STRUCTURE FOR ADDING A TEMPORAL DIMENSION TO THE MODEL



The relevant assumptions of a two-stage model with temporal dimension, is that one set of decisions is taken before any of the uncertainty is revealed, and all (other) operational decisions are taken when there is full knowledge of the uncertain parameters: The assumptions here are that knowledge of future PIR/PUR volumes will not affect the waste flows at time t, and each decision is made either completely informed or completely uninformed of the uncertain realization.

An extension to this regard would be to increase the number of stages where new information becomes available. However, transforming each period into a stage of its own will surely be extremely computationally demanding. An intermediate solution could be a 3-stage formulation, as shown in Figure 7. The Figure shows a setting where the locational decision needs to be made upfront, while capacity decisions (the total number of incremental capacity increases to purchase denoted here by Z and their locations determined by z_{j0}) are made when it is known which branch of the tree of possible scenarios will be realized. Finally, flow decisions are assumed to be made when all information regarding the uncertain parameters is fully known.

FIGURE 7. POSSIBLE STAGE STRUCTURE FOR ADDING A TEMPORAL DIMENSION TO THE MODEL



It would also be possible to move the capacity decisions for each location to the final stage, constrained by the total capacity purchased earlier. This models the option to relocate personnel and or machinery over time. This does require the modelling assumption that waste volumes for some future time horizon are already known at the time of making a relocation decision, as such a relocation decision does anticipate on these values.

IMPROVED ZONAL AGGREGATION

If the model is to be applied to a larger region, solving it will also become more complex and time-consuming. This can be addressed in one of two ways:

- Better exploitation of model structure, by employing more sophisticated solution techniques from the stochastic programming literature and/or restructuring the model in an attempt to eliminate the binary variables in the second stage. Something along this line is likely needed to allow for a multi-stage or multi-period variant of the model to be solved for problems on a realistic scale.

- Better reduction techniques. We have developed aggregation methods that under some conditions are able to better preserve information than by using square zones: An algorithm has been devised for deterministic location problems. It could be worthwhile to investigate whether it is possible to extend this methodology to the stochastic setting.

MULTIMODAL TRANSPORTATION FLOWS

For onward logistics toward downstream processing, alternative modes can already be modelled by including different artificial sink nodes, representing the cost of choosing different modes. It would be possible to devise a model where, for example, barges can also be used for regional transportation from bigger rough-sorting facilities to fine-sorting & treatment locations: This requires additional indexing on mode for flow variables, with specific emission and cost parameters per mode.

5. Dynamic model for remoted areas with forecasting

5.1. Introduction

In the scope of this task, the analysis has been limited to sandwich panel buildings. This decision was based on insights gathered during stakeholder consultations, particularly with a Polish company specialized in building deconstruction and recycling. According to their experience, polyurethane foams used in conventional buildings are typically integrated with other construction materials—such as being embedded within walls—which makes their selective removal technically challenging and economically unviable.

The interviewee emphasized that while domestic buildings rarely offer viable opportunities for foam recovery, large-size industrial or commercial halls constructed using sandwich panels present a much higher potential for end-of-life (EoL) foam extraction. It was estimated that approximately 5% of the total building mass in such facilities may consist of recoverable foam materials. Therefore, focusing on sandwich panel structures provides a more realistic and targeted approach for assessing the potential of EoL foam recovery within the built environment.

The presented model encompasses various stages, including the identification of waste sources, collection routes, and processing facilities. It analyses the flow of materials from the point of disposal to recycling or final treatment, ensuring minimal environmental impact. By employing advanced data analytics and geographic information systems (GIS), the model evaluates the most effective logistics strategies to reduce costs and emissions associated with waste transport. It was crucial to determine the availability and timing of waste containing PUR Foam. In previous phases of the project, it was established that the largest stream would come from sandwich technology buildings that are to be demolished

The simulation will play a crucial role in evaluating the potential outcomes of different policies and system structures, as well as identifying effective methods for the utilization and recycling of available polyurethane foam (PUR) waste. Our analysis will encompass various factors, including the cost-effectiveness of collection methods, the feasibility of establishing dedicated foam collection points. By considering these factors comprehensively, we aim to identify the optimal policy and system structure

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that not only maximizes the collection and recycling of polyurethane foam but also minimizes environmental impact and costs associated with its management.

Key features of the model include:

1) Parameterization: The model will be parameterized using design parameters related to the collection, storage, and transportation systems, as well as the distances to separation sites. This will ensure that the model accurately reflects the operational realities of waste logistics.
2) Outputs: The model aims to generate critical outputs, including:
   a) Total mass of waste and PUR components in the future.
   b) Costs associated with the collection and transportation systems.
   c) Optimal distribution of separation centers.

It was crucial to gather information on future streams of PUR Foam, which was achieved through the analysis of GIS systems and Street View images. These tools enabled the precise identification of potential waste sources and the optimization of collection routes.

5.2. Data collection

In our research we have to assess the future availability of PUR from buildings that will be dismantled. We will focus on estimating the quantity of PUR foam that will become available for recycling or disposal as these buildings reach the end of their lifespan, which is typically around 30 years. By understanding the lifespan of buildings and the timing of potential dismantling, we can anticipate the volume of PUR foam that may enter the waste stream in the future.

Due to the relatively recent adoption of polyurethane foam (PUR) technology in related region, we do not have access to historical data regarding the number of buildings reaching the end of their lifespan for dismantling. As a result, the current stream of PUR waste is relatively small compared to Western Europe. Therefore, we need to adopt a more proactive approach to address this issue. On the other hands in Poland, there are no known specific data sources that provide a comprehensive list of buildings constructed using PUR sandwich panel technology. This is why more universal methods need to be considered to gather such information.

In order to overcome the lack of historical data and official sources regarding the number of buildings reaching the end of their lifespan for dismantling we have a proposed approach. Our initial step will be to utilize publicly available GIS data as a foundation for our analysis. This data will provide us with a general overview of the building stock in the region. To further refine our analysis, we will leverage satellite maps and street view images. These visual resources will allow us to limit our set of potential buildings. Lastly, to obtain more detailed and accurate data, we will focus on gathering specific information for a limited number of buildings from formal sources By combining these approaches, starting with publicly available GIS data, analyzing satellite maps and street view images, and then obtaining detailed data for a subset of buildings, we can overcome the lack of historical data and develop a comprehensive understanding of the potential availability of PUR waste from dismantled buildings in our region.

To obtain a list of buildings constructed using sandwich panel technology in Poland, our approach could involve the following steps:

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- **Retrieve building data from the GIS system** - Begin by retrieving data on buildings with an area exceeding 2000 square meters from the GIS (Geographic Information System) database. This data would serve as the initial dataset for further analysis.

- **Develop a dedicated tool to identify potential buildings constructed using polyurethane foam (PUR) sandwich technology** - Create a custom web application that integrates satellite imagery and street view functionality. This application would allow operators to view the satellite map and street-level images of the selected areas, enabling them to identify potential buildings constructed with sandwich panels. In this step a set of qualification rules to determine which buildings should be further analyzed are established. These rules may include criteria such as focusing on newly constructed buildings rather than older industrial areas, prioritizing buildings located closer to transportation hubs and new parking facilities.

- **Extract construction data from GIS** - Extract relevant construction data from the GIS system, such as the date of construction or the year when the building was added to the database. This data will provide an indication of when the building was constructed and will be used for the initial analysis.

- **Review and validation process** - Engage relevant stakeholders, such as personnel from local municipalities or construction departments, to review and validate the buildings that have been identified and shortlisted in the previous steps. These individuals would have the expertise to confirm the construction methods used.

It's important to note that this process would require collaboration between GIS experts, software developers, and local authorities to ensure accurate identification and validation of the buildings. The involvement of professionals familiar with construction techniques and local regulations would be crucial to obtaining reliable results.

5.2.1. Retrieve building data from the GIS system

In order to gather data on buildings constructed using sandwich technology, the initial step involved extracting data from the GIS system. Following this, a program was developed that allowed the operator to view satellite images of the building, with the analyzed building highlighted in red, alongside the camera's location (blue triangular). On the other side, the Street View image was displayed. This setup enabled the operator to determine whether the building was constructed using old technology (such as regular bricks, masonry, etc.) or the new sandwich technology. Below are tables presenting examples of buildings constructed with sandwich technology, as well as those classified as old.

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Table 11: Views of Buildings Identified with Sandwich Technology

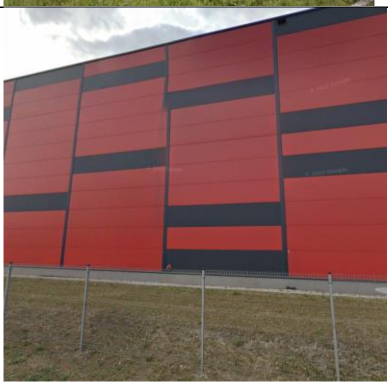
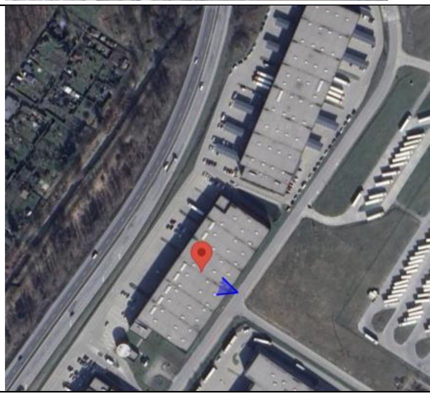
	Street View	Satelite View
1		
2		
3		
4		

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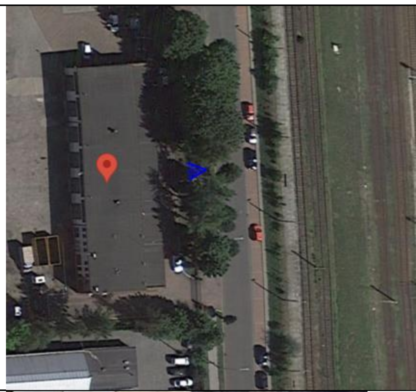
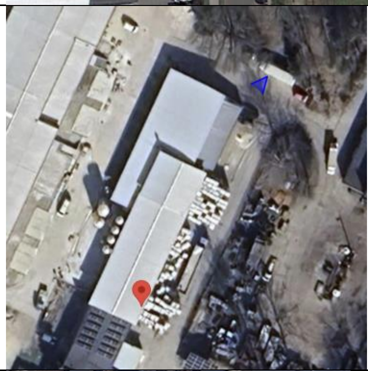
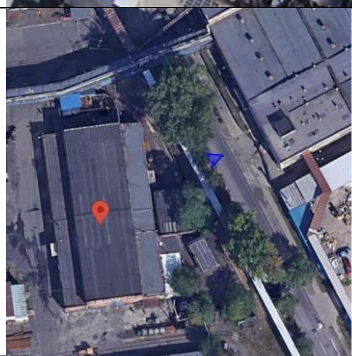
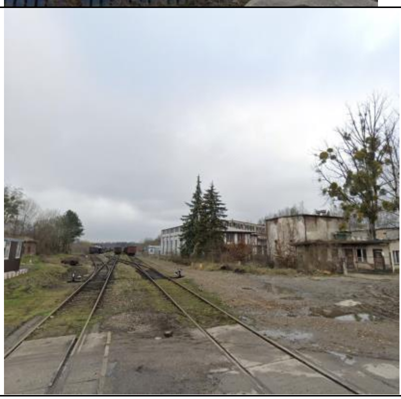
TABLE 12: VIEWS OF BUILDINGS IDENTIFIED AS TRADITIONAL TECHNOLOGY

	STREET VIEW	SATELITE VIEW
1		
2		
3		
4		

5.2.2. Overview of Sandwich Building Statistics in GZM

Based on the analysis of a list containing 2,192 buildings within the studied area, 770 were identified as constructed using sandwich technology. It was assumed that the disclosure of these buildings in the GIS system closely correlates with their completion dates. Consequently, statistical data were prepared, detailing the years in which these buildings were erected and their total surface area. These

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findings are presented in Table 13 and on Figure 8, highlighting the significance of understanding construction trends and spatial development in the region. Such analysis contributes to the broader discourse on architectural methodologies and urban planning practices.

The table presents data regarding the buildings identified in the previous step, including the following columns: year – the year in which the building was constructed, count – the number of buildings in that year, floor area – the total floor area of the buildings identified in that year (in square meters).

TABLE 13. YEAR, COUNT AND FLOOR AREA BUILDINGS CONSTRUCTED IN SANDWICH TECHNOLOGY

Year	Count	Floor area
2010	2	77 181
2011	7	49 243
2012	76	2 594 108
2013	124	1 275 383
2014	45	561 331
2015	34	739 688
2016	32	609 144
2017	25	827 058
2018	18	516 708
2019	76	1 583 545
2020	30	1 020 102
2021	26	931 675
2022	59	1 009 294

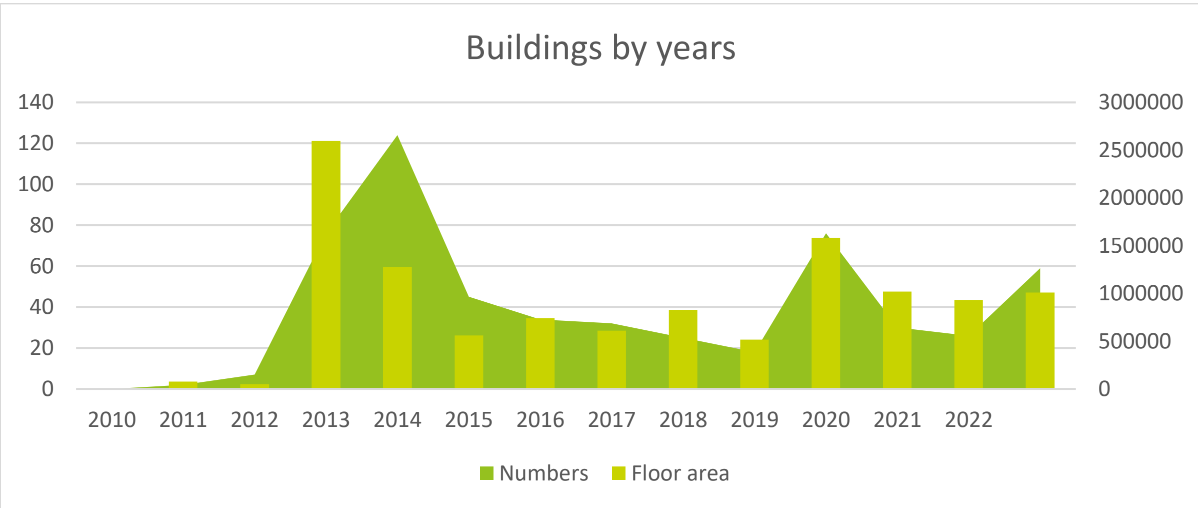

FIGURE 8. NUMBER AND FLOOR AREA BUILDINGS CONSTRUCTED IN SANDWICH TECHNOLOGY

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Based on the after mentioned data, forecasts for the availability of used sandwich panels have been developed. Two building lifespans were considered: 25 and 30 years. Additionally, since the calculations were based on floor area, an average wall height of 5 meters and a panel thickness of 10 cm were assumed. Furthermore, it was assumed that the buildings are square in shape to facilitate the calculation of the perimeter based on the floor area.

TABLE 14. AVAILABILITY OF PUR FOAM OVER TIME BASED ON LIFESPAN PARAMETERS OF 25 AND 30 YEARS.

Year	PUR availability [m3]	
	lifespan 30y	lifespan 25y
2035		667
2036		533
2037		3865
2038		2710
2039		1798
2040	667	2064
2041	533	1873
2042	3865	2183
2043	2710	1725
2044	1798	3020
2045	2064	2424
2046	1873	2317
2047	2183	2411
2048	1725	
2049	3020	
2050	2424	
2051	2317	
2052	2411	

5.3. PUR Foam transportation

The packaging methods for polyurethane (PUR) foam significantly influence its handling, transportation, and overall efficiency in storage. Among the available options, the solid form stands out with a density range of 50-70 kg/m³, providing a robust solution for various applications. This packaging method ensures durability and stability, making it suitable for demanding environments.

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The big bag option offers a slightly lower density, ranging from 40-60 kg/m³. This method is advantageous for bulk handling and can facilitate easier loading and unloading processes. While it may not provide the same structural integrity as solid packaging, it remains a popular choice for its versatility.

In contrast, the loose form, with a density of 20-40 kg/m³, is the least dense option and is typically used for applications where flexibility and ease of use are prioritized. This packaging method allows for quick distribution and is often employed in scenarios where immediate application is required.

Lastly, the compacted form presents the highest density, ranging from 200-400 kg/m³. This method is ideal for maximizing storage efficiency and minimizing transportation costs due to its reduced volume. However, it may require specialized handling equipment due to its weight.

Ultimately, the choice of packaging method should be guided by specific operational needs, including storage capacity, transportation logistics, and application requirements. Each option presents unique advantages that can be leveraged depending on the context of use.

The information provided in the following sections regarding the transportation of PUR foam is based on the knowledge and contacts of the individuals preparing this report. It is important to note that this data does not constitute a commercial offer and is not based on information provided by transportation companies. Additionally, transportation service prices are dependent on fluctuating fuel costs, which may affect their rates. Therefore, it is advisable to regularly verify current rates and transport conditions before making any decisions.

5.3.1. Mode of transportation

The transportation of polyurethane (PUR) foam can be effectively accomplished through various means, including rail and road transport, as well as hybrid systems that combine both methods. This analysis aims to evaluate the capabilities of vehicles and trains in the context of PUR foam logistics, highlighting when each mode of transport may be more advantageous.

Rail transport offers several benefits, particularly for long-distance shipments. Trains can carry large volumes of goods, making them cost-effective for bulk transportation. Additionally, railways often have a lower environmental impact compared to road transport, contributing to sustainability goals. However, the limitations of rail transport include dependency on fixed routes and schedules, which can lead to delays if connections or transfers are required.

On the other hand, road transport provides greater flexibility and accessibility. Vehicles can reach locations that may not be serviced by rail, allowing for direct delivery to end users. This method is particularly advantageous for shorter distances or when timely delivery is crucial. However, road transport can be subject to traffic congestion and higher fuel costs, which may affect overall efficiency.

In summary, the choice between rail and road transport for PUR foam will depend on several factors, including distance, volume, delivery timelines, and cost considerations. For large shipments over long distances, rail transport may be preferable due to its capacity and lower operating costs. Conversely, for shorter distances or when flexibility is paramount, road transport may be the better option. Each method has its own advantages and disadvantages, and a hybrid approach could potentially optimize logistics by leveraging the strengths of both systems.

The transportation of polyurethane (PUR) foam can be effectively managed using various vehicle types, each offering distinct capacities and pricing structures. The walking floor trailer, with a capacity of 75 m³, presents the highest volume option but comes at a cost of €1.5 per kilometer. In contrast, the dry freight trailer, which can accommodate 67 m³, offers a more cost-effective solution at €1.3 per kilometer. The dump body trailer, while having a lower capacity of 55 m³, is priced at €1.4 per kilometer,

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making it a less favorable option in terms of cost efficiency compared to the dry freight trailer. Lastly, the compactor trailer, also with a capacity of 67 m³, provides the lowest transportation cost at €1.2 per kilometer.

When considering these options, the dry freight trailer emerges as a balanced choice, offering a reasonable capacity with competitive pricing. However, for larger shipments, the walking floor trailer may be justified despite its higher cost due to its greater volume capacity. The choice of transport method ultimately depends on specific logistical needs, budget constraints, and the nature of the PUR foam being transported.

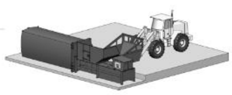
Transporting polyurethane (PUR) foam by train offers a range of options, each with specific capacities and associated costs that can influence logistics strategies. The covered wagon stands out as a highly efficient choice, with a capacity of 138 m³ per wagon. With a total of 30 wagons available, this method can accommodate up to 4,140 m³ of PUR foam, making it ideal for large-scale shipments.

Another option, the hooper wagon, has a slightly lower capacity of 81 m³ per wagon. With 40 wagons in a train, it can transport a total of 2,430 m³. This method is particularly suited for bulk materials, providing a good balance between capacity and ease of loading and unloading.

The flatcar, with a capacity of 67 m³ per wagon and a total of 30 wagons, allows for the transportation of 2,680 m³ of PUR foam. While it may not offer the same volume as the covered wagon, it is versatile and can accommodate various types of cargo, including oversized items.

In terms of cost, transporting a train of these wagons typically ranges from €25,000 to €30,000 per train, which can be a cost-effective solution for large shipments compared to road transport. Ultimately, the choice of wagon type will depend on the specific logistical requirements, including volume, loading and unloading capabilities, and budget considerations. The covered wagon is particularly advantageous for large shipments, while the hooper and flatcar options provide flexibility for different types of cargo. Each method presents unique benefits that can be leveraged based on the operational context.

TABLE 15. TYPES OF TRANSPORT AND FORMS OF PUR FOAM

		Road	Rail
	• solid • 50-70 kg/m3	• „walking floor" trailer • 75 m3 • 1.5 euro / km	• covered wagon • 138 m3 • 30 wagons (4140 m3)
	• bigbag • 40-60 kg/m3	• dry freight trailer • 67 m3 • 1.3 euro / km	• covered wagon • 138 m3 • 30 wagons (4140 m3)
	• loose • 20-40 kg/m3	• dump body trailer • 55 m3 • 1.4 euro / km	• hooper wagon • 81 m3 • 40 wagons (2430 m3)
	• compacted • 200-400 kg/m3	• compactor trailer • 67 m3 • 1.2 euro • partialy owned equipment	• flatcar • 67 m3 • 30 wagons (2680 m3) • 25 - 30k euro per train

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5.4. Model assumptions

5.4.1. Data Overview and Assumptions

This section outlines the key data inputs and assumptions that form the basis for the foam recycling simulation. The dataset focuses on two primary elements: (1) buildings in the GSM area of Poland that contain foam in their structures, and (2) recycling collection points where foam can be collected, processed, and transported to Germany for final recycling.

5.4.2. Data on Buildings

The dataset includes **554 buildings** in the GZM area of Poland, each of which has used foam materials in its construction. These buildings vary in size, type, and year of construction. This information is critical in determining when the foam will become available for recycling upon the demolition of each building. The following data points are provided for each building:

- **Date of Construction**: The year the building was constructed. This allows us to estimate the demolition year based on the building's assumed life cycle.
- **Surface Area**: The total surface area of the building, which will be used to estimate the volume of foam available for recycling after demolition.
- **Geographic Location (Latitude and Longitude)**: Each building’s precise geographical coordinates are provided, allowing for the calculation of distances between the buildings and the recycling collection points.

5.4.3. Incorporating Household Appliance Foam (Bolecin Site)

In addition to the 554 buildings, the dataset includes a 555th entry representing foam generated from recycled household appliances at the Bolecin site. This collection point processes foam from items such as refrigerators and other household appliances. Since household appliance foam recycling is a significant source of PUR foam, its contribution is integrated into the overall simulation framework to ensure a more comprehensive analysis of foam demand in the region.

The Bolecin site generates an average of 57,670 m^3 of foam annually. To reflect this in the simulation, this value is evenly distributed across the months of the entire planning horizon. The annual foam generation is divided by 12 to give a constant monthly foam volume of approximately 4,805.83 m^3. This value is added as a new row in the building dataset (the 555th row), ensuring that the foam generated from household appliances is included in the total demand.

By adding this constant monthly demand, the simulation accounts for the foam recycling contributions from the Bolecin site throughout the entire planning horizon, enhancing the accuracy of foam demand estimations.

5.4.4. Demolition Timeline Assumption

In this simulation, it is assumed that each building will be demolished **25 years** after its construction date. For example, a building constructed in 1995 will be demolished in the year 2020, making its foam available for recycling in that year.

This demolition timeline is based on industry-standard estimates for the lifecycle of buildings that incorporate foam materials. However, it is important to note that the **25-year lifecycle assumption can be adjusted** if updated information becomes available from other sources. The generality of the framework ensures that such adjustments can be made without impacting the overall structure or performance of the model.

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5.4.5. Classification of Buildings

The dataset includes buildings classified into five categories based on their usage. These classifications are as follows:

1. **Industrial**: Factories and large industrial complexes.
2. **Manufacturing**: Facilities dedicated to production and manufacturing.
3. **Service**: Commercial buildings, including offices and service-based industries.
4. **Transportation**: Buildings related to transportation services, such as terminals and depots.
5. **Warehouse**: Storage facilities for goods and materials.

While these categories represent different building types, the same formula for calculating the extractable foam volume is applied uniformly across all building types. This assumption allows us to simplify the foam recycling process while still accounting for the varying sizes and purposes of the buildings.

5.4.6. Foam Volume Calculation

The volume of foam that can be extracted from each building is directly related to its surface area. The following formula is used to estimate the available foam volume based on the building's surface area:

$$Foam\ Volume\ (m^3) = \sqrt{Surface\ Area\ (m^2)} \times 4 \times 5 \times 0{,}12$$

Where:

- ***Surface Area (m²):*** The total surface area of the building, as provided in the dataset.
- $\sqrt{\boldsymbol{Surface\ Area}\ (\boldsymbol{m^2})}$: The square root of the surface area represents a scaling factor related to the dimensions of the building.
- $\boldsymbol{4 \times 5 \times 0{,}12}$: Conversion factor related to the specific characteristics of foam use in the building structure.

This formula is applied uniformly to all buildings, regardless of their type or classification, to calculate the volume of foam that can be extracted during demolition. For example, for a building with a surface area of 1,000 m², the foam volume would be calculated as follows:

$$Foam\ Volume\ (m^3) = \sqrt{1000} \times 4 \times 5 \times 0{,}12 = 75{,}89\ (m^3)$$

This calculated foam volume is critical for determining:

1. **Transportation Requirements**: The volume of foam that needs to be transported from the building to the nearest recycling collection point facilitated.
2. **Collection Point Processing**: How much foam each collection point will need to process and condense before transporting it to Germany.
3. **Cost Estimation**: Transportation and processing costs are directly linked to the foam volume, as costs are typically calculated on a per-cubic-meter (m³) basis.

By using this formula, the model ensures that the foam volume is consistently calculated across all buildings, providing a standardized input for further cost and logistics calculations.

5.4.7. Data on Recycling Collection Points

The dataset includes **32 potential recycling collection points** in the GSM area, which serve as candidate locations for collecting foam from demolished buildings. Each collection point is defined by its precise **geographical location (latitude and longitude)**, allowing us to calculate the distances between the buildings and the collection points, as well as from the collection points to Germany for further recycling.

The assignment of buildings to collection points will be optimized based on the total cost, which includes transportation costs, fixed costs, and operating costs. Only the collection points that offer a cost advantage will be facilitated.

To visualize the geographic distribution of the buildings and collection points, we provide the following map. **Blue points** represent the potential collection points, while **red points** represent the buildings containing foam materials. This spatial relationship is critical in determining the transportation costs for the model.

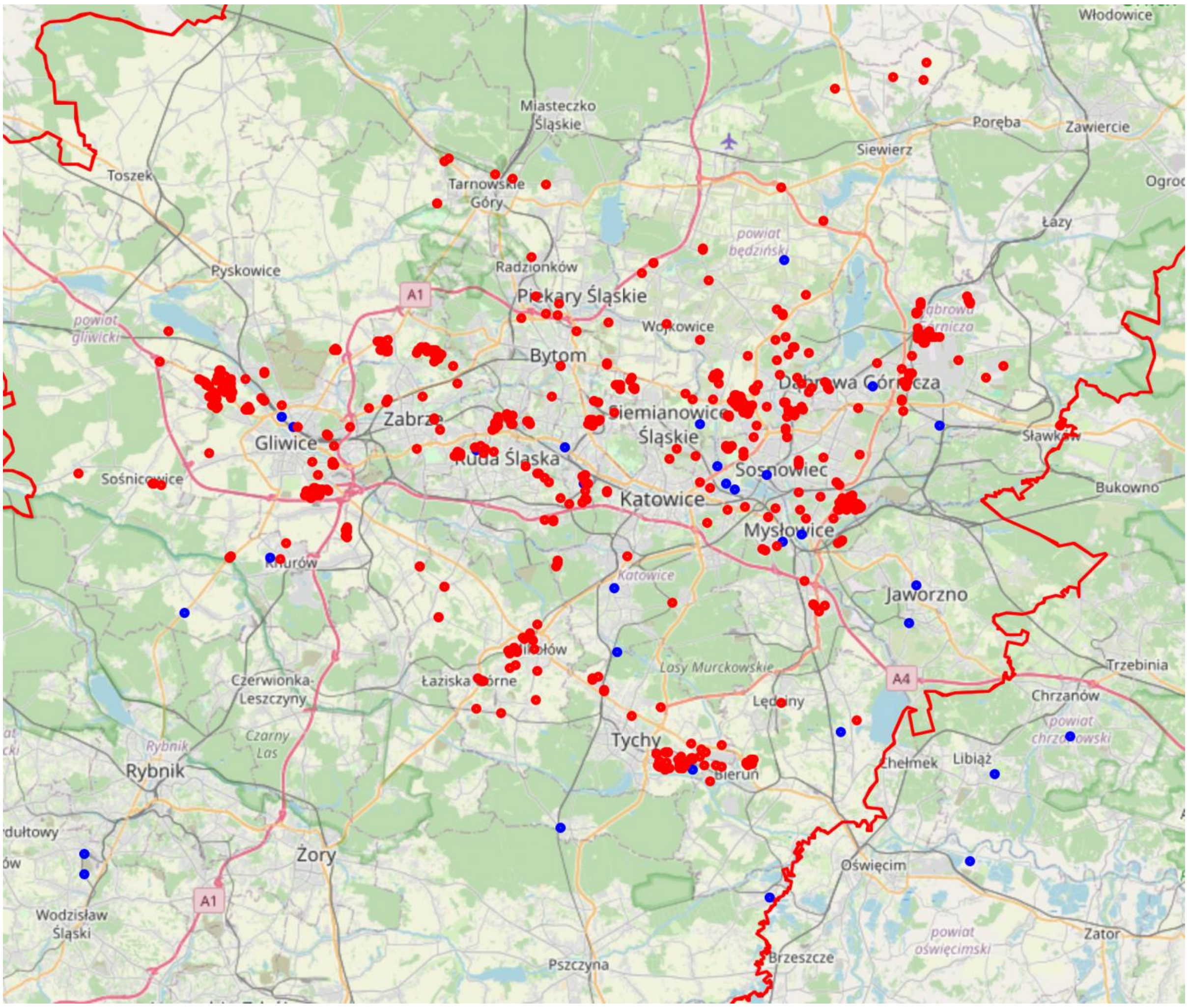

FIGURE 9. MAP OF THE GZM REGION SHOWING THE LOCATIONS POTENTIAL COLLECTION POINTS (BLUE) AND BUILDINGS CONTAINING FOAM MATERIALS (RED).

Below geographic distribution is used to calculate distances for the foam collection and transportation cost model

5.4.8. Transportation from Collection Points to Germany

Once foam is collected and condensed at the recycling collection points, it will be transported via **railway** to a recycling facility in Germany. While not all 32 collection points will necessarily be used, those that are facilitated will act as hubs for this transport. The decision to use a particular collection point is influenced by the total foam volume it can handle and the overall transportation costs from the building to the collection point and then onward to Germany.

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- **Direct Transport via Railway**: Foam is transferred directly from the facilitated collection points to a recycling facility in Germany. This transportation represents a significant portion of the overall cost, and optimizing the building-to-collection-point assignments helps minimize these expenses.
- **Internal Transportation within Poland**: Foam is transported from the demolition site to the collection points using trucks. The cost of this internal transportation is based on a rate per cubic meter per kilometer (m^3/km). However, specific cost values are applied later during the optimization phase to maintain the generality of the model.

5.4.9. Cost Structure and Assumptions

The total cost of foam collection, processing, and transportation is based on several key components, which are designed to be adjustable as new information becomes available. These components include fixed costs, operating costs, and transportation costs, as outlined below:

Fixed Costs for Collection Points

Each potential collection point incurs a **fixed cost** if it is selected and facilitated for use. These costs are one-time expenses that include:

- **Setup and Facilitation Costs**: The costs of preparing the collection point to receive, handle, and condense the foam. This may include acquiring the necessary machinery, setting up infrastructure, and staffing the facility.
- **Connection to the Railway Network**: One of the key fixed costs involves making the collection point capable of sending condensed foam directly to Germany via the railway network. This may include infrastructure upgrades, such as building or improving access to the nearest railway line, establishing loading facilities, and ensuring the collection point can handle the logistics of railway transport. The decision to facilitate a collection point will therefore depend on both its proximity to the main railway network and the cost of these connection upgrades.

The model will determine whether the fixed costs of facilitating a collection point, including railway connection costs, are justified by the volume of foam available for collection and the overall cost optimization strategy.

Operating Costs for Collection Points

Once a collection point is facilitated, it incurs monthly **operating costs**. These costs include:

- Labor costs for operating the collection point.
- Machinery operation and maintenance.
- The cost of condensing foam and preparing it for transport.

Operating costs are only incurred during the months when the collection point is active and processing foam.

Transportation Costs

- **Within Poland**: The cost of transporting foam from each building to its assigned collection point is calculated based on the volume of foam and the distance traveled. The transportation is done by trucks, and the cost is applied on a per-cubic-meter per kilometer (m^3/km) basis. This cost factor will be crucial in determining the most efficient assignments of buildings to collection points.
- **To Germany**: After the foam is condensed at the collection points, it is transported via railway to a recycling facility in Germany. The transportation costs for this leg of the journey depend on the total volume of foam and the distance between the collection point and the recycling facility. The decision to use specific collection points will factor in both the transportation costs and the fixed costs of connecting those points to the railway network.

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The cost structure is designed to remain flexible, ensuring that changes in building lifecycles, demolition timelines, or transportation costs can be incorporated without requiring major modifications to the model. This adaptability ensures that the model can accommodate new data from other work packages in the project, such as updated cost factors, foam volume calculations, or additional constraints related to railway or truck transport.

5.4.10. Generality of the Model

While this methodology is based on a **25-year building lifecycle**, the framework is flexible and can accommodate changes to the lifecycle assumption if new data becomes available. For instance, if it is later determined that buildings have a longer or shorter lifecycle, the demolition timeline can be adjusted accordingly without impacting the structure of the model. The foam volume calculations, cost structure, and transportation logistics remain valid regardless of the specific timeline, ensuring the model is robust and adaptable.

5.5. Mathematical Model

The core objective of the foam recycling project is to minimize the total cost of transporting foam from demolished buildings to collection points within the GSM area of Poland and then further transporting it to Germany for recycling. This section outlines the mathematical model used to optimize the assignment of buildings to collection points and the selection of collection points to be facilitated.

5.5.1. Objective

The goal is to minimize the **total cost**, which includes:

1. **Transportation costs** from buildings to collection points (via trucks).
2. **Fixed costs** of facilitating collection points, which include setup and connection to the railway network.
3. **Operating costs** for the collection points, incurred monthly as long as the collection point is operational.
4. **Transportation costs** from the collection points to the recycling facility in Germany (via railway).

5.5.2. Decision Variables

The decision variables in this optimization problem are both binary and continuous. They include the following:

Binary Variables:

- X_{mjc}: A binary decision variable that indicates whether foam (PUR) demand from building *j* in month *m* is sent to potential collection point *c*:

$$X_{mjc} = \begin{cases} 1, & \text{if demand from building j in month m is sent to collection point c} \\ 0, & \text{otherwise} \end{cases}$$

- S_c: A binary decision variable indicating whether potential collection point *c* is opened (facilitated):

$$S_c = \begin{cases} 1, & \text{if collection point c is opened} \\ 0, & \text{otherwise} \end{cases}$$

- WM_{cm}: A binary decision variable indicating whether collection point *c* is operational (working) in month *m*:

$$WM_{cm} = \begin{cases} 1, & \text{collection point c is working in month m} \\ 0, & \text{otherwise} \end{cases}$$

Positive Continuous Variables:

- P_c: A continuous variable representing the **total amount of PUR foam** accumulated at collection point *c* during the planning horizon:

$$P_c \geq 0$$

- *TC*: A continuous variable representing the **total cost** to be minimized. This includes all transportation, fixed, and operating costs throughout the planning horizon.

5.5.3. Cost Components

Transportation Costs (Buildings to Collection Points)

The transportation cost from each building to a collection point is based on the **distance** between the building and the collection point, the **amount of foam generated** in a specific month, and the **capacity of the trucks** used for transport. The transportation cost for sending foam from building *j* in month *m* to collection point *c*, denoted as $cost_{mjc}$, is calculated as follows:

$$cost_{mjc} = \left\lceil \frac{D_{j_m}}{Truck\ Capacity} \right\rceil \times Distance(j, c) \times ct$$

Where:

- $\boldsymbol{D_{jm}}$ is the foam volume generated from building *j* in month *m*.
- **Truck Capacity** is the volume (in cubic meters) that each truck can carry.
- $\boldsymbol{Distance(j, c)}$ is the distance between building jjj and collection point ccc in kilometers.
- $\boldsymbol{ct}$ is the cost per kilometer per truck.

The **ceiling function** $\left\lceil \frac{D_{j_m}}{Truck\ Capacity} \right\rceil$ ensures that the number of trucks required to transport the foam is always rounded up to the nearest whole number, as fractional trucks are not possible. This number is then multiplied by the distance and the cost per kilometer for each truck, *ct*, to give the total transportation cost for that month.

Fixed Costs for Facilitating Collection Points

The fixed cost of facilitating collection point *c*, denoted as cf_c, includes:

- The cost of setting up the collection point for foam processing and condensation.
- The cost of connecting the collection point to the railway network for transportation to Germany.

This fixed cost is incurred if and only if collection point *c* is opened, i.e., $S_c = 1$.

Operating Costs for Collection Points

Each collection point that is opened incurs monthly **operating costs**, denoted as co_c. These costs include:

- Labor and operational costs for collecting and condensing foam.
- Overhead and maintenance costs for each month *m* that the collection point *c* is operational.

Transportation Costs (Collection Points to Germany)

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Once foam is collected and condensed at the collection points, it is transported to a recycling facility in Germany via railway. The transportation cost for sending foam from collection point ccc to Germany, denoted as tct_ctc, depends on:

- The total **volume of foam** accumulated at collection point ccc.
- The **condensing factor**, which reduces the volume of foam before transport.
- The **distance** from collection point ccc to the recycling facility in Germany.
- The **unit cost per m³** for railway transport.

The transportation cost factor to Germany is calculated as follows:

$$TG_c = \frac{Distance(c, recycling\ point\ in\ Germany) \times railway\ cost\ per\ m^3}{Condensing\ Factor}$$

The term $\frac{1}{Condensing\ Factor}$ gives the effective volume of foam that needs to be transported after condensation, and this volume is multiplied by the distance and the unit railway cost to calculate the total transportation cost.

5.5.4. Objective Function

The objective of the model is to minimize the total cost, *TC*, which includes:

1. Transportation costs from buildings to collection points (via trucks).
2. Fixed costs for opening and facilitating collection points.
3. Operating costs for collection points on a monthly basis.
4. Transportation costs from collection points to Germany (via railway), which account for the foam condensing factor.

TC can be expressed as follows:

$$\min TC = \sum_{c \in C} S_c \times cf_c + \sum_{m \in M} \sum_{c \in C} WM_{cm} \times co_c + \sum_{c \in C} \sum_{j \in J} \sum_{m \in M_j} X_{mjc} \times cost_{mjc} + \sum_{c \in C} P_c \times TG_c$$

5.5.5. Constraints

The optimization model is subject to the following constraints:

1. Demand Assignment Constraint: Foam from each building in a given month must be assigned to exactly one collection point:

$$\sum_{c \in C} \boldsymbol{X_{jmc} = 1} \quad \forall \boldsymbol{j \in J, m \in M_j}$$

2. Collection Point Facilitation Constraint: A collection point can only receive foam if it is opened and facilitated:

$$\sum_{j \in J} \sum_{m \in M_j} \boldsymbol{X_{mjc} \leq S_c \times |C| \times |M_j|} \quad \forall \boldsymbol{c \in C}$$

3. Collection Point Operation Constraint: A collection point can receive foam only if it operates in month *m*:

$$\sum_{j \in J \mid m \in M_j} \boldsymbol{X_{mjc} \leq WM_{cm} \times bigM} \quad \forall \boldsymbol{c \in C, m \in M}$$

4. **PUR Accumulation Constraint**: The total amount of PUR foam accumulated at collection point ccc must equal the sum of foam assigned to it over the entire planning horizon:

$$P_c = \sum_{j \in J} \sum_{m \in M_j} D_{jm} \times X_{mjc} \quad \forall c \in C$$

5.5.6. Generality and Flexibility of the Model

This mathematical model provides a flexible framework for optimizing the foam recycling process. It can accommodate changes to:

- **Building lifecycles**: If the demolition timeline changes, the model can adjust the month-wise foam generation and collection.
- **Cost factors**: All cost components, such as transportation rates, fixed setup costs, and operating expenses, can be modified and replaced as new data becomes available.

5.5.7. Parameter Values and Model Inputs

In this section, we define the specific parameter values and inputs used to solve the mathematical model for optimizing the foam recycling process. These values are based on the data provided, including assumptions about demolition timelines, foam availability, and transportation costs.

Building Data and Demolition Timeline

- Number of Buildings: 554 buildings in the GSM area.
- Expected Demolition Year: For each building, the expected demolition year is calculated based on the construction date and the assumption that the building will be demolished 25 years after construction.

Demolition Timeline:

- **Demolition Season**: Buildings are typically demolished during the summer season to avoid unfavorable weather (e.g., rain, snow). Therefore, it is assumed that the demolition process will occur during the months of March to September.
- **Demolition Rate *dt***: The demolition time for each building depends on the parameter *dt*, which indicates the number of square meters that can be demolished per day. For this dataset, we assume that the demolition rate is 600 m^2/day.
- **Demolition Timeframe**: For each building, the total demolition time is distributed across the months between March and September. In cases where the building is large and the demolition rate is low, the demolition process may exceed this summer period.

Foam Availability Calculation

- **Monthly Distribution of Foam Availability**: The total foam volume for each building is calculated, and this total volume is evenly distributed across the days in the demolition period.
- **Monthly Foam Volume D_{jm}**: The foam available from building *j* in month *m* is calculated by dividing the total foam volume for the building by the number of days in the demolition period. This volume is then aggregated into monthly values based on the number of demolition days in each month.

Truck and Transportation Costs (Building to Collection Point)

- **Truck Capacity**: Each truck has a capacity of 40 m^3.
- **Transportation Cost per Kilometer *ct***: The cost for transporting foam via truck is 16 PLN/km per truck.
- **Distance Data**: The distances between buildings and potential collection points are provided based on the geographical locations of the buildings and collection points.

Collection Point Costs

- **Fixed Cost for Facilitating Collection Point cf_c**: The fixed cost for opening and facilitating a collection point is set to 100,000 PLN. This cost includes setting up the collection point to handle foam and connecting it to the railway network.
- **Monthly Operating Cost co_c**: The operating cost for a collection point that is active in a given month is 15,000 PLN/month. This cost covers labor, machinery, and maintenance for collecting and condensing foam.

Condensing Factor and Transportation to Germany

- **Condensing Factor**: Foam collected at the collection points is reduced in volume by a condensing factor of 10. This means the foam volume is reduced to one-tenth of its original size before being transported to Germany.
- **Railway Transportation Cost per Cubic Meter**: The cost of transporting foam from collection points to the recycling facility in Germany via railway is 30 PLN/m³

5.6. Results and Analysis

This section presents the key outcomes from the foam recycling optimization model, including the selection of collection points, the operational timeline, foam accumulation, and associated costs. Visualizations are provided to illustrate how foam flows from buildings to collection points, the costs involved, and the months in which collection points are active.

5.6.1. Collection Point Selection

The optimization model identifies 2 collection points that are opened and facilitated for foam collection and transport. These points are chosen based on the cost minimization strategy, which considers factors such as transportation costs, fixed setup costs, and the volume of foam generated by the demolished buildings.

- **Opened Collection Points**:
  - **Point 1**: [*Jamicon Katowice*]
  - **Point 2**: [*Wostal Gliwice*]

A map is provided below, showing the geographical distribution of the buildings and collection points. The map highlights which collection points were selected and the buildings assigned to each collection point.

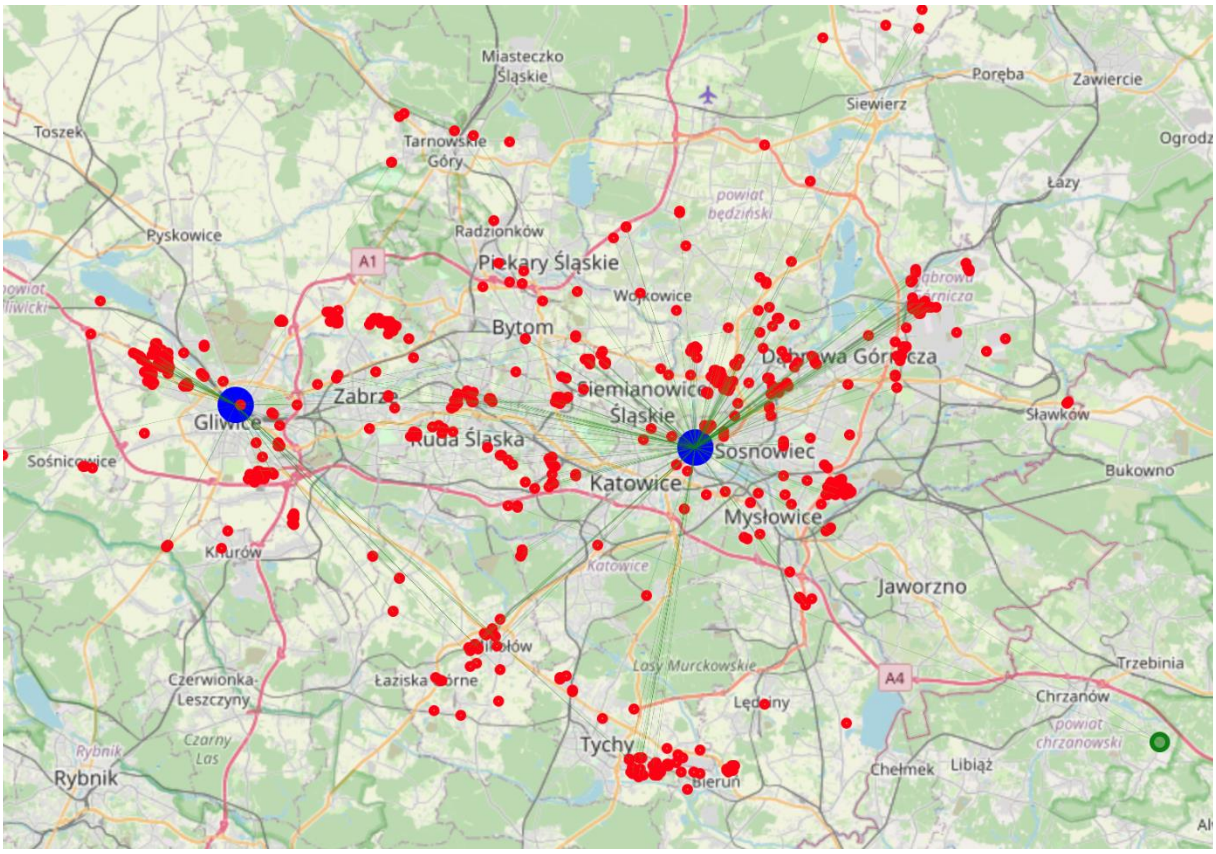

FIGURE 10. SELECTED COLLECTION POINTS AND THEIR ASSIGNED BUILDINGS

5.6.2. Total Cost Breakdown

The total cost for the foam recycling process is broken down into several components:

1. **PSZOK Costs:** The one-time setup costs for facilitating each collection point and operating costs
2. **Condensing Costs**: Cost of condensing foam in PSZOK locations.
3. **Transportation Costs**: Costs for transporting foam from the buildings to the collection points via trucks
4. **Transportation to Germany**: Costs for transporting the condensed foam from the collection points to the recycling facility in Germany via railway.

A breakdown of the total cost is provided below, showing the contribution of each component to the overall cost.

TABLE 16. COSTS FOR SELECTED TRANSPORT OPTIONS OF PUR FOAM

Cost Component	Covered Solid	Covered BigBag	Hooper	Flatcar
PSZOKS costs	702 845	702 845	702 845	702 845
Condensing costs	913 551	606 892	200 225	3 752 150
Transport by vehicle	39 344	39 344	39 344	39 344
Transport to GERMANY cost	338 694	403 129	906 366	284 319

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101036854

Cost Component	Covered Solid	Covered BigBag	Hooper	Flatcar
Total Cost	1 994 435	1 752 210	1 848 780	4 778 658

5.6.3. CO2 emission results

As global awareness of climate change intensifies, understanding the impact of different solutions on CO2 emissions has become crucial. This analysis aims to evaluate various strategies and their effectiveness in reducing carbon emissions. By comparing these solutions, we can identify the most sustainable options that contribute to a greener future. This study will explore alternative energy sources, technological innovations, and policy implementations, providing insights into their potential to mitigate climate change.

TABLE 17. CO2 EMISSION FOR SELECTED TRANSPORT OPTIONS OF PUR FOAM

CO2 emission componanet [t]	Covered Solid	Covered BigBag	Hooper	Flatcar
Truck	13 896	13 896	13 896	13 896
Train	14 341	12 748	18 590	58 426
Total annual emission [t]	28 237	26 644	32 486	72 322

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