UNIVERZA NA PRIMORSKEM
FAKULTETA ZA MATEMATIKO, NARAVOSLOVJE IN
INFORMACIJSKE TEHNOLOGIJE

Master's thesis
(Magistrsko delo)

Discrete-Event Simulation Model for Wood Waste Reverse Supply Chains

(Simulacijski model diskretnih dogodkov za reverzne dobavne verige lesnih odpadkov)

Ime in priimek: *Nikola Kovačević*
Študijski program: *Podatkovna znanost, 2. stopnja*
Mentor: *doc. dr. Balázs Dávid*
Somentor: *dr. Črtomir Tavzes*

Koper, 2025

Ključna dokumentacijska informacija

Ime in PRIIMEK: Nikola KOVAČEVIĆ

Naslov magistrskega dela: Simulacijski model diskretnih dogodkov za reverzne dobavne verige lesnih odpadkov

Kraj: Koper

Leto: 2025

Število listov: 45 Število slik: 25 Število tabel: 4
Število prilog: 4 Število strani prilog: 4
Število referenc: 58

Mentor: doc. dr. Balázs Dávid

Somentor: dr. Črtomir Tavzes

Ključne besede: simulacija diskretnih dogodkov, reverzna dobavna veriga, lesni odpadki, krožno gospodarstvo, politika zalog

Izvleček: Reverzne dobavne verige za lesne odpadke so težavne za optimizacijo zaradi razdrobljenih podatkov in razpršenih procesov. V nalogi razvijemo (i) interaktivno vizualizacijsko orodje na osnovi uradnih regionalnih podatkov ARSO (2016–2023) za usklajevanje in analizo tokov nastajanja, zbiranja in obdelave ter (ii) SimPy-temeljeni simulacijski model diskretnih dogodkov (DES) za slovensko reverzno verigo, parametriziran s politiko zalog (PUSH proti PULL) in strategijo zalog (ON_DEMAND, REORDER_50, REORDER_90). Model zajema logistiko prevoza, kapacitetne omejitve, odločitve ob prekoračitvah in signaliziranje povpraševanja med generatorji, zbiralci in predelovalci. Šest konfiguracij (2 × 3) ocenimo s 100 ponovitvami Monte Carlo z analizo strošek-okoljski vpliv, poročamo o storitveni ravni, skupnih emisijah, odlaganju na odlagališču, izkoriščenosti skladiščenja in učinkovitosti. Analiza razkriva pomembne kompromise med konfiguracami dobavne verige. PULL ON_DEMAND se izkaže kot optimalna strategija, ki doseže tako najnižji okoljski vpliv (pod 1M kgCO_2e) kot najnižje stroške (pod 25M €). PUSH ON_DEMAND kaže rahlo slabšo uspješnost s stroški pod 30M € in emisijami okoli 1,25M kgCO_2e. REORDER_50 politike kažejo zmerne povečanja obeh metrik, pri čemer PULL konfiguracije zahtevajo 31M € in proizvajajo približno 1M kgCO_2e, medtem ko PUSH variante stanejo okoli 34M € z 1,3M kgCO_2e emisijami. REORDER_90 strategije predstavljajo najmanj ugodno možnost, zlasti za PULL sisteme, ki zahtevajo 58M € in proizvajajo 2,4M kgCO_2e emisij. Predlagani okvir, ki združuje analitiko in simulacijo, dokazuje, da ON_DEMAND strategije, zlasti v PULL konfiguracijah, ponujajo superiorňo uspješnost v ekonomski in okoljski dimenziji ter zagotavljajo obnovljiv pristop za testiranje politik in podporo prednostni obravnavi materialnih tokov z večjo vrednostjo v okviru ciljev krožnega gospodarstva.

Key document information

Name and SURNAME: Nikola KOVAČEVIĆ

Title of the thesis: Discrete-Event Simulation Model for Wood Waste Reverse Supply Chains

Place: Koper

Year: 2025

Number of pages: 45 Number of figures: 25 Number of tables: 4
Number of appendices: 4 Number of appendix pages: 4
Number of references: 58

Mentor: Assist. Prof. Balázs Dávid, PhD

Co-Mentor: Črtomir Tavzes, PhD

Keywords: discrete-event simulation, reverse supply chain, wood waste, circular economy, inventory policy

Abstract: Reverse supply chains for wood waste remain difficult to optimize due to fragmented data and isolated operations. This thesis develops (i) an interactive visualization tool built on ARSO's official regional datasets (2016–2023) to harmonize and analyze generation, collection, and treatment flows, and (ii) a SimPy-based discrete-event simulation (DES) of Slovenia's reverse chain parameterized by inventory policy (PUSH vs. PULL) and stock strategy (ON_DEMAND, REORDER_50, REORDER_90). The transport logic, capacity constraints, overflow decisions, and demand signaling are modeled to capture system dynamics across generators, collectors, and treatment operators. Six policy configurations (2×3) are evaluated via 100-run Monte Carlo experiments through cost-environmental impact analysis, reporting service level, total emissions, landfill overflow, storage utilization, and efficiency. The analysis reveals significant trade-offs across supply chain configurations. PULL ON_DEMAND emerges as the optimal strategy, achieving both the lowest environmental impact (under 1M $kgCO_2e$) and lowest cost (under 25M €). PUSH ON_DEMAND demonstrates slightly degraded performance with costs under 30M € and emissions around 1.25M $kgCO_2e$. REORDER_50 policies show modest increases in both metrics, with pull configurations requiring 31M € and generating approximately 1M $kgCO_2e$, while push variants cost around 34M € with 1.3M $kgCO_2e$ emissions. REORDER_90 strategies represent the least favorable option, particularly for pull systems, which demand 58M € and produce 2.4M $kgCO_2e$ emissions. The combined analytics–simulation framework demonstrates that ON_DEMAND strategies, especially in pull configurations, offer better performance across both economic and environmental dimensions, providing a reproducible approach for policy testing and supporting prioritization of high-value material pathways within circular economy goals.

List of Contents

List of Tables

List of Figures

List of Appendices

List of Abbreviations

i.e.	that is
e.g.	for example
EWC	European Waste Catalogue
ARSO	Slovenian Environment Agency
DES	Discrete Event Simulation
KPIs	Key Performance Indicators
FIFO	First-In-First-Out
LIFO	Last-In-First-Out
MDPs	Markov Decision Processes
RL	Reinforcement Learning
JIT	Just-In-Time
OSB	Oriented Strand Board
MDF	Medium-Density Fiberboard

If all that awaits is the void, why cling to a single idea?

Lear,
Nine Sols, 2024

ACKNOWLEDGMENTS

I would like to thank my supervisors Assist. Prof. Balázs Dávid, PhD and Črtomir Tavzes, PhD, for their guidance throughout this two-year journey. It has been exciting to experience how the research scope evolved over the months and how our shared ambitions to showcase ideas continued growing. My sincere appreciation goes to them for their expertise and mentorship, which were essential to both my development as a researcher and the realization of this research.

This academic milestone could never have been reached without the constant support of my family and friends. Through moments of doubt, and the times I had to miss moments with them, they remained my source of motivation.

Most of all, this work would not have been possible without the encouragement of my girlfriend and best friend Une Vuletić. Her support, especially when I felt I had reached a dead end, consistently gave me the strength to push forward.

I dedicate this work to my sisters, Aleksandra-Milica and Teodora, hoping to demonstrate what we are all capable of achieving.

1 INTRODUCTION

Wood waste is a growing environmental and economic concern worldwide, driven by construction, manufacturing, and demolition activities. If not managed properly, it represents both a lost resource and a significant burden—contributing to greenhouse gas emissions, pollution, and rising landfill costs. Recent years have seen an increase in wood waste generation due to expanding construction sectors, including a big increase in renovations/refurbishments for structural and energy improvements of the building stock, alongside growing demand for wood-based packaging, contributing to these challenges [54].

The environmental and economic consequences of wood waste mismanagement are profound. Conventional disposal methods, such as land-filling and incineration, release harmful greenhouse gases like methane and carbon dioxide, while slow decomposition under anaerobic conditions creates long-term environmental hazards [41, 49]. Beyond ecological damage, improper disposal poses public health risks due to associated pollution, further underscoring the urgency of sustainable solutions [40]. At the same time, wood waste remains a vastly underutilized resource, with substantial volumes that could be repurposed into valuable raw materials or energy sources if managed effectively [3, 36]. For instance, converting wood waste into bio-energy or composite building materials offers promising pathways for economic growth and resource efficiency, aligning with circular economy principles [20, 35]. Countries like Slovenia, with abundant wood resources, are well-positioned to adopt sustainable waste management practices that prioritize reuse and life-cycle extension, demonstrating the feasibility of such approaches [26].

To fully realize these opportunities, effective reverse supply chains are essential. Unlike traditional forward supply chains, which move products from raw materials to consumers, reverse supply chains focus on recovering value from used products through collection, reprocessing, and redistribution [27, 44]. Wood waste—whether in the form of sawmill residues, wood chips, or demolition debris—presents unique logistical and environmental challenges, but also significant potential for energy recovery and impact reduction [18]. However, transitioning to a circular economy for wood waste requires overcoming systemic barriers, including gaps in implementing reuse and recycling strategies at scale [19]. One major obstacle is the logistical cost associated with low energy density and transportation inefficiencies, particularly in utilizing forestry residues and dispersed wood waste streams [56].

Addressing these challenges requires innovative approaches to optimize wood waste recovery. This thesis first develops a visualization tool based on real-world data to analyze existing wood waste flows and system dynamics, which informed the design and structure of a discrete-event simulation (DES) model for reverse supply chains in wood waste management, drawing on existing research [21]. By integrating waste generation, collection, transport, and treatment processes within a simulation framework, the study explores strategies for maximizing resource recovery across different scenarios. The transport system operates at two levels: from generators to collection centers with capacity and distance constraints, and from collection centers and treatment facilities using priority-based scheduling and travel time calculations. The goal is to provide insights that bridge the gap between theoretical circular economy principles and practical, scalable solutions for wood waste management.

The model framework prioritizes maximal biogenic carbon storage through a hierarchical approach that emphasizes higher-value products over lower-value ones. This strategy recognizes that different wood waste recovery pathways offer varying degrees of carbon sequestration potential and economic value.

This thesis is structured as follows: (i) Chapter 2 examines related work in detail; (iii) Chapter 3 defines the research problem, objectives, scope, and limitations; (iv) Chapter 4 describes the development of the visualization tool, including data cleaning, harmonization, and plot generation to analyze waste flow patterns by categories and types over time; (v) Chapter 5 presents the discrete event simulation (DES) model developed based on the insights from the visualization tool; (vi) Chapter 6 discusses results and findings; and (vii) Chapter 7 concludes the thesis.

2 LITERATURE REVIEW

The integration of wood waste into sustainable supply chains has gained significant attention as industries worldwide strive to enhance resource efficiency and mitigate environmental impacts. Various case studies illustrate innovative strategies for converting wood waste into valuable resources across multiple sectors, particularly in energy production, material recycling, and composite manufacturing.

Management of biomass within supply chains faces inherent challenges, notably around uncertainty in wood quality and availability. Robust scheduling mechanisms that consider variability in delivery processes, alongside improved logistics, are critical to optimizing supply chain operations for wood waste [10].

2.1 WOOD WASTE REVERSE SUPPLY CHAINS

Supply chains traditionally focus on the forward flow of materials and products. A supply chain is defined as a system of organizations, people, activities, information, and resources involved in moving a product or service from supplier to customer, involving the transformation of natural resources, raw materials, and components into a finished product delivered to the end customer [53]. However, the linear "take-make-dispose" model has evolved to include reverse flows. Reverse supply chain management (RSCM) is defined as the effective and efficient management of the series of activities required to retrieve a product from a customer and either dispose of it or recover value [44]. These reverse supply chains consist of activities required to collect used products from consumers and reprocess them to either recover their leftover market values or dispose of them. It has become increasingly common for companies involved in traditional forward supply chains to also carry out collection and reprocessing of used products, creating integrated forward and reverse supply chain systems [27].

Reverse logistics in the wood-product sector encompasses the bidirectional flow of materials from consumer back to producer or specialized processors, aimed at recovering value through reuse, recycling, re-manufacturing, energy recovery, or safe disposal [8]. This approach aligns with evolving European bio-economy and circular-economy frameworks, driven by regulatory initiatives such as the EU Sustainable Development Strategy and the 2012 Bioeconomy for Europe initiative [9, 15]. Central to effective wood waste management is the concept of cascading use, whereby reclaimed wood undergoes successive down-cycling through high-value applications—from structural reuse to particleboard feedstock—before final energy recovery, thereby maximizing carbon storage while reducing virgin material demand [8].

The practical implementation of these principles reveals significant complexity in operational frameworks. Germany's waste wood supply chain exemplifies this challenge, particularly regarding A I category materials—untreated or mechanically treated wood suitable for direct material and energy recovery. Current legislative incentives under policies like the Renewable Energy Act (EEG 2017) [23] inadvertently bias most A I flows toward incineration rather than higher-value cascade applications. This misalignment demonstrates how regulatory frameworks can undermine circular economy objectives despite well-intentioned design. The hierarchical decision-making structure (as seen on Figure 1) governing these systems spans strategic site and technology selection, tactical collection and transport logistics, and operational sorting and processing workflows, with performance heavily influenced by seasonal availability, facility location, and throughput capacities [14, 24].

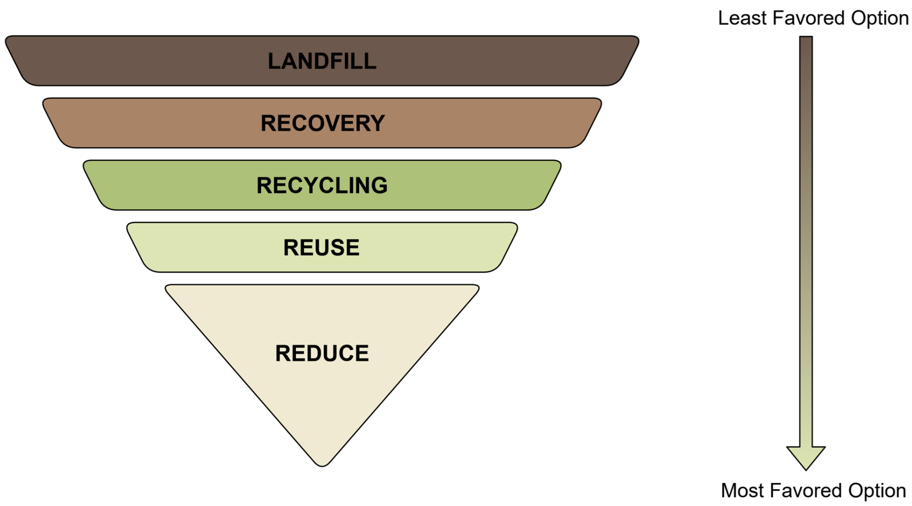

Figure 1: Scheme of the European Waste Framework Directive [14, 24].

Cross-border collaboration emerges as a crucial strategy for optimizing resource utilization and overcoming domestic market limitations. The Lithuania-Poland biomass trade exemplifies how international cooperation can enhance forest preservation while advancing sustainable energy production. Rather than relying solely on productive wood or fossil fuels, these integrated networks efficiently utilize wood waste streams including branches, bark, and stumps. This cluster-based approach reduces transportation and storage costs while minimizing air pollution, demonstrating that transnational reverse supply chains can simultaneously address economic efficiency and environmental protection [58].

The comprehensive nature of wood waste reverse supply chains involves a diverse network of stakeholders spanning sawmills, panel producers, demolition firms, recyclers, transport providers, and municipal waste collectors. These actors coordinate complex logistical processes—collection, transportation, transshipment, labeling, and storage—alongside technological operations including quality control, sorting, drying, cleaning, fractionation, and densification. However, this complexity introduces substantial challenges: seasonal and spatial dispersion of biomass sources, wide variability in material form and contamination levels, high processing costs, and insufficient information systems for post-consumer wood recovery. Despite these obstacles, significant opportunities exist for enhancing circularity through expanded biomass energy production, innovative decontamination technologies, strengthened collection infrastructures, and increased community awareness of wood's reuse potential [32].

Addressing the fragmentation that often hinders closed-loop implementation, recent research has proposed comprehensive frameworks for integrating up-cycling into wood-waste reverse supply chains. Mojica et al. [39] advance a four-pillar approach that reorganizes conventional supply chain agents to incorporate secondary-material valorization, establishes formal ”secondary materials manager” roles for overseeing collection and processing, deploys digital tools for material tracking and stakeholder coordination, and creates collaborative governance structures aligning manufacturers, waste managers, designers, and policymakers. This holistic template extends material lifecycles while reducing reliance on virgin timber, offering practical guidance for designing sustainable, closed-loop logistics networks in both domestic markets and cross-border contexts [39].

The evolution of wood waste reverse supply chains demonstrates both the potential and limitations of circular economy implementation. While regulatory frameworks provide necessary direction, their translation into effective operational systems requires careful attention to economic incentives, technological capabilities, and cross-border coordination mechanisms.

2.2 CASE STUDIES IN WOOD SUPPLY CHAINS

Reverse logistics, as a core component in the operationalization of a circular economy, plays a pivotal role in ensuring the effective re-integration of wood waste into the supply chain. Borges et al. [7] contend that such reverse flows challenge the conventional “take-make-dispose” model by promoting recycling, reusing, and re-manufacturing of materials.

Closed-loop supply chain practices are increasingly advocated for their potential to minimize waste and enhance resource utilization in wood-related industries. These practices emphasize the recovery and recycling of wood materials, which can lead to substantial reductions in waste generation and environmental pollution [49]. For instance, research indicates that leveraging wood waste as a bio-energy feedstock can produce significant emissions savings while optimizing local and regional waste management strategies [48]. As mentioned in the Section 2.1, effective supply chain processes that utilize wood waste can also contribute positively to forest preservation and enhance energy efficiency in biomass energy production [58].

Farjana and Ashraf [19] developed an integrative conceptual framework and accompanying system dynamics model to identify and map the key performance indicators (KPIs) that drive sustainability in closed-loop wood waste supply chains. Starting with a harmonization of existing classification schemes, they adopt the manufacturing-process taxonomy (untreated, treated, engineered wood) and delineate six life-cycle stages—collection, screening, quality control, recovery/disposal, recycling (direct and indirect), reuse, and energy recovery. By analyzing environmental and socio-economic "hotspots" at each stage, the authors extract twelve critical KPIs (e.g. transportation distance, separation strategy, cascading potential, material circularity index) and illustrate their inter-dependencies via a causal-loop system dynamics diagram. Computational insights highlight how variations in these KPIs can inform policy and operational decisions to maximize circularity, minimize environmental impact, and balance stakeholder costs and benefits [19].

2.3 DATA INTEGRATION CHALLENGES

Data integration challenges in reporting final waste numbers are a significant impediment to achieving accurate, comprehensive, and reliable waste management systems. One of the core issues is the inherent heterogeneity of data sources. Waste management systems often amalgamate information from various origins such as operational logs, sensor data, manual records, and institutional reports. This heterogeneity can result in inconsistent data formats, differing classification schemes, and varying reporting intervals, all of which contribute to double counting or the omission of key data elements [33].

A particularly salient challenge is the reconciliation of data throughout different stages of the waste management life-cycle—from generation, collection, transport, to final disposal. Studies examining extractive waste in Poland have highlighted that even with European Union regulations, there remain issues in producing complete, consistent, and integrated waste reports. In these cases, data from multiple sources are often not aligned due to disparate recording practices and a lack of standardized reporting frameworks, complicating the accurate assessment of waste that reaches the final disposal stage [33].

2.4 INVENTORY MANAGEMENT

Inventory management represents a critical component of supply chain operations, encompassing the strategic planning, implementation, and control of material flows from suppliers to end customers. Singh and Verma define inventory management as "the continuing process of planning, organizing and controlling inventory that aims at minimizing the investment in inventory while balancing supply and demand" [53]. This process requires balancing competing requirements such as service levels, cost minimization, and asset utilization, which becomes increasingly complex as business needs evolve. The scope extends beyond simple stock control to include replenishment lead time optimization, carrying cost management, demand forecasting, and quality management considerations.

Modern inventory management has evolved to incorporate sophisticated analytical approaches that optimize different aspects of inventory control. ABC analysis categorizes inventory items into three classes based on their value and importance to the business, enabling prioritized management strategies [17, 22, 46]. Just-in-Time (JIT) methodology minimizes inventory holding costs by receiving goods only when needed for production or sale, thereby reducing storage expenses [17, 29]. Similarly, Order on Demand maintains minimum inventory quantities, ordering products only as customers place orders [12].

Inventory valuation methods such as First-In-First-Out (FIFO) and Last-In-First-Out (LIFO) provide different approaches to cost accounting with distinct tax implications. FIFO assumes the oldest inventory is sold first while LIFO assumes the newest inventory is sold first, directly impacting financial reporting and inventory turnover calculations [11]. Technological advancements have transformed inventory control through AI integration, specialized software, bar-code systems, and cloud-based platforms that provide real-time visibility and enable data-driven decision making. Reinforcement learning (RL) has emerged as a particularly promising approach for solving complex inventory management problems modeled as Markov Decision Processes (MDPs). RL teaches agents optimal control policies through simulation-based learning, utilizing exploitation and exploration mechanisms in the interaction between learning agents and their environment, making it well-suited for dynamic inventory optimization in complex supply chain scenarios [17, 25].

Recent research has focused on incorporating environmental considerations into inventory management frameworks. Babaeinesami et al. [5] propose a multiechelon, closed-loop supply chain model for wood products that explicitly incorporates environmental pollution costs into inventory control. Their mixed-integer programming formulation spans five echelons (suppliers, factories, wholesalers, retailers, recovery centers) and minimizes total logistics, production, shortage, and environmental penalty costs.

To solve large-scale instances efficiently, they customize a genetic algorithm—tuned via the Taguchi method [30]—to handle raw-material and product flows, vehicle routing frequencies, and storage capacities. Their computational experiments demonstrate that the genetic algorithm achieves near-optimal costs compared to exact solutions while drastically reducing runtime, with sensitivity analysis revealing that production and environmental costs are most responsive to demand fluctuations [5].

Building on circular economy principles, Aiello et al. [2] propose a stochastic inventory model for closed-loop supply chains that explicitly embeds the four "R" options (reduce, reuse, recycle, recover) into ordering decisions. By extending the classic newsvendor framework, they introduce parameters for the fraction of returned items routed to each recovery path, factoring in both collection costs and variable salvage values based on product condition. Their numerical experiments quantify how adopting a circular strategy—versus a linear one—lowers optimal order quantities and leftover stock but increases lost sales, a trade-off they term the "cost of circularity" [2]. In the context of reverse supply chains, inventory management becomes particularly complex as it must accommodate bidirectional material flows, including returned products, defective goods, and waste materials requiring processing or disposal. For wood waste reverse supply chains, this involves managing collection, sorting, processing, and redistribution of waste materials while maintaining operational efficiency and minimizing environmental impact. [50]

2.5 DISCRETE-EVENT SIMULATION IN SUPPLY CHAIN MANAGEMENT

Discrete-Event Simulation (DES) has emerged as a powerful analytical tool for studying supply chain dynamics and transport logistics, particularly in complex systems where uncertainty and stochastic elements play critical roles. By portraying a supply chain as a sequence of discrete events (e.g., arrivals, departures, and processing steps), DES enables detailed representation of operational policies and aids in evaluating alternative strategies and system responses to uncertainty. This modeling paradigm is particularly relevant in industries where dynamics such as transportation, inventory replenishment, and network configuration significantly affect performance [34, 47].

Logistics and supply chain systems are particularly well-suited for simulation modeling due to their inherent characteristics: complex networks of facilities with interconnected linkages, stochastic relationships between system components, and the ability to generate quantifiable data. The size, complexity, and stochastic nature of these systems, combined with the detailed level of investigation required and the intricate inter-relationships between components, make simulation modeling an appropriate analytical approach for understanding such systems [37].

The validation of simulation models in supply chain research employs multiple methodological approaches to ensure model credibility. Subject matter experts (SMEs), including both academic scholars and practitioners, are consulted during the conceptual development phase to ensure model components and their relationships accurately reflect real-world systems. Structured model walk-throughs and simulation result reviews with independent SME panels help establish face validity by confirming that results align with expert expectations of system behavior.

However, input-output transformation validation—comparing simulation data directly to real-world data—presents significant challenges. The complexity of actual supply chains exceeds simulated models, making it difficult to isolate variable effects in real data. Additionally, companies are often reluctant to share comprehensive data across all research variables. While partial datasets spanning limited supply chain levels can validate corresponding model segments, obtaining complete multi-level supply chain data for a single product remains problematic.

Unlike traditional optimization approaches that provide deterministic solutions, DES enables researchers and practitioners to model the inherent variability in supply chain operations and visualize the associated risks and margins. In forestry supply chains, DES models such as the Weather-driven Analysis of Forest Fuel Systems (WAFFS) have proven particularly valuable for analyzing scenarios involving multiple decision variables including production timing, storage capacity allocation, and resource utilization patterns [13].

The simulation approach allows for comprehensive testing of operational scenarios by varying key input parameters such as departure dates, production lead times, storage availability, and shift configurations, while tracking critical output metrics including total costs, resource utilization, and delivery performance. A significant advantage of DES over deterministic calculations is its ability to reveal the risk of operational failures - for instance, scenarios where production capacity constraints or storage limitations result in incomplete shipments, which deterministic models might incorrectly suggest are feasible.

Ivanov's study [28] represents a significant advancement in discrete-event simulation applications for supply chain management, demonstrating how DES can effectively analyze complex multi-level resilience relationships that traditional analytical methods struggle to capture. Using anyLogistix software [4], the research employs a sophisticated 365-day simulation framework to examine the intricate dependencies between product-level, firm-level, and network-level supply chain resilience across three distinct network configurations.

The study's key contribution lies in revealing that higher firm and network resilience do not automatically translate to enhanced product-level resilience, particularly when supply chains intersect at critical suppliers - a finding with profound implications for both traditional supply chain optimization and emerging applications in waste management and resource recovery systems. The methodology's strength is evidenced through rigorous validation procedures, sensitivity analyses with extended network structures, and practical applicability demonstrated via the Sony PlayStation supply chain case study [6].

While the research acknowledges limitations including unlimited capacity assumptions and focus on operational rather than financial metrics, it establishes a robust DES framework that could be readily adapted for optimizing circular economy networks, waste processing facility configurations, and resource recovery system resilience under various disruption scenarios [28]. This capability to model and analyze uncertainty makes DES an indispensable tool for supply chain management, particularly in industries where the costs of delivery failures are substantial and where multiple stakeholders must coordinate their operations within tight scheduling windows.

2.6 RESEARCH GAP IDENTIFICATION

The literature review reveals a gap in the application of discrete-event simulation to wood waste reverse supply chains, despite its proven effectiveness in traditional supply chain management. While existing research has advanced understanding of individual system components, several limitations persist.

Current research predominantly employs deterministic optimization models that fail to capture the inherent stochasticity of wood waste systems. As noted in the literature, wood waste reverse supply chains face "seasonal and spatial dispersion of biomass sources, variability in material form and contamination levels," [14,24,32,58] yet existing frameworks do not adequately model these uncertainties. The bidirectional flows, uncertain material quality, and variable availability patterns characteristic of these systems require simulation approaches capable of representing stochastic interactions.

Wood waste reverse supply chains involve diverse stakeholders including "sawmills, panel producers, demolition firms, recyclers, transport providers, and municipal waste collectors." Despite conceptual frameworks for coordination, research lacks simulation models that analyze how stakeholder interactions and coordination mechanisms affect system performance under uncertainty.

These gaps collectively indicate a need for a discrete-event simulation model designed for wood waste reverse supply chains. Such a model would integrate stochastic elements with operational constraints and multi-stakeholder coordination, addressing current limitations while providing practical tools for optimizing cascading use strategies and improving circular economy implementation in the wood products industry.

3 PROBLEM DEFINITION

3.1 PROBLEM STATEMENT

Effective management of wood waste within a circular economy framework faces significant systemic challenges that undermine resource recovery and environmental sustainability. The primary issue lies in the fragmented nature of reverse supply chains for wood waste, where inefficiencies arise from disconnected processes between waste generation, collection, and treatment operations. These inefficiencies are compounded by substantial data quality issues that plague wood waste management systems globally.

Current wood waste management suffers from inconsistent data reporting across jurisdictions, with fragmented databases, varying aggregation levels, and evolving reporting standards that create analytical discontinuities. This data fragmentation severely limits the ability to understand material flows, identify critical bottlenecks, and develop evidence-based policies for improving resource recovery. Furthermore, the lack of integrated analytical frameworks means that wood waste management is typically addressed in silos rather than as a comprehensive system, preventing optimization of the entire reverse supply chain.

The absence of robust decision-support tools that can handle data inconsistencies while providing actionable insights represents a critical gap in transitioning toward sustainable wood waste management practices. Without proper analytical frameworks, stakeholders cannot effectively evaluate intervention strategies, optimize logistics, or make informed investments in infrastructure improvements.

3.2 RESEARCH QUESTIONS

1. **Understanding Material Flows Amid Data Challenge:** How can fragmented and inconsistent wood waste data be systematically integrated and harmonized to create a comprehensive understanding of material flows throughout the reverse supply chain?

2. **Identifying Systemic Inefficiencies:** Where are the critical bottlenecks and inefficiencies in current wood waste management systems, particularly at the interfaces between generation, collection, and treatment stages?

3. **Evaluating Optimal Scenarios:** What is the potential impact of different intervention strategies on the overall efficiency and sustainability of wood waste reverse supply chains?

3.3 RESEARCH OBJECTIVES

The primary objectives of this research are structured to address the identified problem statement through a systematic methodological approach:

- **Data Integration and Analysis Framework:** Develop and validate a methodology for integrating diverse annual wood waste data sources into a consistent analytical framework, transforming fragmented data from Slovenia into structured datasets and creating visualizations to analyze material flows and identify patterns in wood waste generation and management.
- **Model Construction:** Construct a discrete-event simulation model based on the data-driven insights, representing key operational entities in wood waste reverse supply chains, including their inventory management dynamics, capacity constraints, and operational inter-dependencies.
- **Validation and Testing:** Validate the simulation model against historical data and utilize it to test the efficacy of various intervention strategies under different operational scenarios.

3.4 CASE STUDY CONTEXT: SLOVENIA

Slovenia provides an ideal case study context for this research due to several characteristics that enhance the relevance and applicability of the findings. As a European Union member state, Slovenia follows standardized EWC coding systems [57], ensuring consistency with European waste management frameworks and facilitating transferability of results to other EU contexts.

It is one of the few EU countries on track to meet both the targets to prepare 55% of municipal waste for reuse and recycling, and recycling 65% of all packaging waste by 2025. As one of the most forested countries in the EU, Slovenia's wood processing industry and construction sector generate substantial wood waste streams, making it representative of European patterns while providing sufficient data volume for statistical analysis [16].

The country's geographical area and waste management infrastructure create a manageable scope for system analysis while maintaining real-world complexity. Slovenia's environmental regulatory framework, administered through ARSO [1], provides

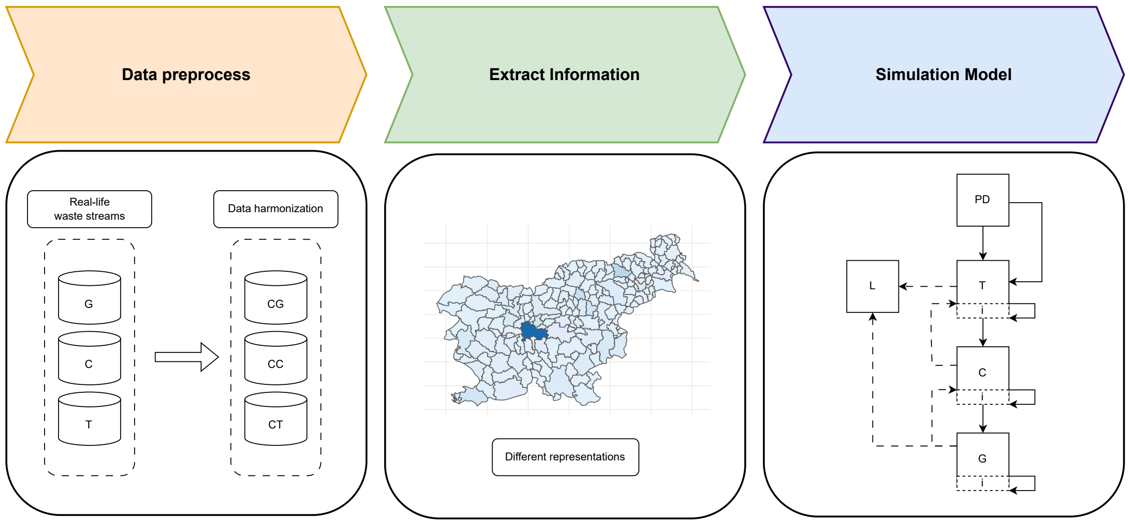

Figure 2: Methodological framework for wood waste reverse supply chain analysis: from fragmented real-world data (G=Generation, C=Collection, T=Treatment) through preprocessing (CG=Cleaned Generation, CC=Cleaned Collection, CT=Cleaned Treatment) and information extraction (different visual representations) to integrated simulation modeling (G=Generator, C=Collector, T=Treatment, L=Landfill, PD=Product Demand) for scenario evaluation.

systematic data collection and reporting that enables empirical analysis. There is potential to develop the circular economy through further investment, which would help Slovenia reduce the generation of waste and improve the re-use and recycling of products Slovenia [16].

Furthermore, Slovenia's position as a transition economy with ongoing infrastructure development presents challenges and opportunities representative of many countries seeking to optimize their waste management systems. The availability of multi-year historical data from ARSO enables both retrospective analysis and validation of predictive models, while the country's size allows for coverage of the entire reverse supply chain from generation to treatment.

Figure 2 illustrates our three-stage methodological approach to address these research challenges within Slovenia's wood waste management system, inspired by Katona et al. [31]. The framework begins with data preprocessing to harmonize waste stream data collected across Slovenia's regions and municipalities, proceeds through information extraction to identify system patterns at regional and municipal levels, and culminates in simulation modeling that enables evaluation of intervention scenarios across Slovenia's reverse supply chain network.

This case study context provides a foundation for demonstrating the applicability of the developed methodology while generating insights that can inform policy and operational improvements both within Slovenia and in similar jurisdictions facing wood waste management challenges.

3.5 LIMITATIONS

Results depend on assumptions that reported data accurately reflects actual waste quantities and that European Waste Catalogue (EWC) codes are consistently applied [57].

Data aggregation introduces additional uncertainties, as waste streams may be consolidated at different temporal and spatial scales, potentially masking variability and seasonal patterns that influence system performance.

The discrete-event simulation model represents a simplified abstraction of real-world systems, with predictive capabilities constrained by under-reporting, misclassifications, and calibration parameters. It is further restricted by insufficient understanding of actual material flows, operational entities, and their interconnections within the waste management network.

4 VISUALIZATION TOOL

The visualization system's analytical capabilities are built on data from ARSO (Environmental Agency of the Republic of Slovenia) [1], the authoritative source for waste management information in Slovenia. The datasets contain comprehensive records of waste generation, collection, treatment, and disposal activities across municipalities and regions (detailed in Table 1), standardized using EWC codes. These datasets are processed and visualized through an interactive web-based tool[1].

EWC codes serve as the classification framework ensuring analytical outputs align with European waste management standards and enable potential integration with broader European systems. The relevant wood and related waste categories are detailed in Table 2, encompassing agricultural/forestry waste, wood/paper production residues, packaging materials, construction/demolition debris, treatment residues, and municipal waste streams.

The tool was developed using R and RStudio [43,45] for data processing and visualization, with interactive visualizations implemented through Plotly [42]. Initially, the development included plans for a discrete-event simulation component using the Simmer package [55] to model material flows based on the processed data. However, as the simulation environment became increasingly complex and served distinct user needs from the visualization component, it was detached from the main tool and developed as a separate Python-based application, as detailed in Chapter 5.

4.1 DATA CHALLENGES

The raw ARSO datasets presented several technical challenges, primarily due to inconsistent data structures, missing values, and changes in reporting templates across years. Temporal coverage spans consistently from 2016 to 2023 across all three waste management datasets (generation, collection, and treatment). However, the reporting methodology evolved in 2019: from 2016-2018, all datasets included both company-level and regional data, while from 2019-2023, all datasets focused exclusively on regional reporting.

Given these data quality constraints and structural inconsistencies, the analytical framework prioritizes regional-level analysis as the primary focus. Regional ag-

[1]The tool is accessible at: https://coachzer.shinyapps.io/WoodWasteVisualization/

Table 1: Statistical Regions of Slovenia

Name	**Largest City**	**Area (km^2)**	**Population (2025)**
Pomurska	Murska Sobota	1,337	113,172
Podravska	Maribor	2,170	331,815
Koroška	Slovenj Gradec	1,041	70,358
Savinjska	Celje	2,301	262,814
Zasavska	Trbovlje	485	57,083
Posavska	Krško	968	75,993
Jugovzhodna Slovenija	Novo Mesto	2,675	148,670
Primorsko-notranjska	Postojna	1,456	53,826
Osrednjeslovenska	Ljubljana	2,334	569,475
Gorenjska	Kranj	2,137	209,921
Goriška	Nova Gorica	2,325	118,096
Obalno-kraška	Koper	1,044	119,627

gregations provide the most reliable and consistent analytical foundation, effectively mitigating individual data point irregularities while maintaining sufficient granularity for meaningful environmental and policy insights. Municipality-level analysis is incorporated where data quality and completeness permit, offering valuable local-level perspectives when feasible. However, the emphasis remains on regional patterns and inter-regional comparisons, which provide the most robust analytical foundation for policy and decision-making purposes.

The variability in ARSO file structures necessitated the development of a flexible data processing framework. Reporting templates varied significantly across years, with different structural characteristics and field definitions, creating primary technical obstacles that included variable numbers of header rows (ranging from 2 to 4 rows across different templates), inconsistent header structures with merged cells causing missing values in Excel files, the need to reconstruct meaningful column names from fragmented multi-level headers, and multiple sheet formats within the same data source requiring different parsing approaches.

To address these challenges, we developed a sheet processing function that adapts to different header configurations. This processing approach handles distinct structural patterns: two-row headers with concatenation requirements, three-row headers with hierarchical groupings requiring forward-filling of merged cells, and four-row headers with nested categorizations. The cleaning and validation phase required manual intervention to standardize formatting patterns and carefully address missing values to avoid introducing bias. All waste quantities were converted from the original kilogram values to metric tons for consistency across visualizations and analysis.

Table 2: Classification of Wood and Related Waste by Source Category

Code	Description
Agricultural/Forestry Waste	
02 01 07	Forestry waste
Wood/Paper Production Waste	
03 01 01	Bark & cork waste
03 01 05	Sawdust, shavings, cuttings, wood, particle board, veneer (excluding 03 01 04)
03 01 99	Other unspecified wood waste (unregistered in data)
03 03 01	Bark & wood waste from pulp/paper production
03 03 08	Waste from sorting of paper and cardboard for recycling
Packaging Waste	
15 01 01	Paper packaging
15 01 03	Wooden packaging
Construction/Demolition Waste	
17 02 01	Construction wood
Waste Treatment Residues	
19 12 01	Paper & cardboard from mechanical treatment
19 12 07	Wood from mechanical treatment (not listed under 19 12 06)
Municipal Waste	
20 01 01	Paper & cardboard from municipal waste
20 01 38	Non-hazardous wood from municipal waste (unspecified)
20 03 07	Bulky waste (may contain wood)

A framework of assumptions and simplifications was established to ensure the tool's functionality despite imperfect data. This framework includes standardized methods for handling missing data, systematic approaches to harmonize inconsistent classification schemes, and protocols to maintain analytical continuity despite structural changes in the data. While these adaptations allow the tool to function effectively and generate meaningful insights, they introduce uncertainty into the results. Users should interpret the outputs with an understanding of these underlying data limitations and the methodological compromises made during development.

4.2 DEVELOPMENT

Development followed four prototype phases focused on creating effective visualizations. The first prototype created a basic interface for wood waste analysis with a split-screen layout (see Figure 22). Parameter controls appeared on the left and visualizations on the right. Testing revealed critical limitations: no filtering options, no tool-tips, and insufficient user guidance. This prototype focused strictly on simulation parameters.

The second prototype addressed usability by adding scenario-based functionality with predefined configurations (see Figure 23). These scenarios allowed users to explore different outcomes through established parameter combinations, serving as educational tools for newcomers and starting points for experienced users.

However, as the visualization capabilities expanded beyond simple parameter display, it became apparent that the analysis and simulation components served different purposes and user needs. The third prototype therefore separated functionality into distinct Analysis and Simulation components (see Figure 24). The Analysis component focused on visualizing cleaned ARSO datasets and addresses the data quality challenges identified in Section 4.1, while the Simulation module handled parameter-based modeling, requiring clear distinctions between empirical data visualizations and simulation outputs.

This separation revealed that both components had grown significantly in complexity and served distinct workflows. Rather than force integration into a single application, the final version was refined to focus exclusively on data analysis and visualization through Plotly plots (see Figure 25). The simulation model was re-imagined as a separate Python-based tool, as detailed in Chapter 5.

4.2.1 Design Choices

The visualization tool employs multiple linked views organized hierarchically from general trends to specific breakdowns by waste type and region 3. This design approach enables users to begin with an overview and progressively explore detailed data through

Figure 3: Main interface of the Visualization Tool, showing the dashboard layout and available analysis options in the navigation sidebar.

interactive drill-down functionality.

With the help of Plotly functionalities, the tool implements interactive visualization elements including filtering, contextual hover details, and zoom/pan navigation controls. The system architecture focuses on four sections: overview, generation, collection, and treatment processes.

The **Overview** section provides system-wide metrics through multiple visualization types. Information boxes display total values for generation, collection, and treatment across all regions. Line charts track these metrics over time to reveal temporal trends. A sankey diagram illustrates waste flow by waste category from generation through treatment (see Figure 4. Regional comparisons appear through stacked bar charts showing generation, collection, and treatment volumes per region, while waste type distributions are displayed using vertical stacked bar charts that break down quantities by waste management.

The **Generation** section utilizes temporal line charts to track aggregate waste volumes, combined regional-temporal charts for comparative analysis across administrative boundaries (see Figure 5, and categorical visualizations to examine waste composition by material type.

The **Collection** section encompasses five integrated modules that provide comprehensive insights into waste collection patterns. Storage analysis enables comparison of waste volumes stored at the beginning versus end of study periods, with filtering capabilities for specific time ranges, waste types, and regions. Waste source classification reveals the origins of collected waste through temporal visualizations via multi-year

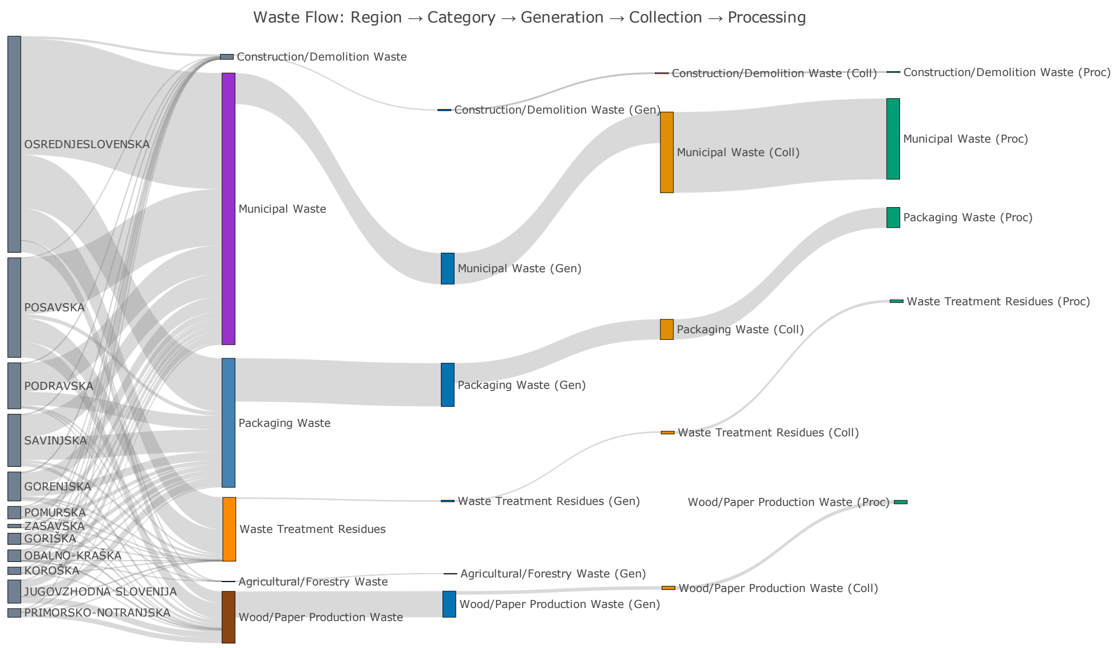

Figure 4: Wood waste flow of Slovenia by waste category.

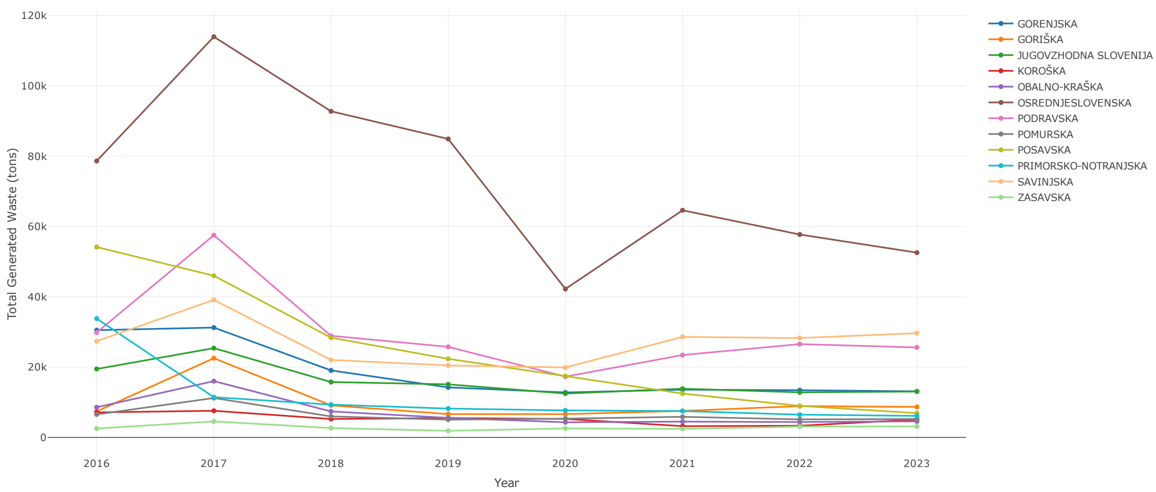

Figure 5: The amount of wood waste generated throughout the years based on the regions.

line charts or various bar chart configurations, distinguishing between registered producers, unregistered producers, collectors, and treatment operators (see Figure 6 for a stacked bar example). Municipal collection trends track collection volumes over time by region and waste type using multi-year line charts, while municipal waste analysis examines total collections per year, municipality-level data, maps showing average collection rates, waste type trends, and regional performance comparisons. The framework concludes with waste flow management, which traces waste destinations including volumes, sources, and export patterns (EU vs non-EU) across different waste types, statistical regions, and time periods.

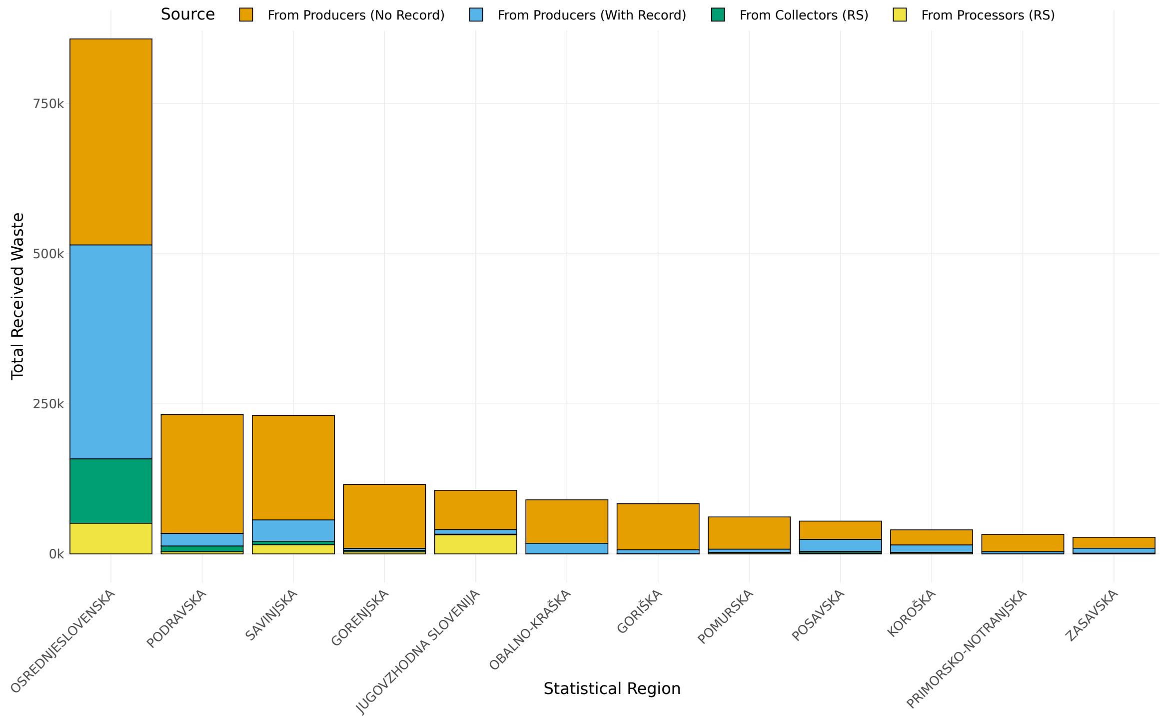

Figure 6: The total amount of wood waste received by the source across statistical regions.

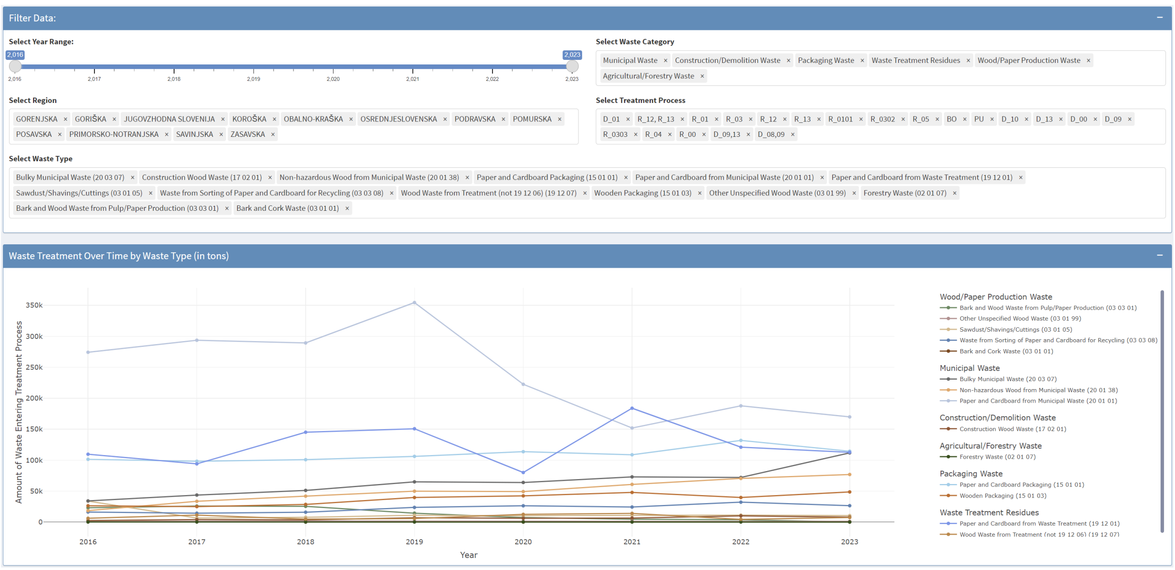

Figure 7: Waste entering treatment processes by waste type, demonstrating available filter controls for year ranges, waste category, waste type, treatment process, and statistical region.

The **Treatment** section comprises five interconnected modules that provide comprehensive oversight of waste processing operations. Storage analysis compares waste volumes stored at treatment facilities between study period start and end points, with breakdowns by waste type and region. Waste reception analysis examines incoming waste streams through multiple analytical perspectives: temporal trends via multi-year line charts showing total volumes and source breakdowns (untreated from storage, own waste, from generators, from collectors, from treatment facilities, and from EU and non-EU origins), regional distribution through configurable bar and pie charts organized by statistical regions, and waste type composition via horizontal bar charts displaying total amounts by waste category. Process flow analysis tracks waste movement through treatment processes with comprehensive filtering capabilities for waste type, treatment method, region, and time period (see Figure 7). Municipal waste processing focuses specifically on municipal streams through four key visualizations: processing volumes by region using bar charts, waste type breakdown via pie charts, collection rates by area through interactive maps, and collection trends by municipality using line charts. The framework concludes with mass balance analysis, which tracks mass changes during treatment processes over time through stacked bar charts showing total mass change by waste type across years.

The tool architecture follows the ”overview first, zoom and filter, then details-on-demand” rule for finding information [51]. This lets users understand waste management systems at different levels of depth.

5 SIMULATION MODEL

The simulation framework implements a discrete-event modeling approach for waste management systems, utilizing SimPy as the core simulation engine [52]. The framework models waste flows from generation through collection to final processing across regional boundaries, with each region containing generators, collectors, and treatment facilities. The system tracks three primary entity categories—generators, collectors, and treatment operators—that interact through event-driven communication protocols, responding to state changes and resource availability via SimPy's event scheduling mechanism.

5.1 BACKGROUND

Discrete-event simulation (DES) is a modeling paradigm that represents systems as sequence of events occurring at discrete points in time. DES focuses on state changes that happen instantaneously at specific moments, making it suited for operational systems like manufacturing, logistics and service processes. The simulation maintains an event list ordered by scheduled event times, advancing through a series scheduling steps: processing the next chronological event, updating system state, and potentially scheduling new future events based on the state change [47].

SimPy implements this DES framework through Python generators and an event-driven architecture. Processes are modeled as generator functions that yield events (such as timeouts, resource requests, or custom events), with the simulation engine managing event scheduling and process continuation. This approach enables modeling of concurrent processes, such as the events of generators, collectors and treatment operators, that can act through shared resources and event signaling while maintaining independent operational logic [38].

For waste management systems, DES captures the asynchronous nature of waste generation, the resource constraints of collection vehicles, and the interdependent demand patterns between supply chain echelons. The event-driven approach naturally models scenarios where a treatment facility's capacity signal cascades upstream through collectors to generators, creating realistic temporal delays and coordination challenges that analytical models cannot easily represent.

5.2 TECHNICAL ARCHITECTURE

The technical architecture employs a hierarchical class structure with `Operational Entity` serving as the base class for all system components. This inheritance enables all entities to experience failures and recovery periods that impact operational efficiency and introduce realistic system disruptions. Configuration management utilizes a centralized `Simulation Config` class that maintains simulation parameters including temporal bounds, random seeds, and operational constraints.

All entities operate under a dual-axis operational paradigm as outlined in Table 3.

Axis	**Options**
Inventory Policy	PUSH, PULL
Stock Strategy	ON_DEMAND, REORDER_50, REORDER_90

Table 3: Dual-axis operational paradigm components

This framework collectively dictates production and procurement logic throughout the reverse supply chain, generating six distinct operational models (2×3) that enable systematic empirical comparison of hybrid inventory strategies.

The framework incorporates realistic capacity constraints through an overflow management system. When entities exceed storage capacity, they choose between capacity expansion or landfill disposal using cost-minimization logic. Both options employ dynamic pricing that escalates with repeated use, reflecting real-world constraints like space limitations and transportation logistics. At each overflow event, entities evaluate current expansion costs versus disposal fees and select the cheaper option. This cost structure discourages reactive management and incentivizes proactive capacity planning, mirroring actual facility management challenges.

Figure 8 provides an overview of the simulation model architecture, illustrating the hierarchical relationships between entities and the flow of materials through the reverse supply chain system.

5.3 MODELING UNCERTAINTY AND VARIABILITY

The model incorporates several stochastic components to capture real-world uncertainty in waste management operations. Entity failures are modeled using failure checks with uniform recovery durations, with failure probabilities varying by scenario severity (low to high levels). Waste generation includes daily variability factors drawn from clipped normal distributions, while treatment conversion efficiency is modeled as normally distributed around base efficiency values. Collector operations introduce randomness through uniform travel distance factors and collection timing jitter.

The model ensures reproducibility through hierarchical random number generation: when a top-level seed is provided, the main simulation seeds both Python's random and NumPy's generators, with the waste generator receiving a random seed for independent stochastic streams while collectors and treatment operators use deterministic seeding for consistent behavior across runs.

5.4 INVENTORY MANAGEMENT FRAMEWORK

The inventory management system models the fundamental supply chain conflict between producing in anticipation of demand versus producing in reaction to it. This conflict is captured through the dual-axis framework described above.

The **Inventory Policy** axis defines strategic philosophy. Under **PUSH** policies, entities operate using forecast-driven approaches, managing operations based on internal state projections and "pushing" material downstream without explicit immediate orders. **PULL** policies implement lean, demand-driven approaches aligned with Just-in-Time principles, where entities respond primarily to explicit demand signals from downstream customers.

The **Stock Strategy** axis defines tactical execution rules. The **ON_DEMAND** strategy represents continuous operation under PUSH policies or operation only upon signal receipt under PULL policies. Buffer-based strategies (**REORDER_50** and **REORDER_90**) trigger actions when inventory levels cross 50% or 90% capacity thresholds respectively.

5.5 ENTITY MODELING

5.5.1 Waste Generators

Waste Generator entities represent real-world actors that produce wood waste, serving as material sources that create initial supply-side pressure in the reverse supply chain. These entities introduce specified quantities and types of waste over time, incorporating variability through random seasonal fluctuations that reflect market and operational uncertainties.

Generator behavior is driven by a primary SimPy process handling waste generation through an infinite loop that advances the simulation clock by defined generation frequencies. Each iteration performs operational failure/recovery checks, calculates seasonal factors, and executes strategy-specific generation logic.

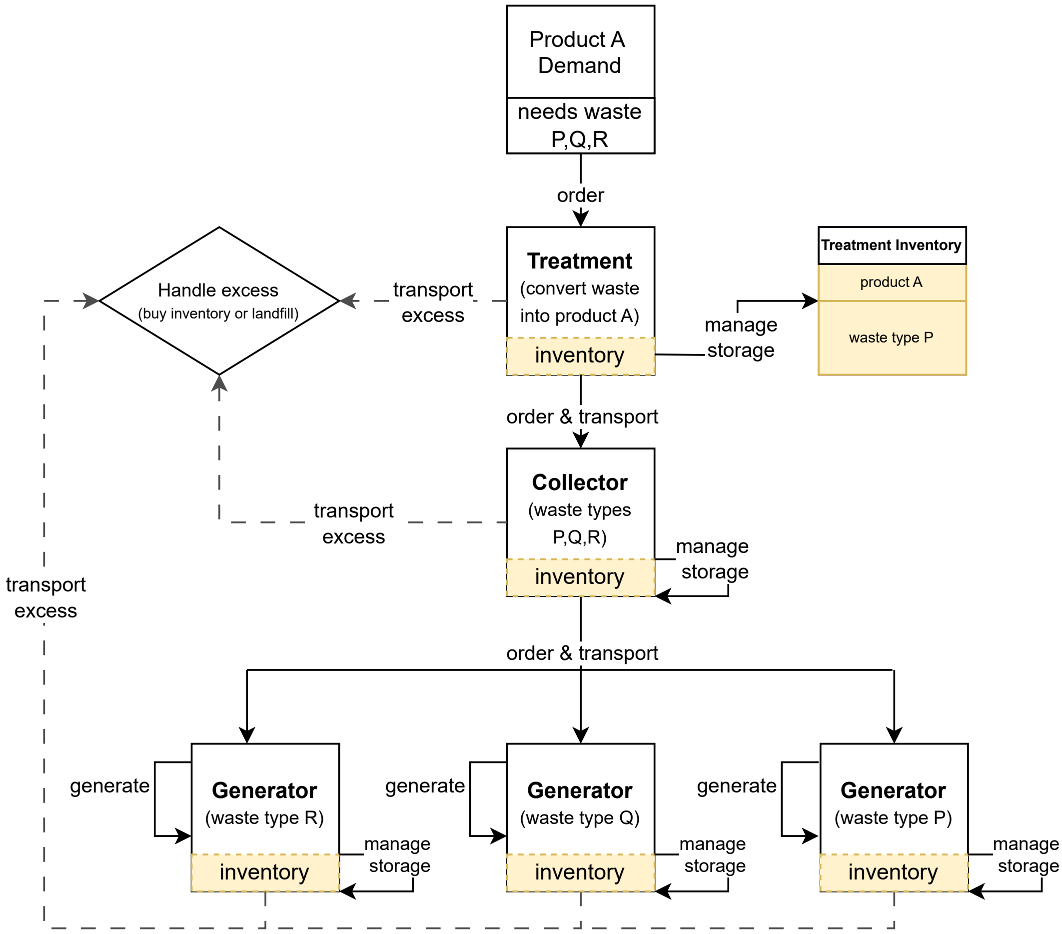

Figure 8: Model overview.

Under **PUSH** policies, generators produce waste proactively. The **ON_DEMAND** strategy maintains continuous production regardless of stock levels, representing a make-to-stock model. Buffer strategies (**REORDER_90/50**) monitor storage levels post-production, creating demand signals to notify collectors when thresholds are exceeded.

PULL implementation transforms generators into demand-responsive entities. The **ON_DEMAND** policy scales generation proportionally to demand signals when signals are present, while maintaining minimal baseline generation (10% of normal rates) when no demand signals exist to prevent system stagnation. **REORDER_90/50** primarily respond to downstream signals while maintaining minimal generation when stock levels approach depletion, ensuring availability when demand arrives.

5.5.2 Collector Companies

Collector Company entities serve as commercial intermediaries, operating as mid-stream buffers managing bidirectional material flows between upstream generators and downstream treatment operators. Collected material is stored in finite-capacity **Collection Centers** that decouple generation events from treatment scheduling.

Collector efficiency operates as a dynamic multiplier recalculated at each decision point based on inventory policy adaptation, storage utilization performance, and demand signal responsiveness.

PUSH policies focus on maintaining collection center inventory through proactive upstream collection, triggering collection when storage utilization falls below predetermined thresholds. **PULL** policies enable collectors to respond to treatment operator demand signals and function as demand relays: upon receiving signals without sufficient inventory, collectors propagate new signals upstream to PULL-configured generators, creating authentic multi-echelon PULL systems with cascading demand transmission.

5.5.2.1 Transport

The transport system creates a demand-driven network linking generators, collectors, and treatment facilities through coordinated signaling and vehicle management. Treatment facilities initiate the process by broadcasting capacity signals upstream, which collection centers receive and translate into targeted collection requests for generators within their service areas.

Collection centers serve as intermediate coordination hubs, receiving waste from multiple generators and coordinating deliveries to treatment facilities. A dedicated transport manager handles long-haul movements between collection centers and treatment facilities, while individual collectors manage local vehicle fleets for generator-to-collection-center operations. This two-tier structure enables local optimization while maintaining broader network coordination.

Vehicle dispatch follows a prioritization heuristic that allocates 80% of collection effort to generators within the same region and 20% to adjacent regions, ranking generators by current waste volume. Collection operations coordinate vehicle assignments, calculate travel times, and manage on-site processes that transfer waste subject to generator supply, vehicle capacity, and collection center storage constraints. All transport activities update the global simulation state to ensure consistency across entities and time steps.

5.5.3 Treatment Operators

Treatment Operator entities represent industrial facilities (e.g. particle board plants, recycling centers) that serve as final waste customers and value-adding stages. These entities consume waste as raw material, performing transformation according to predefined recipes with specific efficiency and cost profiles, generating demand patterns that drive upstream supply chain behavior.

The architecture separates procurement from production through concurrent processes. The main production loop operates at processing intervals, checking for operational failures before executing core conversion routines. The procurement loop independently determines material sourcing requirements through inventory management policies.

PUSH implementation employs proactive ordering logic, monitoring raw material inventory levels and triggering collection requests when stocks fall below reorder points. **PULL** implementation links raw material demand directly to final product requirements, creating specific material signals based on processing needs for make-to-order production systems.

When production capacity or inputs are constrained, operators employ dynamic scoring mechanisms ranking transformation tasks by strategic weight (ABC analysis), demand gap, conversion efficiency, and input availability. This composite scoring enables balanced trade-offs between high-value items and readily available, urgent-demand products when inputs are scarce.

6 RESULTS AND ANALYSIS

This chapter presents the results of our simulation study, analyzing the performance of six operational models across multiple dimensions. We examine inventory management dynamics, including storage level variations and capacity utilization patterns across different entity types and regions. Additionally, we evaluate the total economic costs associated with each strategy, encompassing transportation, storage, and processing expenses. Finally, we assess the environmental impact achieved through different inventory management approaches. These results provide insights into the trade-offs between operational efficiency, economic viability, and environmental benefits in reverse wood waste supply chain management.

6.1 INVENTORY MANAGEMENT

As mentioned in Section 5.2, we have six operational models which enable systematic empirical comparison of our hybrid inventory strategies. The simulation runtime for each strategy was 365 time units, representing a real-world scenario of one operational year. Our model defines one generator, collector, and treatment operator per region, resulting in 12 entities of each type distributed across the simulation environment. All of them are capable of experiencing failure events.

The demand is based on three engineered wood products with distinct characteristics and carbon storage potential. Table 4 summarizes the key specifications:

Table 4: Product specifications and biogenic carbon storage potential

Product	**Density Range (kg/m^3)**	**Wood Content (%)**	**Biogenic Carbon Stock ($kgCO_2e/^3$)**
Particle Board	600-800	92.5	-585.31
OSB	600-680	95.0	-1,213.60
MDF	500-1,000	82.0	-516.00

These products utilize different waste stream combinations based on processing compatibility and material properties. Particle board demonstrates the highest versatility, accepting five waste types including construction wood (17 02 01), sawdust and wood cuttings (03 01 05), wooden packaging (15 01 03), bark and cork waste (03 01 01), and non-hazardous municipal wood (20 01 38). OSB production utilizes four waste streams: construction wood, sawdust and wood cuttings, wooden packaging, and non-hazardous municipal wood. MDF, while having the most specialized requirements, accepts four waste types: sawdust and wood cuttings, bark and cork waste, non-hazardous municipal wood, and paper packaging (15 01 01). The negative biogenic carbon stock values indicate carbon sequestration, with OSB demonstrating the highest storage potential per cubic meter.

The national demand configuration drives production priorities through ABC analysis based on total biogenic carbon impact, considering both per-unit carbon storage and demand volumes. This waste-to-product mapping flexibility creates complex inventory optimization challenges, as some waste streams can serve multiple product lines while others have limited applications.

We now examine the differences in storage levels across operational models for each entity type, analyzing how inventory strategies perform under varying demand patterns and supply chain configurations with these multi-product waste stream dependencies.

6.1.1 Generation Inventory

Push strategies maintain consistently high storage utilization with frequent saturation events, particularly in the simulation's latter half. This reflects their proactive inventory pre-positioning regardless of downstream demand. Pull strategies demonstrate more dynamic, demand-responsive behavior with lower average utilization and greater temporal variability, contributing to superior efficiency by allocating resources to actual rather than anticipated needs.

REORDER_90 amplifies these differences: push strategies show aggressive storage accumulation leading to widespread saturation, while pull strategies maintain balanced levels while achieving high service performance. Regional variations are more pronounced under pull policies, indicating better adaptation to local generation patterns and downstream constraints.

6.1.2 Collection Inventory

Push policies create sustained high storage utilization, with ON_DEMAND showing the most aggressive accumulation. Multiple regions experience prolonged near-maximum utilization, reflecting push systems' tendency to pre-position inventory based on forecasted rather than actual demand.

Pull policies exhibit lower average utilization with greater temporal variability. ON_DEMAND maintains predominantly low storage levels with efficient turnover, while REORDER_90 demonstrates selective, strategically-timed high utilization periods that respond to actual demand signals.

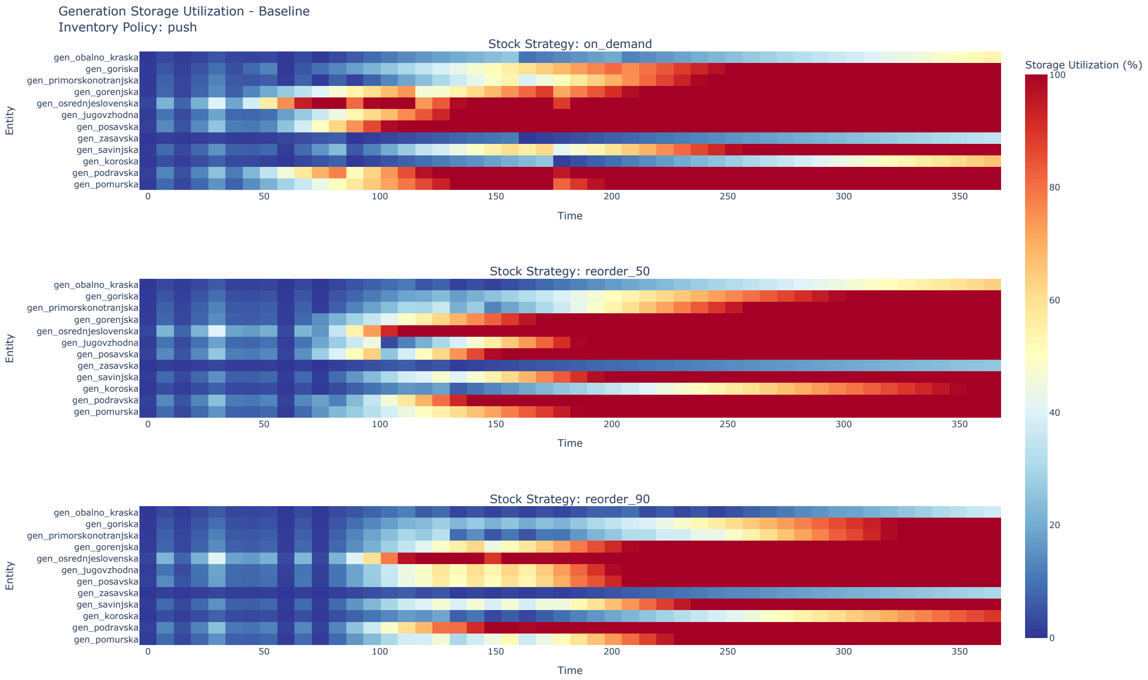

Figure 9: PUSH - Generation storage comparison between inventory policies.

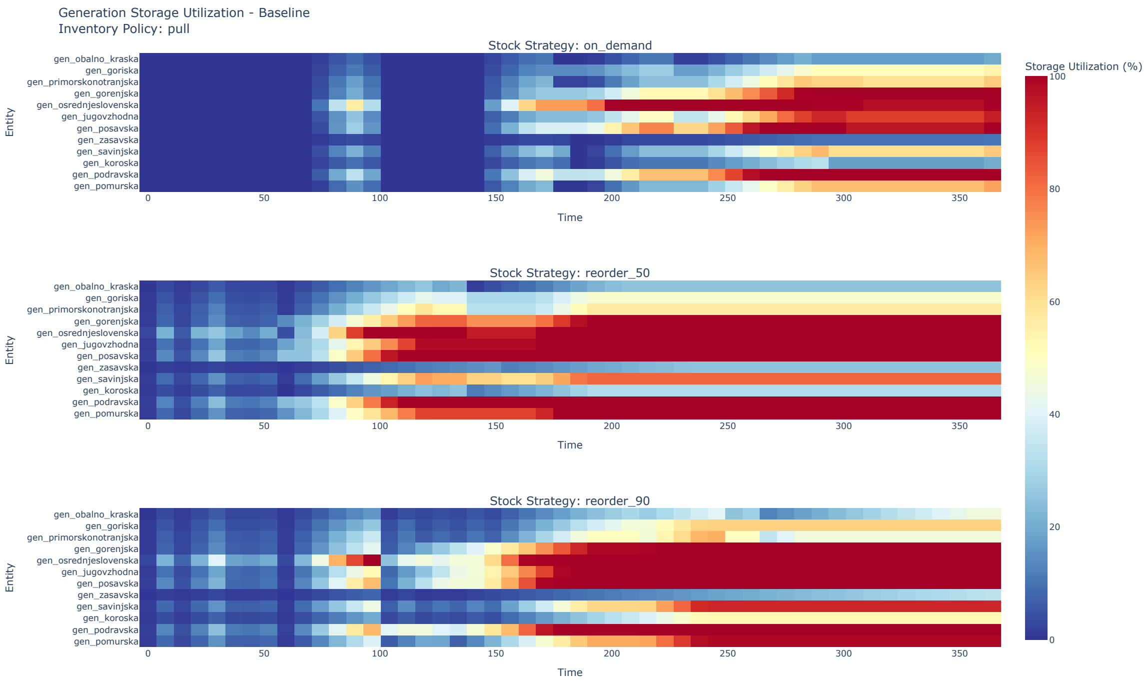

Figure 10: PULL - Generation storage comparison between inventory policies.

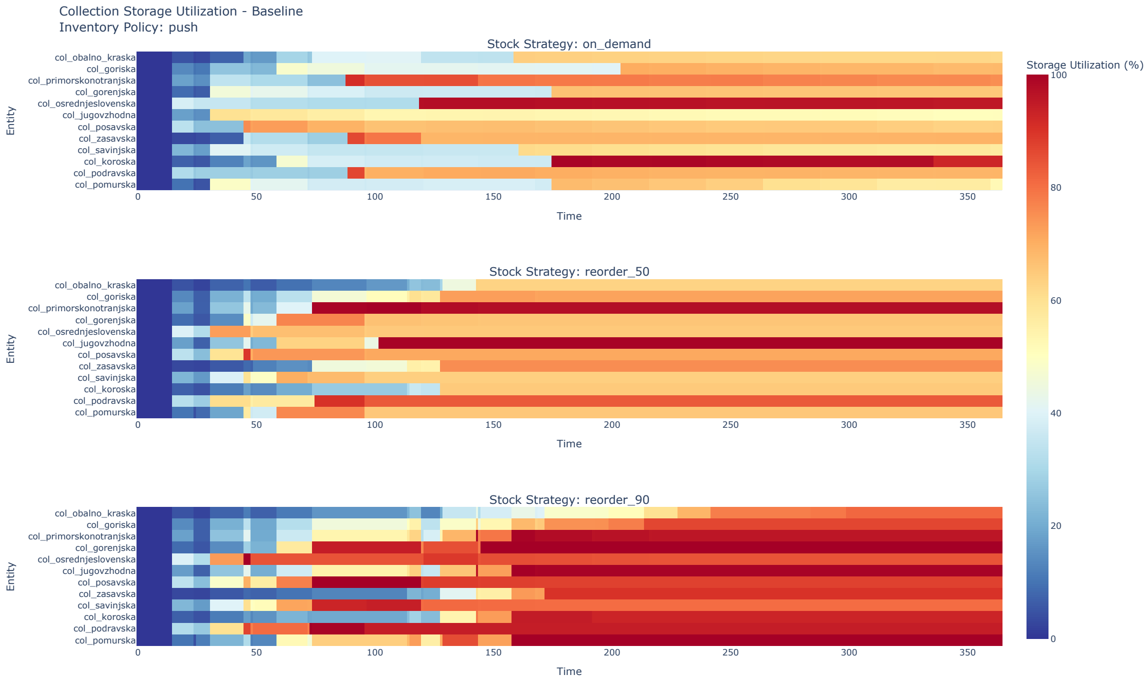

Figure 11: PUSH - Collection storage comparison between inventory policies.

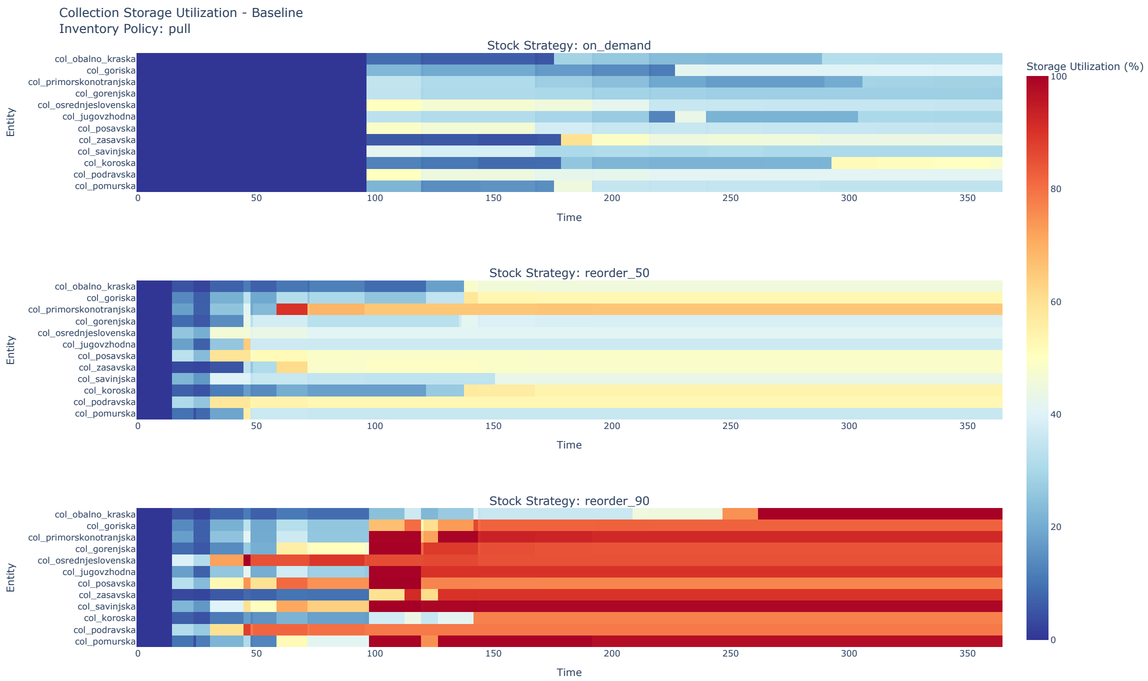

Figure 12: PULL - Collection storage comparison between inventory policies.

6.1.3 Treatment Inventory

6.1.3.1 Waste Storage

Push policies show progressive waste accumulation across all strategies, with utilization increasing over time as collection continues based on forecasted processing needs. This leads to input buffer overflow as the system pushes more waste than can be immediately processed.

Pull policies maintain better synchronization between waste input and processing rates, avoiding the persistent overflow characteristic of push strategies. Even under REORDER_90, pull strategies maintain better responsiveness to processing capacity constraints.

6.1.3.2 Product Storage

Both policies show similar patterns under ON_DEMAND and REORDER_50 with consistently low utilization, reflecting the hierarchical nature where finished goods first fill product-to-sell storage before overflowing here.

Under REORDER_90, certain facilities experience sustained high utilization as processing exceeds downstream demand rates, indicating production rather than policy constraints. The similarity between push and pull suggests this storage serves primarily as an overflow mechanism.

6.1.3.3 Product-to-Sell Storage

Both policies demonstrate nearly identical utilization patterns across all strategies. This convergence suggests product-to-sell storage operates as a critical bottleneck where upstream policy differences become less influential than downstream demand characteristics and facility-specific processing-to-demand ratios.

Under higher reorder thresholds, this staging area becomes saturated regardless of upstream inventory philosophy, as processing capacity exceeds the rate at which finished goods can be sold.

6.2 COMPARISON OF COSTS AND ENVIRONMENTAL IMPACT

The cost-environmental impact analysis, Figure 16, reveals trade-offs across the six supply chain configurations examined. Pull ON_DEMAND emerges as the performing strategy, achieving both the lowest environmental impact (under 1M kgCO_2e) and lowest cost (under 25M €). Push ON_DEMAND demonstrates slightly higher performance

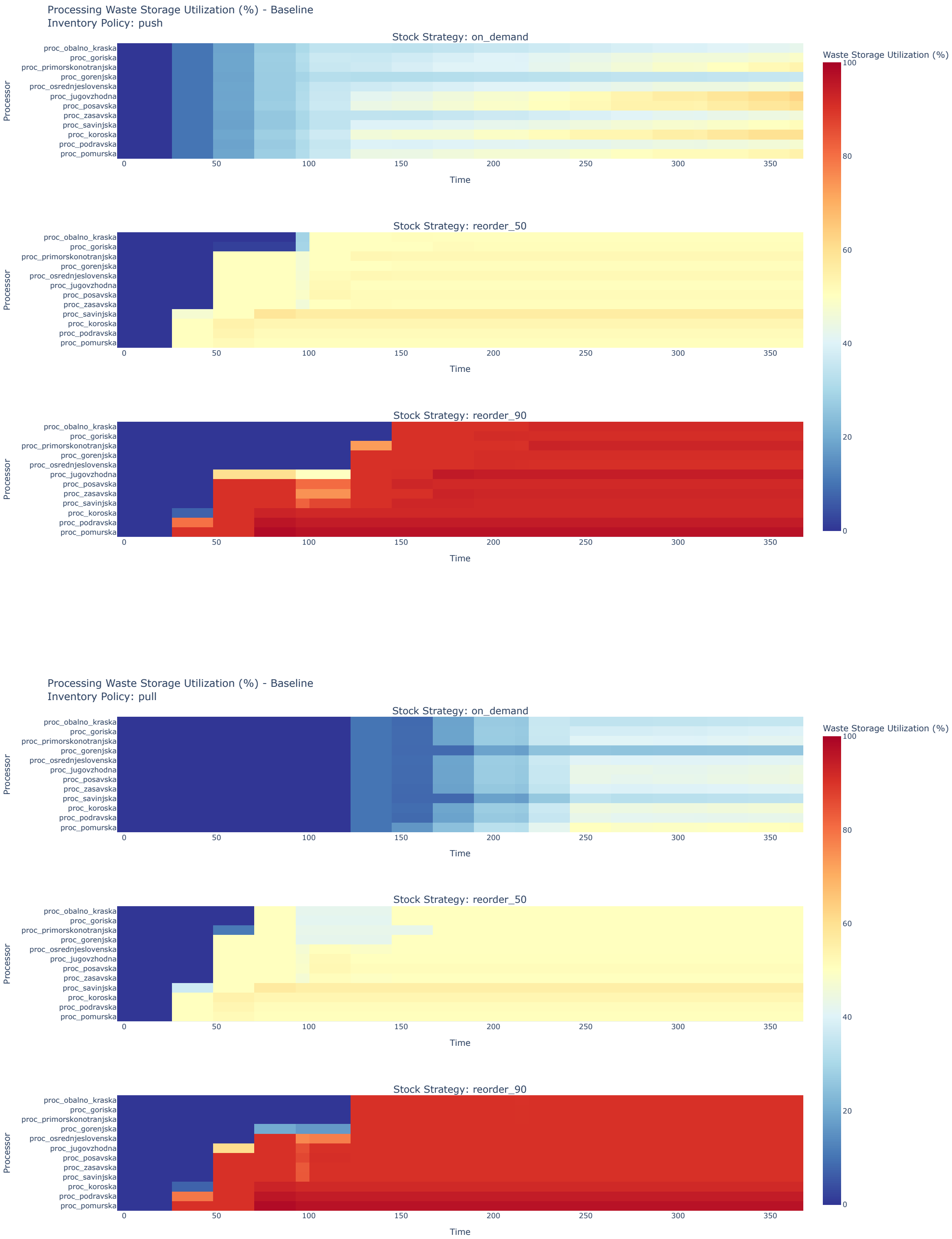

Figure 13: PUSH (top) and PULL (bottom) - Waste storage comparison between inventory policies

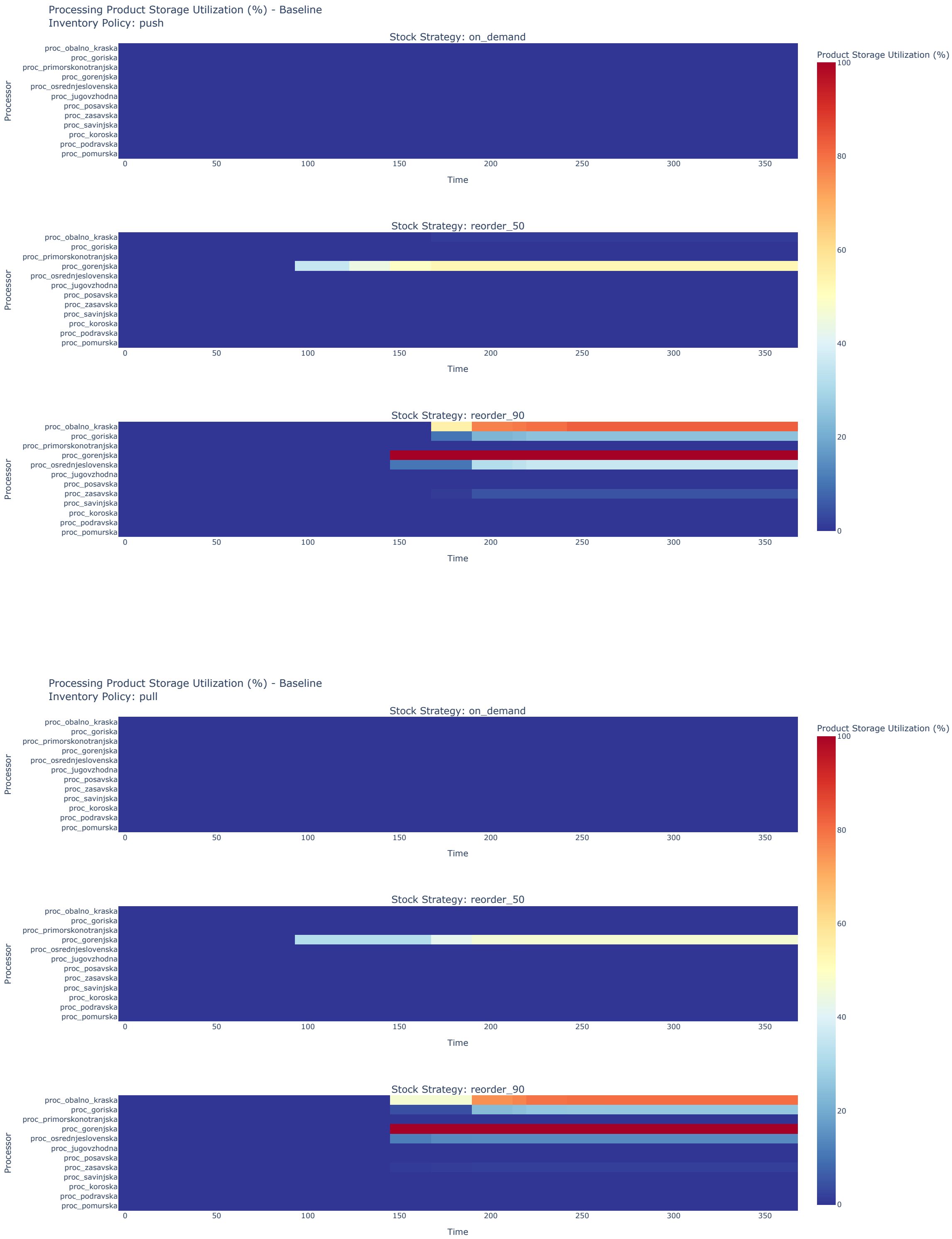

Figure 14: PUSH (top) and PULL (bottom) - Product storage comparison between inventory policies

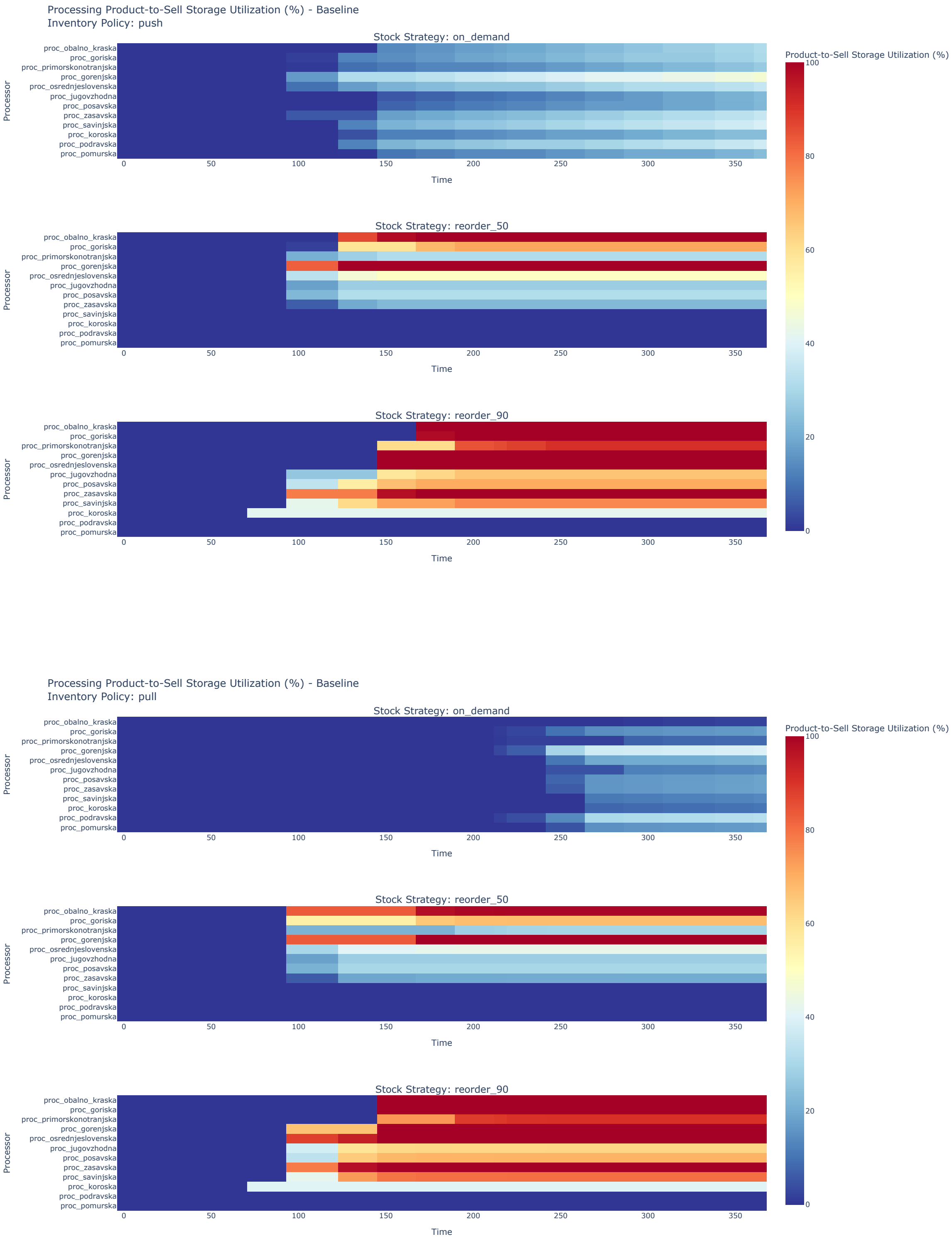

Figure 15: PUSH (top) and PULL (bottom) - Product-to-sell storage comparison between inventory policies

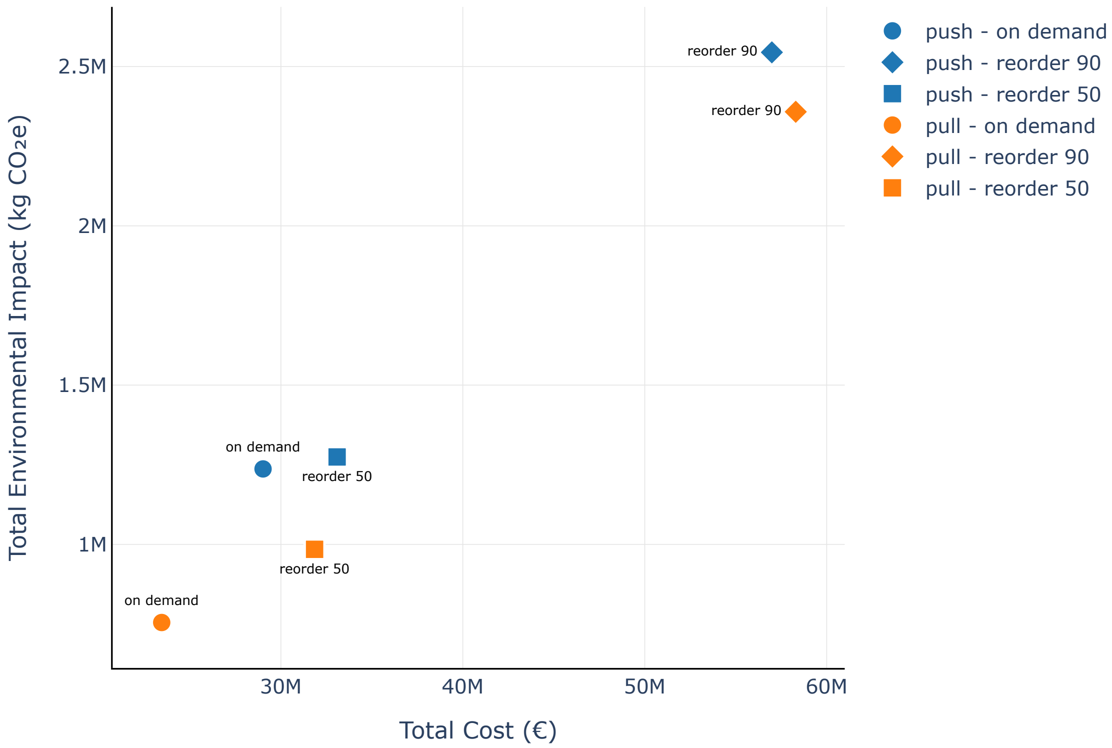

Figure 16: Analysis of total cost versus environmental impact for different supply chain strategies, comparing push and pull systems.

on both dimensions, with costs under 30M € and emissions around 1.25M kgCO_2e. The REORDER_50 policies show modest increases in both metrics, with pull configurations requiring 31M € and generating approximately 1M kgCO_2e while push variants cost around 34M € with 1.3M kgCO_2e emissions. REORDER_90 strategies represent the least favorable option, particularly for pull systems, which demand 58M € and produce 2.4M kgCO_2e emissions. This analysis demonstrates that ON_DEMAND strategies, especially in pull configurations, offer superior performance across both economic and environmental dimensions, while REORDER_90 policies impose significant penalties in both cost and sustainability metrics.

6.2.1 Monte Carlo Analysis

We performed 100 independent Monte Carlo replications for each `InventoryPolicy` × `StockStrategy` combination, holding all scenario parameters constant. Each replication used a unique random seed to capture stochastic variability in generation, failures, transport, and processing.

Per replication we recorded service level (overall and per product), landfill overflow, storage utilization, generated/collected/processed volumes, collection/processing rates and total emissions. We report means with 95% confidence intervals across the 100 replications.

All strategies achieved high service levels ($>$ 98.0%), as shown in Figure 17. Pull with REORDER_90 delivered exceptional efficiency (19.5% overall efficiency, Figure 20) and the lowest emissions (489k kgCO_2e, Figure 18) with moderate landfill overflow (564m^3, Figure 19). Push with REORDER_90 achieved the highest average service level (99.0%) but at the cost of the highest emissions (634k kgCO_2e) and substantial landfill overflow (2,013m^3). On-demand policies were consistently less efficient across all metrics, with pull on-demand achieving the lowest overall efficiency (16.1%) and push on-demand showing poor landfill management.

The efficiency comparison (Figure 20) reveals that collection efficiency remains relatively stable across configurations (24.7%-62.3%), while processing efficiency shows greater variation (12.3%-35.6%). Pull strategies consistently outperform push strategies in overall system efficiency, with pull REORDER_90 achieving the highest overall efficiency (19.5%) compared to push REORDER_90 (19.1%).

Environmental impact analysis shows pull ON_DEMAND and pull REORDER_50 as the most environmentally friendly options (242k and 283k kgCO_2e respectively), while push strategies, particularly with REORDER_90, generate significantly higher emissions. The landfill overflow patterns indicate that reorder strategies, especially when combined with push policies, create substantial waste management challenges.

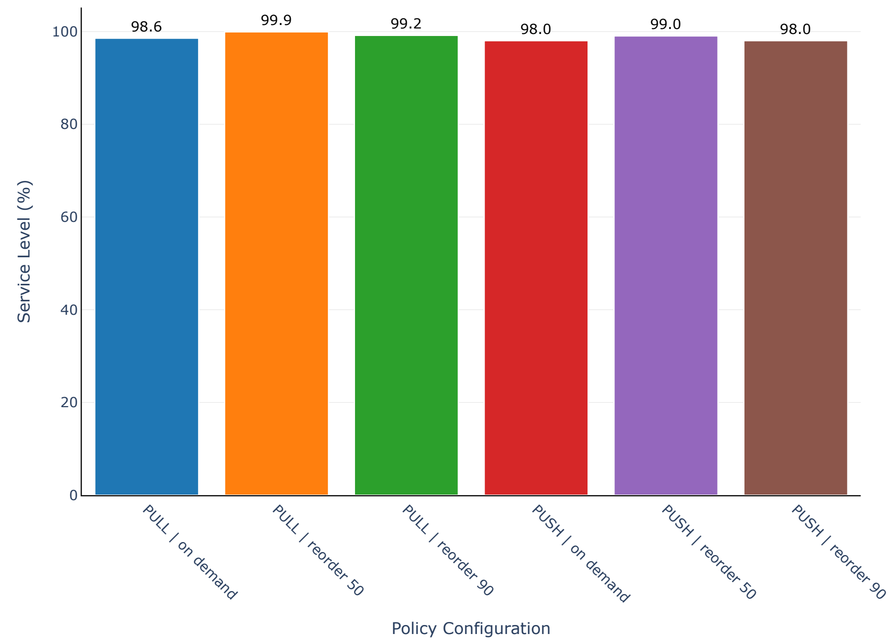

Figure 17: Service level performance across policy configurations. All strategies achieve high service levels above 98.0%, with push REORDER_90 reaching 98.0%.

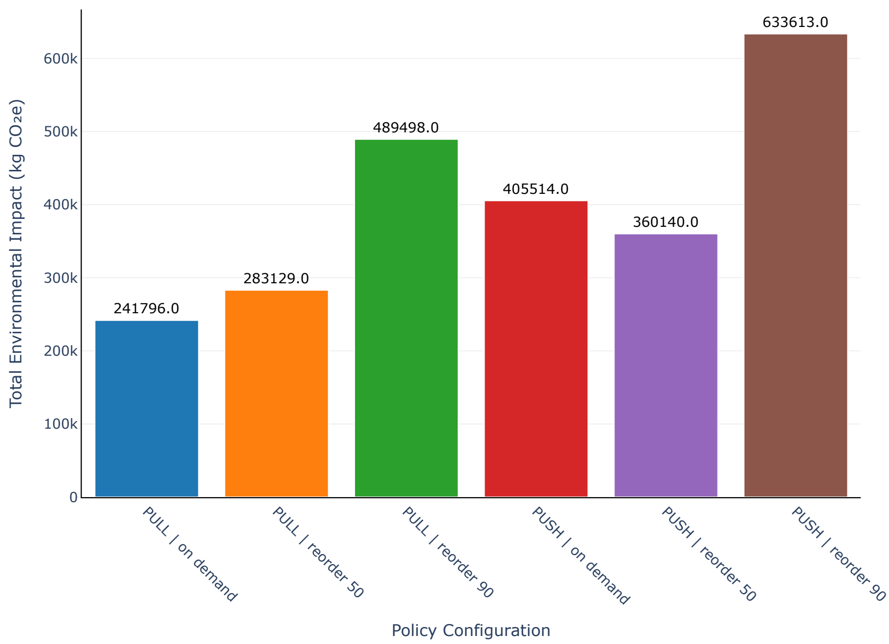

Figure 18: Total environmental impact across policy configurations. Pull on-demand shows the lowest emissions (242k kgCO_2e), while push REORDER_90 generates the highest (634k kgCO_2e).

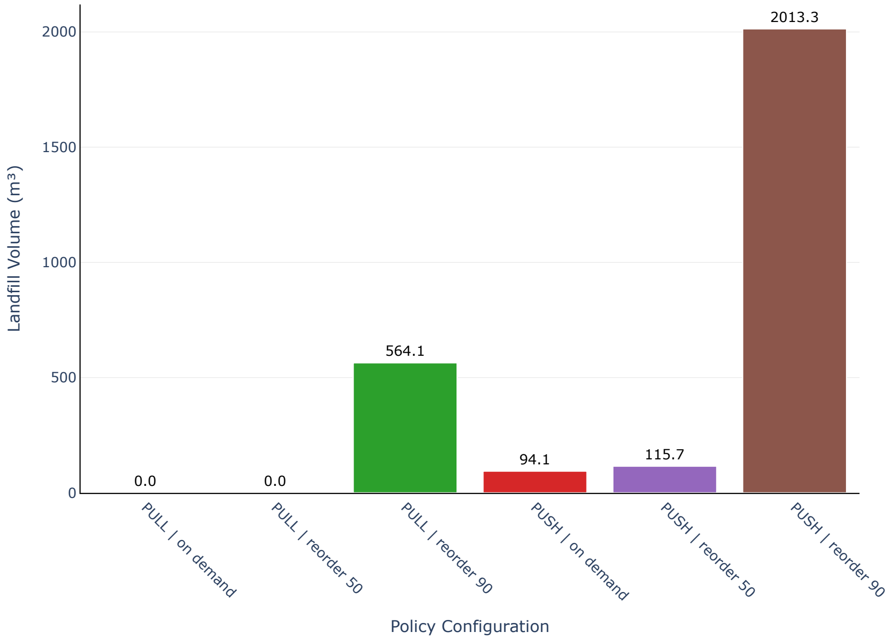

Figure 19: Landfill overflow volumes across policy configurations. Pull on-demand and REORDER_50 show no overflow, while push REORDER_90 creates substantial overflow (2,013m^3).

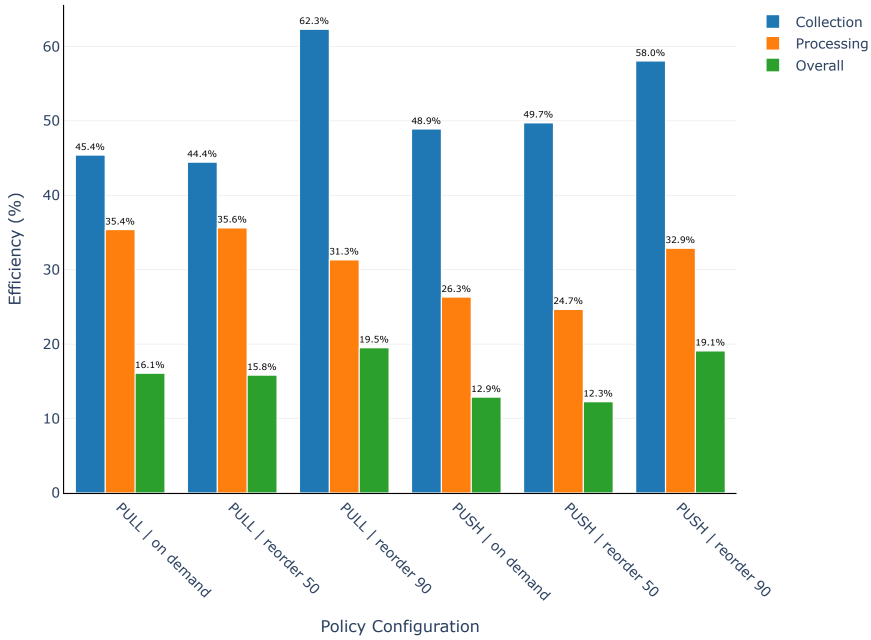

Figure 20: System efficiency comparison across policy configurations. Collection, processing, and overall efficiency metrics show pull strategies consistently outperforming push strategies in overall efficiency, with pull REORDER_90 achieving the highest overall efficiency (19.5%).

7 CONCLUSION

This thesis has presented a comprehensive two-part analysis of wood waste management systems in Slovenia, combining data visualization and simulation-based inventory management strategies for reverse wood waste supply chains. The research developed both an interactive visualization tool for analyzing empirical waste management data and a discrete event simulation model for evaluating operational strategies.

The first component involved creating a web-based visualization tool using R and Plotly to analyze ARSO datasets spanning 2016-2023. This tool addresses data quality challenges inherent in the raw datasets and provides interactive visualizations across four key areas: overview, generation, collection, and treatment processes. The visualization framework enables users to explore wood waste patterns across Slovenia's twelve statistical regions through hierarchical drill-down functionality, from general trends to specific breakdowns by waste type and region.

The second component focused on simulation-based analysis of inventory management strategies in reverse wood waste supply chains. Through the development and application of a discrete event simulation model, we evaluated six distinct operational configurations combining push and pull inventory strategies with three reorder policies: ON_DEMAND, REORDER_50, and REORDER_90.

The research addressed a gap in sustainable waste management by quantifying the trade-offs between proactive inventory positioning and demand-responsive operations in multi-product, multi-region supply networks. Our analysis encompassed multiple performance dimensions including storage utilization patterns, service level achievement, total system costs, greenhouse gas emissions, and overall operational efficiency across a simulated one-year operational period.

7.1 KEY FINDINGS AND CONTRIBUTIONS

The simulation results reveal that pull-based inventory strategies consistently outperform push-based approaches across most performance metrics. Pull ON_DEMAND emerged as the best performing configuration, achieving both the lowest environmental impact and lowest total costs, while maintaining service levels above 98%. This strategy's success stems from its demand-responsive nature, which prevents excessive inventory accumulation and reduces waste overflow to landfills.

Conversely, push strategies, particularly when combined with aggressive reorder policies like REORDER_90, demonstrated significant performance penalties. Push REORDER_90 generated the highest emissions, despite achieving the highest service level (99.0%). This highlights the critical trade-off between service level optimization and environmental sustainability in waste management operations.

The Monte Carlo analysis across 100 replications confirmed these findings, with pull strategies demonstrating better overall system efficiency (19.5% for pull REORDER_90 compared to 19.1% for push REORDER_90) and more stable performance across varying operational conditions.

7.2 UP-SCALING THE MODEL

The simulation architecture allows for increase in scope and depth. The modular architecture allows for incorporation of additional waste streams and products without needing major structural adjustments.

The current wood waste focus represents only one segment of the broader waste management ecosystem. Figure 21 illustrates potential products that could be integrated into the simulation framework.

Each new product category would introduce unique characteristics including generation patterns, storage requirements, transportation constraints, and processing technologies. More importantly, each product type would contribute distinct biogenic carbon stock values that feed into the ABC analysis framework, enabling the simulation to prioritize products based on their carbon storage potential. This diversification would allow the model to optimize processing decisions by focusing first on waste streams with the highest biogenic carbon content, supporting carbon sequestration objectives while maintaining operational efficiency across multi-stream waste facilities.

7.3 SUGGESTIONS AND LIMITATIONS

These findings demonstrate that demand-driven inventory approaches reduce both operational costs and environmental impact, suggesting waste management practitioners should prioritize pull-based strategies with conservative reorder policies. The analysis reveals that downstream bottlenecks often determine system performance more than upstream inventory policies, indicating capacity investments should focus on demand-side constraints rather than inventory optimization alone.

However, the model's focus on wood waste in a single geographic location limits its applicability. The simulation assumes perfect information flow and excludes real-world complications such as quality variability, regulatory changes, and market volatility.

		EWC Code												
		02 01 07	03 01 01	03 01 05	03 03 01	03 03 08	15 01 01	15 01 03	17 02 01	19 12 01	19 12 07	20 01 01	20 01 38	20 03 07
PRODUCTS	Energy	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
	Particleboard	yes	yes	yes	yes	no	no	yes	yes	no	yes	no	yes	yes
	OSB	no	no	yes	no	no	no	yes	yes	no	yes	no	yes	yes
	Fibreboard	no	no	yes	no	no	no	yes	yes	no	yes	no	yes	yes
	Wood pellets	no	no	yes	no	no	no	yes	yes	no	yes	no	yes	yes
	Wood briquettes	no	no	yes	no	no	no	yes	yes	no	yes	no	yes	yes
	Wood wool	no	no	yes	no	no	no	yes	yes	no	yes	no	yes	yes
	Wood flour	no	no	yes	no	no	no	yes	yes	no	yes	no	yes	no
	Wood pulp	no	no	yes	no	no	no	yes	yes	yes	yes	yes	yes	yes
	Biorefinery feedstock	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
	Thermal/sound insulation	no	no	no	no	yes	yes	no	no	no	no	no	no	no
	Tenotiles feedstock	no	no	no	no	yes	yes	no	no	no	no	no	no	no
	Recycled paper packaging	no	no	no	no	yes	yes	no	no	no	no	yes	no	no
	Wood packaging	no	no	no	no	no	no	yes	no	no	no	no	no	no
	Solid wood	no	no	no	no	no	no	no	yes	no	yes	no	yes	no
	Chips & particles	no	no	no	no	no	no	yes	yes	no	yes	no	yes	no
	Reclaimed furniture	no	no	no	no	no	no	no	no	no	no	no	no	yes

Figure 21: Potential products for model expansion showing waste code compatibility. Orange labels indicate products currently implemented in the simulation. Green labels represent European Waste Catalogue (EWC) codes compatible with each product category, while red labels indicate incompatible codes that cannot be processed through the respective waste streams.

8 DALJŠI POVZETEK V SLOVENSKEM JEZIKU

Lesni odpadki so vse večji okoljski in gospodarski problem po vsem svetu, ki ga povzročajo gradbena, proizvodna in rušilna dejavnost. Če se z njimi ne ravna pravilno, predstavljajo izgubljen vir in znatno breme, saj prispevajo k emisijam toplogrednih plinov, onesnaževanju in naraščanju stroškov odlagališč. V zadnjih letih se je zaradi širitve gradbenega sektorja povečala količina lesnih odpadkov, vključno z velikim povečanjem obnov/prenov za strukturne in energetske izboljšave stavbnega fonda, skupaj z naraščajočim povpraševanjem po embalaži na osnovi lesa, kar prispeva k tem izzivom [54].

Okoljske in gospodarske posledice nepravilnega ravnanja z lesnimi odpadki so velike. Konvencionalne metode odstranjevanja, kot so odlaganje na odlagališčih in sežiganje, sproščajo škodljive toplogredne pline, kot sta metan in ogljikov dioksid, medtem ko počasno razpadanje v anaerobnih pogojih ustvarja dolgoročne nevarnosti za okolje [41, 49]. Poleg ekološke škode neustrezno odstranjevanje zaradi onesnaževanja predstavlja tveganje za javno zdravje, kar še dodatno poudarja nujnost trajnostnih rešitev [40]. Hkrati lesni odpadki ostajajo močno neizkoriščena surovina, saj bi se lahko znatne količine, če bi se učinkovito upravljale, ponovno uporabile kot dragocene surovine ali viri energije [3, 36]. Na primer, pretvorba lesnih odpadkov v bioenergijo ali kompozitne gradbene materiale ponuja obetavne poti za gospodarsko rast in učinkovito rabo virov, kar je v skladu z načeli krožnega gospodarstva [20, 35]. Države, kot je Slovenija, z bogatimi lesnimi viri, so v dobrem položaju za sprejetje trajnostnih praks ravnanja z odpadki, ki dajejo prednost ponovni uporabi in podaljšanju življenjskega cikla, kar dokazuje izvedljivost takšnih pristopov [26].

Da bi te priložnosti v celoti izkoristili, so nujne učinkovite povratne dobavne verige. Za razliko od tradicionalnih naprednih dobavnih verig, ki prevažajo izdelke od surovin do potrošnikov, se povratne dobavne verige osredotočajo na pridobivanje vrednosti iz rabljenih izdelkov z zbiranjem, ponovno predelavo in redistribucijo [27, 44]. Lesni odpadki – bodisi v obliki ostankov iz žagarn, lesnih sekancev ali ruševin – predstavljajo edinstvene logistične in okoljske izzive, vendar tudi znaten potencial za pridobivanje energije in zmanjšanje vpliva [18]. Prehod na krožno gospodarstvo za lesne odpadke pa zahteva premagovanje sistemskih ovir, vključno z vrzeli pri izvajanju strategij ponovne uporabe in recikliranja v velikem obsegu [19]. Ena od glavnih ovir so logistični stroški, povezani z nizko energijsko gostoto in neučinkovitostjo prevoza, zlasti pri uporabi gozdarskih ostankov in razpršenih tokov lesnih odpadkov [56].

Ta disertacija je sestavljena iz naslednjih delov: (i) Poglavje 2 podrobno obravnava sorodna dela; (iii) Poglavje 3 opredeljuje raziskovalni problem, cilje, obseg in omejitve; (iv) Poglavje 4 opisuje razvoj vizualizacijskega orodja, vključno z čiščenjem podatkov, usklajevanjem in ustvarjanjem grafikonov za analizo vzorcev pretoka odpadkov po kategorijah in vrstah v časovnem obdobju; (v) Poglavje 5 predstavlja model diskretne simulacije dogodkov (DES), razvit na podlagi spoznanj iz vizualizacijskega orodja; (vi) Poglavje 6 obravnava rezultate in ugotovitve; in (vii) Poglavje 7 zaključuje disertacijo.

8.1 OPIS PROBLEMA

Glavni izziv pri ravnanju z lesnimi odpadki je v sistemski neučinkovitosti povratnih dobavnih verig, kjer nepovezani procesi med nastajanjem odpadkov, zbiranjem in obdelavo preprečujejo optimalno izkoriščanje virov. Te neučinkovitosti še poslabšujejo pomembne težave s kakovostjo podatkov, vključno z neenotnimi standardi poročanja, razdrobljenimi podatkovnimi bazami in različnimi ravnmi agregacije v različnih jurisdikcijah. Odsotnost integriranih analitičnih okvirov, ki bi lahko obravnavali te neskladnosti podatkov in hkrati zagotavljali uporabne informacije, predstavlja kritično oviro za izvajanje trajnostnih praks ravnanja.

8.2 RAZISKOVALNI PRISTOP

Ta diplomsko delo obravnava te izzive z dvojnim metodološkim pristopom. Najprej je bil razvit celovit sistem vizualizacije podatkov z uporabo dejanskih podatkov Agencije za okolje Republike Slovenije (ARSO) za analizo obstoječih tokov lesnih odpadkov in dinamike sistema. Sistem obdeluje podatke o odpadkih, standardizirane z uporabo kod Evropskega kataloga odpadkov (EWC) v več kategorijah, vključno z odpadki iz kmetijstva/gozdarstva, ostanki proizvodnje lesa/papirja, embalažnimi materiali in gradbenimi/ruševinami.

Drugič, na podlagi spoznanj iz vizualizacijske analize je bil z uporabo SimPy razvit model diskretne simulacije dogodkov (DES) za modeliranje operacij povratne dobavne verige za ravnanje z lesnimi odpadki. Simulacijski okvir izvaja hierarhično strukturo razredov z operativnimi subjekti, ki predstavljajo proizvajalce, zbiralce in obrate za obdelavo, ki med seboj komunicirajo prek protokolov komunikacije, ki jih poganjajo dogodki, prek regionalnih.

9 REFERENCES

[1] Agencija Republike Slovenije za okolje (ARSO). Poročila in publikacije o odpadkih, 2025. *(Cited on pages 12 and 15.)*

[2] G. Aiello, C. Muriana, S. Quaranta, and I. A. S. Abusohyon. A sustainable inventory management model for closed loop supply chain involving waste reduction and treatment. *Cleaner Logistics and Supply Chain*, 16:100244, September 2025. *(Cited on page 8.)*

[3] P. Akhator, A. Obanor, and A. Ugege. Nigerian Wood Waste: A Potential Resource for Economic Development. *Journal of Applied Sciences and Environmental Management*, 21(2):246, 2025. *(Cited on pages 1 and 44.)*

[4] anyLogistix. anylogistix: Supply chain optimization, simulation & design software tool. *(Cited on page 9.)*

[5] A. Babaeinesami, P. Ghasemi, A. P. Chobar, M. R. Sasouli, and M. Lajevardi. A new wooden supply chain model for inventory management considering environmental pollution: A genetic algorithm. *Foundations of Computing and Decision Sciences*, 47(4):383–408, 2022. *(Cited on pages 7 and 8.)*

[6] BBC. Playstation 5 supply issues finally fixed after three years, says sony. *BBC News*, 2023. *(Cited on page 10.)*

[7] F. Borges, I. Gammarano, K. Imbiriba, F. Palácios, M. Silva, G. Dias, and D. Araujo. Strengthening global development: the role of reverse logistics in the circular economy. *Concilium*, 24:262–280, 2024. *(Cited on page 5.)*

[8] M. Burnard, Č. Tavzes, A. Tošić, A. Brodnik, and A. Kutnar. The role of reverse logistics in recycling of wood products. In S. S. Muthu, editor, *Environmental Implications of Recycling and Recycled Products*, pages 1–30. Springer Singapore, 2015. Series Title: Environmental Footprints and Eco-design of Products and Processes. *(Cited on pages 3 and 4.)*

[9] E. Commission, D.-G. for Research, and Innovation. *Innovating for sustainable growth – A bioeconomy for Europe*. Publications Office, 2012. *(Cited on page 3.)*

[10] B. Dávid, O. Ősz, and M. Hegyháti. Robust scheduling of waste wood processing plants with uncertain delivery sources and quality. *Sustainability*, 13:5007, 2021. *(Cited on page 3.)*

[11] S. Eilon. FIFO and LIFO policies in inventory management. *Management Science*, 7(3):304–315, 1961. Publisher: Institute for Operations Research and the Management Sciences (INFORMS). *(Cited on page 7.)*

[12] Elizaveta Tikhomirova. Inventory planning: Choosing the right policy, Septemeber 2024. Accessed: [2025-07-14]. *(Cited on page 7.)*

[13] J. Enström, A. Eriksson, L. Eliasson, A. Larsson, and L. Olsson. Wood chip supply from forest to port of loading – A simulation study. *Biomass and Bioenergy*, 152:106182, Sept. 2021. *(Cited on page 9.)*

[14] European Commission. Waste Framework Directive. Accessed: 2025-07-15. *(Cited on pages VII, 4, and 10.)*

[15] European Commission, May 2025. *(Cited on page 3.)*

[16] European Commission, 2025. Accessed: [2025-07-29]. *(Cited on pages 12 and 13.)*

[17] Evan Tarver. 17 essential inventory management techniques, June 2024. Accessed: [2025-07-14]. *(Cited on page 7.)*

[18] S. Farjana, O. Tokede, and M. Ashraf. Environmental impact assessment of waste wood-to-energy recovery in australia. *Energies*, 16:4182, 2023. *(Cited on pages 1 and 44.)*

[19] S. H. Farjana and M. Ashraf. Developing the conceptual framework for the key performance indicators for sustainable wood waste supply chain. *Environment, Development and Sustainability*, 2023. *(Cited on pages 1, 6, and 44.)*

[20] S. H. Farjana, O. Tokede, and M. Ashraf. Environmental Impact Assessment of Waste Wood-to-Energy Recovery in Australia. *Energies*, 16(10):4182, 2023. *(Cited on pages 1 and 44.)*

[21] G. S. Fishman. *Discrete-Event Simulation*. Springer New York, New York, NY, 2001. *(Cited on page 2.)*

[22] B. E. Flores and D. Clay Whybark. Multiple criteria abc analysis. *International journal of operations & production management*, 6(3):38–46, 1986. *(Cited on page 7.)*

[23] B. F. M. for Economic Affairs and C. Action. The next phase of the energy transition: The 2017 renewable energy sources act. *(Cited on page 4.)*

[24] C. A. Garcia and G. Hora. State-of-the-art of waste wood supply chain in germany and selected european countries. *Waste Management*, 70:189–197, 2017. *(Cited on pages VII, 4, and 10.)*

[25] I. Giannoccaro and P. Pontrandolfo. Inventory management in supply chains: a reinforcement learning approach. *International Journal of Production Economics*, 78(2):153–161, 2002. *(Cited on page 7.)*

[26] Government of the Republic of Slovenia. Waste management, 2025. *(Cited on pages 1 and 44.)*

[27] S. Gupta, editor. *Reverse Supply Chains: Issues and Analysis.* CRC Press, 1st edition, 2013. *(Cited on pages 1, 3, and 44.)*

[28] D. Ivanov. Comparative analysis of product and network supply chain resilience. *International Transactions in Operational Research*, page itor.13612, Jan. 2025. *(Cited on pages 9 and 10.)*

[29] V. R. Kannan and K. C. Tan. Just in time, total quality management, and supply chain management: understanding their linkages and impact on business performance. *Omega*, 33(2):153–162, 2005. *(Cited on page 7.)*

[30] S. K. Karna, R. Sahai, et al. An overview on taguchi method. *International journal of engineering and mathematical sciences*, 1(1):1–7, 2012. *(Cited on page 8.)*

[31] A. I. Katona, Z. Szigetvári, et al. Network-based decarbonization of the waste management sector. 2025. Under review. *(Cited on page 13.)*

[32] A. Kawa. REVERSE SUPPLY CHAIN OF RESIDUAL WOOD BIOMASS. *Logforum*, 2023. *(Cited on pages 5 and 10.)*

[33] J. Kulczycka, E. Dziobek, and A. Szmiłyk. Challenges in the management of data on extractive waste—the polish case. *Mineral Economics*, 33:341–347, 2019. *(Cited on page 6.)*

[34] C. Kögler and P. Rauch. Discrete event simulation of multimodal and unimodal transportation in the wood supply chain: a literature review. *Silva Fennica*, 52, 2018. *(Cited on page 8.)*

[35] D. Maier. The use of wood waste from construction and demolition to produce sustainable bioenergy—a bibliometric review of the literature. *International Journal of Energy Research*, 46(9):11640–11658, 2022. *(Cited on pages 1 and 44.)*

[36] D. Maier. A Review of the Environmental Benefits of Using Wood Waste and Magnesium Oxychloride Cement as a Composite Building Material. *Materials*, 16(5):1944, 2023. *(Cited on pages 1 and 44.)*

[37] I. Manuj, J. T. Mentzer, and M. R. Bowers. Improving the rigor of discrete-event simulation in logistics and supply chain research. *International Journal of Physical Distribution & Logistics Management*, 39(3):172–201, 2009. *(Cited on page 9.)*

[38] N. Matloff. Introduction to discrete-event simulation and the simpy language. *Davis, CA. Dept of Computer Science. University of California at Davis. Retrieved on August*, 2(2009):1–33, 2008. *(Cited on page 23.)*

[39] A. Mojica, J. C. Serrano-Ruiz, B. Andres, and R. De La Torre. A conceptual framework for the upcycling supply chain in the wood sector. *Sustainability*, 17(3):1006, 2025. *(Cited on page 5.)*

[40] J. Owoyemi, H. Zakariya, and I. Elegbede. Sustainable wood waste management in nigeria. *Environmental & Socio-Economic Studies*, 4(3):1–9, 2016. *(Cited on pages 1 and 44.)*

[41] K. Parlak, N. Yilgor, and A. Öngen. Hydrogen-rich syngas production from wood waste and wood waste pellet via gasification in updraft circulating fixed bed reactor. *Research Square*, May 2024. Preprint. *(Cited on pages 1 and 44.)*

[42] Plotly. *(Cited on page 15.)*

[43] Posit, 2024. *(Cited on page 15.)*

[44] C. Prahinski and C. Kocabasoglu. Empirical research opportunities in reverse supply chains. *Omega*, 34(6):519–532, 2006. *(Cited on pages 1, 3, and 44.)*

[45] R. Project. *(Cited on page 15.)*

[46] H. Ravinder and R. B. Misra. Abc analysis for inventory management: Bridging the gap between research and classroom. *American journal of business education*, 2014. *(Cited on page 7.)*

[47] S. Robinson. *Simulation: the practice of model development and use*. Bloomsbury Publishing, 2014. *(Cited on pages 8 and 23.)*

[48] M. Röder and P. Thornley. Waste wood as bioenergy feedstock. climate change impacts and related emission uncertainties from waste wood based energy systems in the uk. *Waste Management*, 74:241–252, 2018. *(Cited on page 6.)*

[49] A. Sami, U. Manzoor, A. Irfan, and F. Sarwar. Characterizing circular supply chain practices in industry 5.0 with respect to sustainable manufacturing operations. *Journal of Management and Research*, 10, 2023. *(Cited on pages 1, 6, and 44.)*

[50] E. M. Schau, I. Gavrić, I. Šušteršič, E. Prelovšek Niemelä, B. Dávid, J. G. Pečnik, D. B. DeVallance, and Č. Tavzes. Modelling the Slovenian Wood Industry's Response to the Greenhouse Gas Paris Agreement and the EU "Fit for 55" Green Transition Plan. *Sustainability*, 15(10), 2023. *(Cited on page 8.)*

[51] B. Shneiderman. The eyes have it: A task by data type taxonomy for information visualizations. In *The craft of information visualization*, pages 364–371. Elsevier, 2003. *(Cited on page 22.)*

[52] T. SimPy, 2025. Accessed: 2025-05-15. *(Cited on page 23.)*

[53] D. Singh and A. Verma. Inventory management in supply chain. *Materials Today: Proceedings*, 5(2):3867–3872, 2018. *(Cited on pages 3 and 7.)*

[54] Statistical Office of the Republic of Slovenia. Več komunalnih odpadkov predvsem zaradi povečanja količine kosovnih odpadkov. Stat.si, 2024. Accessed: 2025-05-15. *(Cited on pages 1 and 44.)*

[55] I. Ucar, B. Smeets, and A. Azcorra. simmer: Discrete-event simulation for r. *Journal of Statistical Software*, 90(2):1–30, 2019. *(Cited on page 15.)*

[56] I. Vitale, R. G. Dondo, M. González, and M. E. Cóccola. Modelling and optimization of material flows in the wood pellet supply chain. *Applied Energy*, 313:118776, 2022. *(Cited on pages 1 and 45.)*

[57] Wikiwaste. European waste catalogue — wikiwaste,, 2022. Accessed: [29-07-2025]. *(Cited on pages 12 and 14.)*

[58] M. Švažas, V. Navickas, E. Krajňáková, and J. Nakonieczny. Sustainable supply chain of the biomass cluster as a factor for preservation and enhancement of forests. *Journal of International Studies*, 12:309–321, 2019. *(Cited on pages 4, 6, and 10.)*

Appendices

APPENDIX A First Visualization Tool Prototype

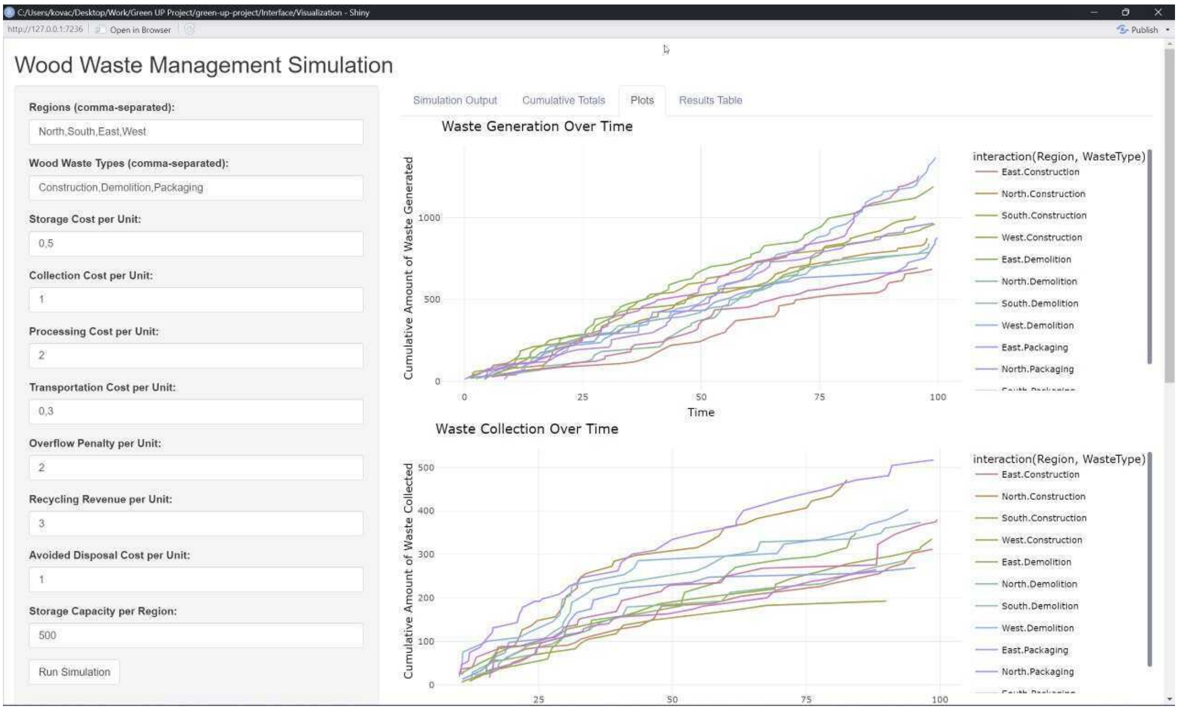

Figure 22: Initial version for defining user made Wood Waste Simulation.

APPENDIX B Second Visualization Tool Prototype

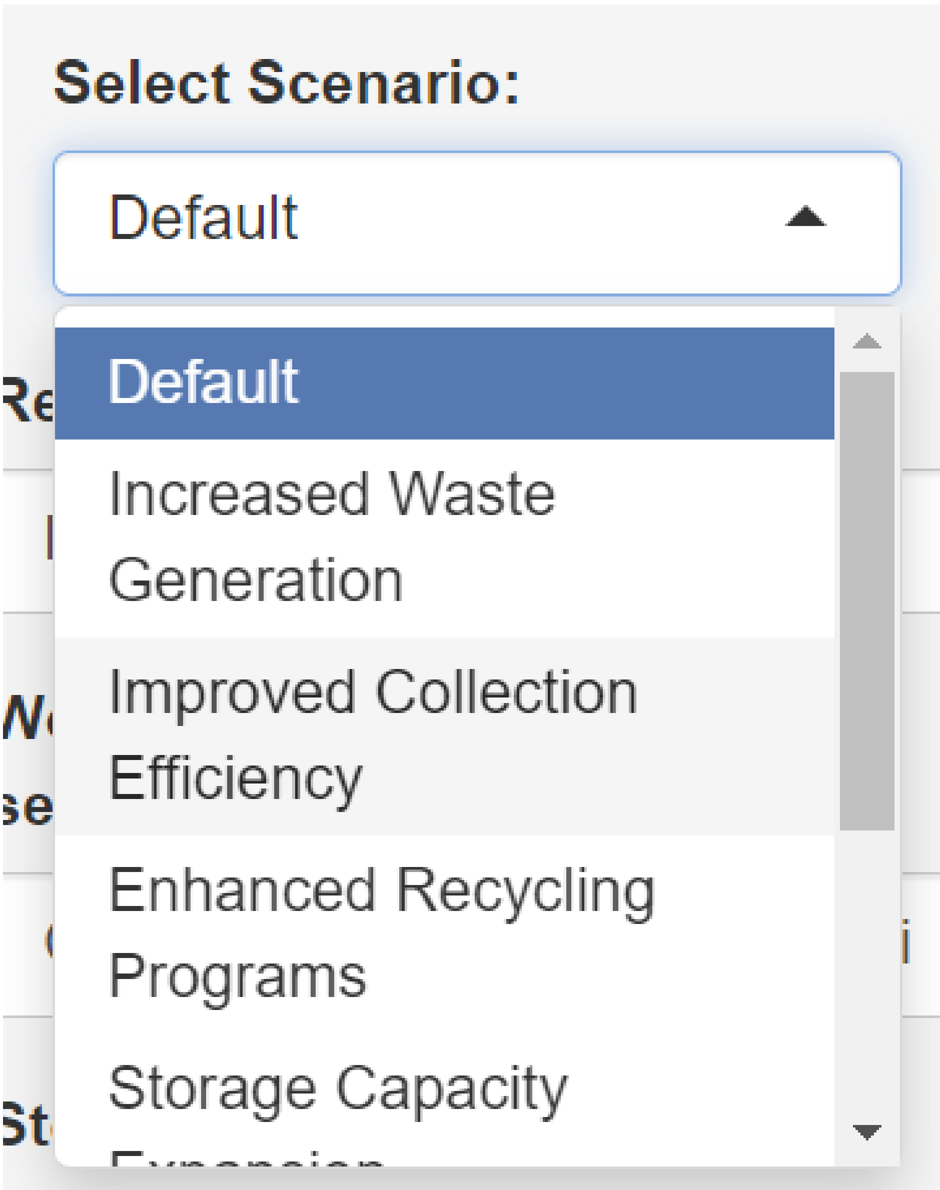

Figure 23: Second version, now with the Scenario options.

APPENDIX C Third Visualization Tool Prototype

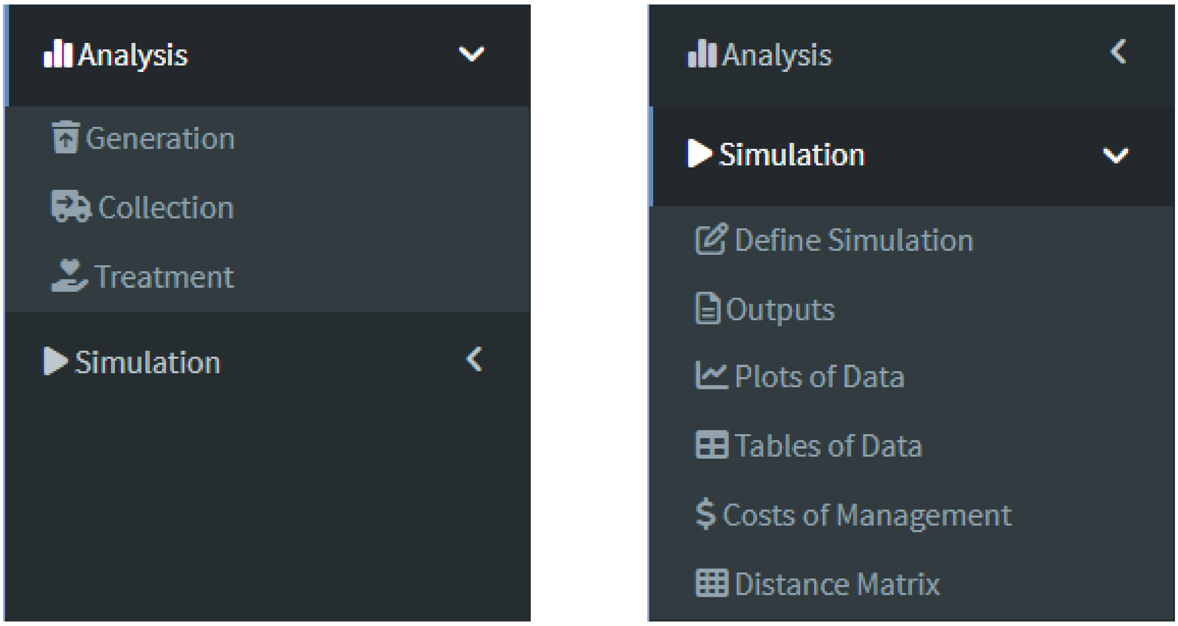

Figure 24: Third version, exploring multiple views.

APPENDIX D Final Visualization Tool Prototype

Figure 25: Interactive tool examining wood waste management patterns across generation, collection, and treatment stages in Slovenia.