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Research paper

Simulation Models for Reverse Logistics Decisions: Insights from a Case Study of Diesel Particulate Filter Remanufacturing

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Abstract

Remanufacturing is vital in circular business models, offering a sustainable way to restore products and reduce resource consumption. In the automotive industry, remanufactured parts are commonly used as spare parts, although their volumes in the market remains limited compared to new spare parts. One main challenge in increasing adoption of remanufacturing is that economic and environmental effects of reverse logistics operations are unknown. This research develops a simulation-based decision support tool for assessing reverse logistics operations in the automotive aftermarket, evaluating the economic and environmental impact of remanufactured versus newly produced spare parts. Using a combination of agent-based and discrete event methods, the simulation analyzes the effectiveness of Scania's reverse logistics network using diesel particulate filter as case study. The findings demonstrate remanufacturing advantages in cost (-82%), carbon footprint emissions (-92%), and virgin material savings (-99%) over new production, therefore supporting the integration of remanufactured parts into circular business models.

Keywords: Circular Business Models · Reverse Logistics · Remanufacturing · Simulation · Agent-based · Discrete Event

1. INTRODUCTION

One central Circular Economy (CE) practice is remanufacturing, which is defined as a process that restores used products to at least their original performance levels, while often consuming fewer resources and less energy compared to producing new items (Remanufacturing.eu, 2017). As a significant sector, the automotive industry exemplifies the growing importance of remanufacturing. Valued at USD 54,7 billion in 2021, this sector is projected to expand at a compound annual growth rate of +7,43% from 2023 to 2028 (PR Newswire, 2022). This growth is driven by increasing environmental concerns, the demand for cost-effective and high-quality parts and the overall expansion of the automotive market. Despite the established practice of remanufacturing spare parts within the industry, the use of remanufactured components remains relatively low, with estimates suggesting that only 5-10% of automotive parts are remanufactured compared to new parts (Parker et al., 2015). One of many notable examples of successful remanufacturing in the heavy-duty vehicles industry is Scania's spare part remanufacturing network. It enables customers to exchange used components with remanufactured alternatives, thereby providing a sustainable and cost-effective solution for vehicle maintenance while supporting CE objectives. Whereas a lot of today's focus is put on futuristic scenarios when it comes to battery returns (Vullum-Bruer et al., 2024), the limited adoption of remanufactured parts in industry so far highlights the need for further advancements and broader acceptance of remanufacturing practices in general (Parker et al., 2015).

Effective remanufacturing relies heavily on well-designed reverse logistics processes, which manage the collection, sorting, and transportation of used components from customers back to manufacturers or third-party remanufacturers. These reverse logistics activities are crucial for ensuring the timely return of used parts

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for remanufacturing and represent a significant component of the cost structure in circular business models (Govindan, 2016). While forward logistics (the flow of goods from raw material extraction to the end customer) has been extensively studied, reverse logistics (which deals with the collection and processing of used products) has received comparatively less attention. Although remanufacturing benefits can be estimated to be 40% to 65% lower in cost compared to new production (Lee et al. 2017), there is a need for more objective evidence to support both economic and environmental benefits of reverse logistics that include remanufacturing operations. To make informed decisions about the use of remanufactured versus new parts, it is essential to evaluate the entire lifecycle of the product, including both forward and reverse logistics processes (Geissdoerfer et al., 2020) (Lieder, 2017). Particularly, operations for reverse logistics, remanufacturing and re-distribution logistics pose great uncertainty for decision-makers, as their economic and environmental cost need to be weighed against potential benefits. This paper aims to fill this research gap by integrating a comprehensive literature review with the development of a simulation-based decision support tool for Scania's aftermarket operations related to remanufactured parts. The simulation model is designed to assess the effectiveness of the reverse logistics network in terms of CO_2-emissions and cost efficiency. The case study focuses on the Diesel Particulate Filter (DPF), an established remanufacturing high-demand automotive component with a limited lifespan that requires periodic replacement. The DPF is a suitable case study part as it has a long legacy of being successfully remanufactured. Hence, the focus of the study can build on an adopted remanufacturing process as basis to focus on the reverse logistics flows. By comparing the environmental and economic impacts of remanufactured DPFs to newly produced DPFs, this study seeks to demonstrate that a well-structured remanufacturing logistics flow offers superior outcomes for the European aftermarket.

The research guiding this paper is to test if a comprehensive reverse logistics network can be modelled, incorporating automotive workshops, intermediate hubs, and remanufacturing facilities, to quantify and compare the environmental impact (CO_2-emissions and material demand) and cost of the reverse logistics flow for DPFs against conventional production logistics. This work highlights the limited attention given to reverse logistics in the context of remanufacturing within circular business models and shows the potential of simulation modeling to quantify supply chain scenarios with a large number of actors. Scientifically, this paper aims to explore the relevance of remanufacturing in the context of circular business models by advancing simulation modeling and comprehensive lifecycle evaluation. Socially, this paper addresses the limited adoption of remanufacturing practices and its potential to increase resource efficiency in automotive industry. Section 2 presents the theoretical framework and literature review, covering relevant theories, concepts, and previous research conducted in the field. Section 3 outlines the methodology employed to address the hypothesis. It details the model design and techniques used as well as includes a case study product of a DPF to demonstrate how the methodology was applied in practice. Section 4 presents the findings of the study, including graphical representations and data tables, followed by interpretations and discussions of the results in section 5. Finally, section 6 summarizes the main findings with their implications, limitations and suggestions for future research. This paper is based on the author's thesis (Tryggvadottir, 2023) and has been extended with additional experiments.

2. THEORETICAL FRAMING

2.1 Circular Business Models

Circular business models have emerged as a sustainable alternative to traditional linear economy models that follow a 'take-make-waste' approach. Circular business models focus on extending the lifecycle of products, minimizing waste, and regenerating natural systems (Geissdoerfer et al., 2020). Central to these models are the concepts of the circular economy and business model innovation. The circular economy aims to create a restorative system where products and materials are kept in use, moving away from the 'end-of-life' mentality aiming towards renewal and waste reduction (Kirchherr et al., 2017) (Lieder & Rashid, 2016). Business model innovation involves creating or adapting models to generate value in new or improved ways, thus ensuring long-term competitiveness and sustainability. Geissdoerfer et al. (2020) define circular business models as "business models that aim to cycle, extend, intensify, and/or dematerialize material and energy loops to reduce resource inputs and minimize waste and emissions output of an organizational system." This definition emphasizes the principles of the circular economy, which aims to keep materials, products, and assets in use for as long as possible and eliminate waste and emissions. Moreover, circular business models encompass various strategies, including product-service systems, take-back schemes, recycling initiatives and collaborative platforms. They aim to balance the creation of commercial value with resource efficiency strategies, such as repair or remanufacturing, by leveraging economic and environmental value embedded in products (Nußholz, 2017).

2.2 Remanufacturing

Remanufacturing is one of several circular practices alongside e.g., reuse, repair, recycling. It is a critical practice within circular business models, involving the steps of disassembly, cleaning, inspection and sorting, reconditioning, and reassembly (Steinhilper, 1998). The expectation is that the performance of remanufactured products will be equivalent to, or even better, than its original performance specifications performance with a warranty equivalent to or better than that of a newly manufactured product.

In general, the remanufacturing industry has received increasing popularity over the past few years, especially in sectors such as automotive, aerospace and electronics. While operating at a relatively small scale today, remanufacturing activities have been growing steadily, with some rough estimates suggesting it could reach a value of USD 100 billion in Europe by 2030 (PR Newswire, 2022). To name some concrete real-world examples, Renault has opened their Re-Factory in France to remanufacture automotive parts (Renault Group, 2022). Volvo Cars has a remanufacturing program for engines in Sweden (Volvo Car Group, 2021), and Caterpillar has a dedicated Cat Reman program for their construction equipment (Ridley, Ijomah & Corney 2019). The growth of the remanufacturing industry is driven by several factors. Firstly, there is a rising demand for sustainable and eco-friendly products as remanufacturing reduces waste and conserves resources, sometimes pushed through legislation. Secondly, remanufacturing comes with cost savings as it is often less expensive than producing new products from scratch. Thirdly, technological and automated advancements are enhancing the efficiency and effectiveness of performing remanufacturing processes (PR Newswire, 2022). As companies embrace remanufacturing practices, they also generate new revenue streams since the remanufactured parts are sold at a lower price to a new customer segment. That customer segment is usually more price sensitive and not willing to pay the premium of a new part but will rather opt for a remanufacturing alternative including a warranty. Hence, companies can broaden their customer base and gain a competitive edge as well as resilience. To ensure the seamless integration of remanufacturing into circular business models, efficient reverse logistics processes and stakeholder engagement (Van Dam & Bakker, 2024) play a pivotal role.

2.3 Reverse Logistics

Reverse logistics play a critical role in enabling remanufacturing since it facilitates the recovery and reuse of end-of-life products and materials. In recent years, research on reverse logistics has expanded and led to the proposal of various definitions. These definitions are largely influenced by the widely recognized definition established by the Council of Logistics Management: “The process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal” (Rogers & Tibben-Lembke, 1998). Reverse Logistics is an essential aspect of sustainable supply chain management, enabling businesses to adopt recovery activities that increase sustainability (Ayvaz et al., 2015). Many companies are lately adopting reverse logistics as a strategic tool for economic benefits and to improve their corporate social image. By efficiently managing product returns companies can create competitive advantages and realize economic benefits (Govindan et al., 2016). Companies operating in industries where product value is high or the return rate is substantial are particularly relying on reverse logistics activities, and therefore allocate significant resources towards improving their return processes (Rogers & Tibben-Lembke, 1998). Reverse logistics flows start with product returns. Product returns can occur for various reasons such as commercial returns, warranty returns, service returns, end-of-use returns, and end-of-life returns (Du & Evans, 2008). To handle returns efficiently, companies must have processes in place for receiving, inspecting, and testing products. Four principal steps have been proposed for handling the return of products: Acquisition, collection, inspection, and sorting into different categories based on their disposition. Main challenges in the reverse flow consists of uncertainty regarding quality, quantity and timing of product returns as well as mismatch between the supply and demand of the returns and remanufactured product (Asif et al., 2012). In this context, simulation modeling offers a powerful tool to quantify, analyze, and optimize the complex dynamics of reverse logistics operations as integral part of the business.

2.4 Simulation Modeling

Simulation modeling is a technique used to replicate real-world systems and analyze their behavior under different conditions. The three most common simulation approaches are system dynamics, discrete event simulation, and agent-based simulation (Borshchev & Grigoryev, 2013). In this section, the focus will be on discrete event and agent-based as these are the most relevant approaches for this work.

2.4.1 Discrete Event Simulation

Discrete event simulation involves representing a system and its changes over time through state variables that change only at specific moments in time, known as events. An event is an instantaneous occurrence that can alter the system's state (Law, 2015). The discrete event modeling method views the system being modeled as a process consisting of a sequence of operations that involve entities. These operations can include delays, resource pooling, process branching, splitting, combining, and others. Queues are present in almost all models since entities compete for resources and can be delayed. The model is typically represented graphically as a process flowchart with blocks representing operations. This type of diagram is familiar to the business world as a process diagram and is widely used to describe process steps. Thus far, discrete event modeling has been the most successful modeling approach applied in the business community (Borshchev & Grigoryev, 2013). One of the key benefits of using a discrete event simulation approach is the ability to identify bottlenecks and inefficiencies within a system. This can be particularly beneficial when it comes to reverse logistics modeling as discrete event models can identify critical points in the supply chain in terms of location of delays, utilization of resources or (in)efficiency of processes. This insight provides the basis for quantification and optimization. As an example, a study was conducted investigating the factors affecting the design of a collection channel for waste lead-acid storage batteries in Taiwan by using discrete event simulation (Yu & Wu, 2010). This study simulated a reverse logistics network that collects and recycles Taiwan's batteries, measuring the performance of the system by its throughput, lead time, average work in progress and transportation cost. Similarly, another study used discrete event simulation to build a sustainable reverse supply chain model for resource conservation through remanufacturing of stator shafts (Ravichandran et al., 2023). The simulation considered different shipment scenarios and return cases and estimated the associated costs and carbon emissions. As the focus of discrete event models is to capture overall system performance, they are, however, limited when it comes to capturing individual decision-making processes and complex system behaviors emerging from them. Furthermore, the application of the studied models remains in the linear business context in which remanufacturing or recycling are handled on an opportunistic basis, without having planned for returns as part of the business model.

2.4.2 Agent-Based Simulation

Agent-based models (ABMs) are used in various fields to model complex systems composed of interacting individual agents. ABMs are a relatively new modeling technique that emerged in the early 2000s and have been gaining increasing attention due to their ability to capture emergent behaviors that are not easily modeled using other traditional modelling methods such as system dynamics or discrete event modeling. ABMs are built on the concept of agents, which are individual entities that interact with each other and their environment. Agents can represent people, animals, organizations, or even abstract concepts such as ideas or beliefs. Each agent is equipped with own set of rules, behaviors and characteristics that define its actions and interactions. Thus, the overall system behavior can be observed and studied as it emerges as a result of many individual actions. For instance, an ABM was used to measure the performance of a reverse logistics enterprise (Pandian & Abdul-Kader, 2017). The agents in this model included collectors, sorters, remanufacturers, recyclers, suppliers, and distributors, and the performance of each of them has been evaluated individually to optimize the efficiency of the reverse logistics system. Utilizing the ABM approach facilitated the interpretation of the system behavior and the evaluation of each agent's distinctive performance more effectively. Another study utilized an ABM to address sustainable benefits of remanufacturing tires (Abdul Kader & Haque, 2011). In this study, various stakeholders of the system were modelled as agents, including the tires themselves, collectors, recyclers, and remanufacturers, and their decision-making processes. The simulation was used to test various scenarios and identify the benefits of increasing the retread percentage of passenger car tires. Moreover, this study took a comprehensive perspective by conducting a comparative analysis of revenue generated from the sales of new and retreaded passenger tires, alongside their respective carbon dioxide emissions. These studies highlight the potential of agent-based simulations to address complex sustainability issues and identify solutions that can have a positive impact on the environment and industry.

2.5 Research Gap

Despite the advancements in simulation modeling for reverse logistics there are shortcomings in the literature, particularly regarding comprehensive models and empirical studies that assess both the environmental and economic benefits of remanufacturing logistics flows compared to conventional production. Existing models often fail to include the full lifecycle of products and the integration of reverse logistics into circular business models. In addition, these studies remain in the linear paradigm in which product returns are initially not anticipated or considered as mandatory cost after conventional sales. The existing ABMs constitute a suitable basis for model development as they capture individual stakeholders of reverse logistics networks in great detail for the case of cell phone and tire remanufacturing. However, these models do not consider automotive context with multiple hundred workshops, varying distances, logistics hubs for aggregation and redistribution or remanufactured parts back to the workshops. This paper aims to address these gaps by developing a simulation model that evaluates an automotive reverse logistics flow, comparing the environmental impact (CO_2-emissions and material demand) and cost of remanufacturing versus cost of new production. The model incorporates discrete event and agent-based simulations to offer a detailed analysis of the reverse logistics operations, providing insights into the effectiveness of circular business practices in the automotive sector.

3. METHODS

This section provides a description of the applied methodology. Figure 1 outlines the process of creating, implementing, and assessing the simulation model for reverse logistics, specifically within the context of Scania's reverse logistics network and DPFs.

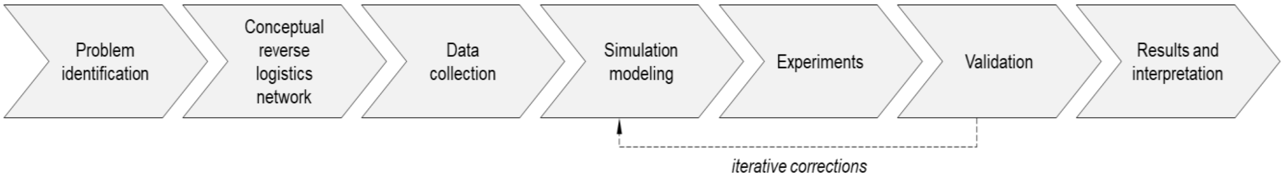


Figure 1. Methodology for Developing a Scania-Specific Reverse Logistics Network

While this section introduces the overall system that is modelled with the DPF case study and the experimental setups, a more detailed description of the model implementation is provided in the appendix. Since the major share of the model deploys agent-based techniques complemented with discrete event features within each agent, the description follows the ODD protocol (Overview, Design, concepts, Details) for ABMs (Grimm, 2010).

3.1 System Description

The reverse logistics network is modeled using a combination of ABM and discrete event approach. This hybrid approach captures the complexity of the reverse logistics process by integrating different modeling techniques to represent both macro-level behaviors and micro-level processes. The key components of the system include five main agents: Workshops, one inspection center, one remanufacturer, one distribution center (DC), and trucks responsible for transportation (see Figure 2).

In the reverse logistics network, customers return used parts in the workshops due to failure or preventive replacement. These parts are then transported to the inspection center, where they are assessed for remanufacturing eligibility. Only parts meeting the remanufacturing criteria are selected and sent in full truckloads to the remanufacturer. At the Remanufacturer, parts undergo another quality check to ensure they meet performance standards for remanufacturing. Parts that fail this check are discarded, while parts that pass this check are remanufactured and subsequently shipped to the DC for storage and distribution to workshops as per demand. The truck agents manage the transportation logistics, ensuring that parts are delivered to the correct locations at the appropriate times between these locations.

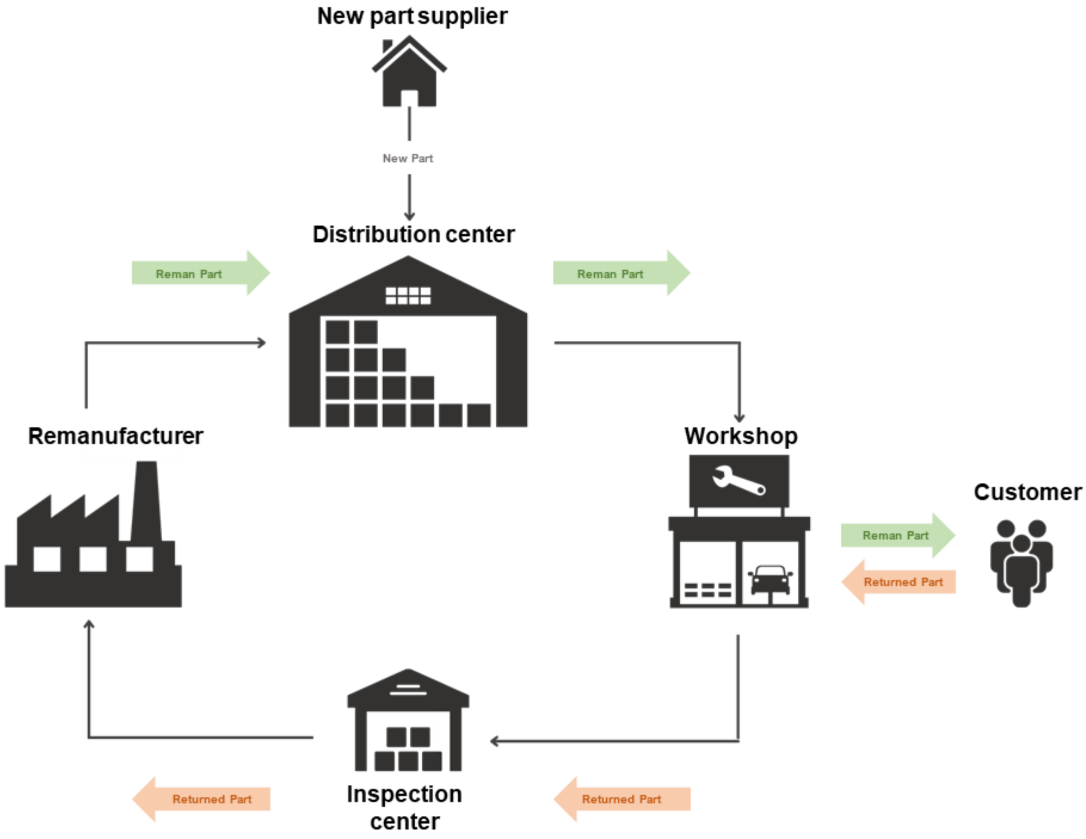


Figure 2. Conceptual Model of the Reverse Logistics Network

The simulation model is designed to handle a variety of data inputs, including location coordinates and return rates for workshops, as well as operational data such as CO_2-factors and cost values for transports. These inputs are essential for modeling the behavior of the reverse logistics network accurately. The model is based on assumptions that influence agent behavior and interaction, for example, the loading and unloading of DPFs where workshop agents and truck agents need to interact. Within each agent there are processes modelled using discrete event features to account for operations, such as remanufacturing or inventory storage processes insides the remanufacturing and DC agents. The cost and CO_2-emissions are calculated as per equations (1) through (4):

$$TC_{new} = c_{prod} + c_{SU-DC} + c_{DC-WS} \quad (1)$$

where

TC_{new}: Total cost for producing and delivering a new spare part
c_{prod}: Cost for producing a new part
c_{SU-DC}: Cost for transporting a part from supplier (SU) to distribution center (DC)
c_{DC-WS}: Cost for transporting a part from distribution center (DC) to workshop (WS)

$$TC_{reman} = c_{WS-IC} + c_{IC-RM} + c_{reman} + c_{RM-DC} + c_{DC-WS} \quad (2)$$

where

TC_{reman}: Total cost for collection, remanufacturing and delivering a reman part
c_{WS-IC}: Cost for transporting a part from workshop (WS) to inspection center (IC)
c_{IC-RM}: Cost for transporting a part from inspection center (IC) to remanufacturer (RM)
c_{reman}: Cost for remanufacturing a part
c_{RM-DC}: Cost for transporting a part from remanufacturer (RM) to distribution center (DC)
c_{DC-WS}: Cost for transporting a part from distribution center (DC) to workshop (WS)

$$TE_{new} = e_{prod} + e_{SU-DC} + e_{DC-WS} \quad (3)$$

where

TE_{new}: Total emission for producing and delivering a new spare part
e_{prod}: Emission for producing a new part
e_{SU-DC}: Emission for transporting a part from supplier (SU) to distribution center (DC)
e_{DC-WS}: Emission for transporting a part from distribution center (DC) to workshop (WS)

$$TE_{reman} = e_{WS-IC} + e_{IC-RM} + e_{reman} + e_{RM-DC} + e_{DC-WS} \tag{4}$$

where
TE_{reman}: Total emission for collection, remanufacturing and delivering a reman part
e_{WS-IC}: Emission for transporting a part from workshop (WS) to inspection center (IC)
e_{IC-RM}: Emission for transporting a part from inspection center (IC) to remanufacturer (RM)
e_{reman}: Emission for remanufacturing a part
e_{RM-DC}: Emission for transporting a part from remanufacturer (RM) to distribution center (DC)
e_{DC-WS}: Emission for transporting a part from distribution center (DC) to workshop (WS)

3.2 Case Study: Diesel Particulate Filter

To illustrate the application of the simulation model, DPFs are included as case study product. A DPF is an after-treatment device used in diesel engine systems to reduce particulate emissions. The diesel engines are known for their high efficiency, durability, reliability and low operating costs making them the most popular engines for heavy-duty vehicles. However, they are also a significant contributor to environmental pollution due to their exhaust system making the DPF a crucial component to reduce their environmental impact (Resitolu et al., 2015). The DPF works by trapping soot and other particulate matter in porous ceramic filter as explained on Figure 3. The trapped particulate matter is burned off at high temperatures during a process called “regeneration”, which occurs automatically while driving. Despite this “regeneration” process proper maintenance is required to ensure the safe and comfortable operation of diesel cars (Valvoline Global Europe, 2024). In that context DPFs need to be replaced or cleaned after a certain number of miles or time.

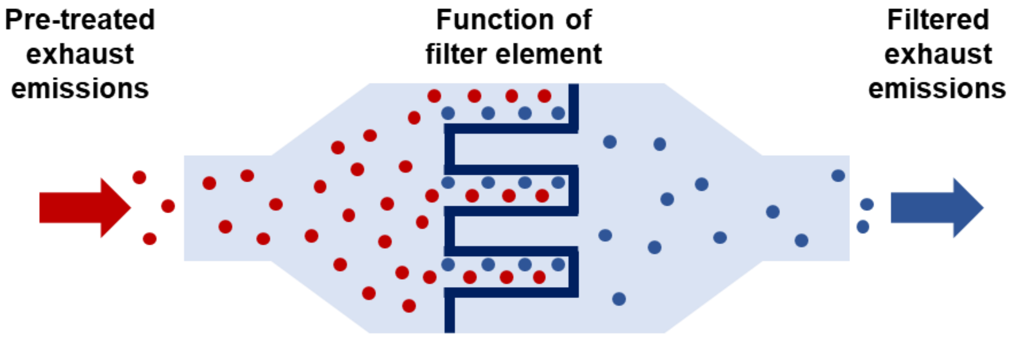


Figure 3. Picture of a DPF with Explanation of its Function Based on Carbase, 2024

DPFs can be remanufactured which is believed to require less material and energy compared to producing a new one from scratch resulting in lower costs and lower emissions. The remanufacturing process of a DPF involves a comprehensive inspection, disassembly, cleaning, and replacement of any damaged or worn components to ensure it meets the required performance standards (Sundin et al., 2016).

3.3 Experiments

After developing the simulation model, two experiments are conducted. These experiments are designed to evaluate the overall system effectiveness of the remanufacturing ecosystem compared to new production, and to analyze what system parameters have greatest impact on cost and emissions in the reverse logistics network.

3.3.1 Baseline Scenario

The first experiment, the baseline Scenario, aims to compare the cost and emission impacts of remanufacturing versus new production of DPFs over a four-year period for the European after-market. Input data is collected through interviews which includes, for example, transportation costs, sizes of truck loads and scrap rates at different locations. This input is confidential due to the commercial nature of the data. During this simulation run, several performance metrics are recorded. These metrics include the number of parts picked up, the number of parts delivered as remanufactured parts, and the number of parts lost during the process, among others. These losses are taken into account when comparing the environmental and economic impacts of remanufacturing versus new production of DPFs. The data collected during the simulation include the following:

- Stock levels
- Number of idle trucks
- Number of waiting orders and completed orders
- Cost and CO_2-emissions associated with new production
- Cost and CO_2-emissions associated with remanufacturing

After the simulation run, the data is analyzed to directly compare the remanufacturing flow and the new production flow of DPFs in Europe. One major assumption is that the number of delivered remanufactured DPFs would have been fulfilled by the same number of new DPFs.

3.3.2 Sensitivity Analysis

The second experiment is a sensitivity analysis to explore how variations in three key parameters affect the model's outcomes: (1) the distance driven with load, (2) the scrap rate at the inspection center, and (3) the remanufacturing success rate at the remanufacturer. Each parameter is varied from -75% to +100% of its baseline value in 25% increments. The goal is to identify which parameters significantly influence the total cost and CO_2-emissions. The results are meant to reveal which variables are most critical for optimizing the reverse logistics network.

3.4 Validation

Validation is essential to confirm the accuracy and reliability of the simulation model. Two main validation methods have been used during simulation development: (1) Manual calculation following a single DPF and (2) stock level validation based on historical data.

A simple calculation was done to manually compare costs and CO_2-emissions for remanufacturing and new production for a single DPF scenario. This calculation considered transportation costs and CO_2-emissions for one workshop, while assuming a successful remanufacturing process. The comparison shows that the simulation results deviate by roughly 5% from the manual calculation. Since the simulation considers pick-ups from different workshops and therefore calculates varying distances, the deviation is considered a reasonable approximation for the flow of multiple hundred DPFs.

The second validation method involved ensuring that the simulation model accurately reflected stock levels at the DC. Historical data has been reviewed to identify average stock levels at the DC. Initially, these stock levels did not correspond to the levels of the simulation. Consequently, corrections needed to be made, and the simulation repeated. More specifically, the order frequency of all workshops to the DC needed to be implemented with one global distribution to reach an average stock level at the DC that mirrors historical data as close as possible. Therefore, an optimization experiment has been carried out to identify the best fitting global triangular distribution for order frequency. Figure 4 summarizes the procedure visually. This validation effort has been time-consuming but ensures that the simulation model is an accurate and reliable representation of real-world dynamics.

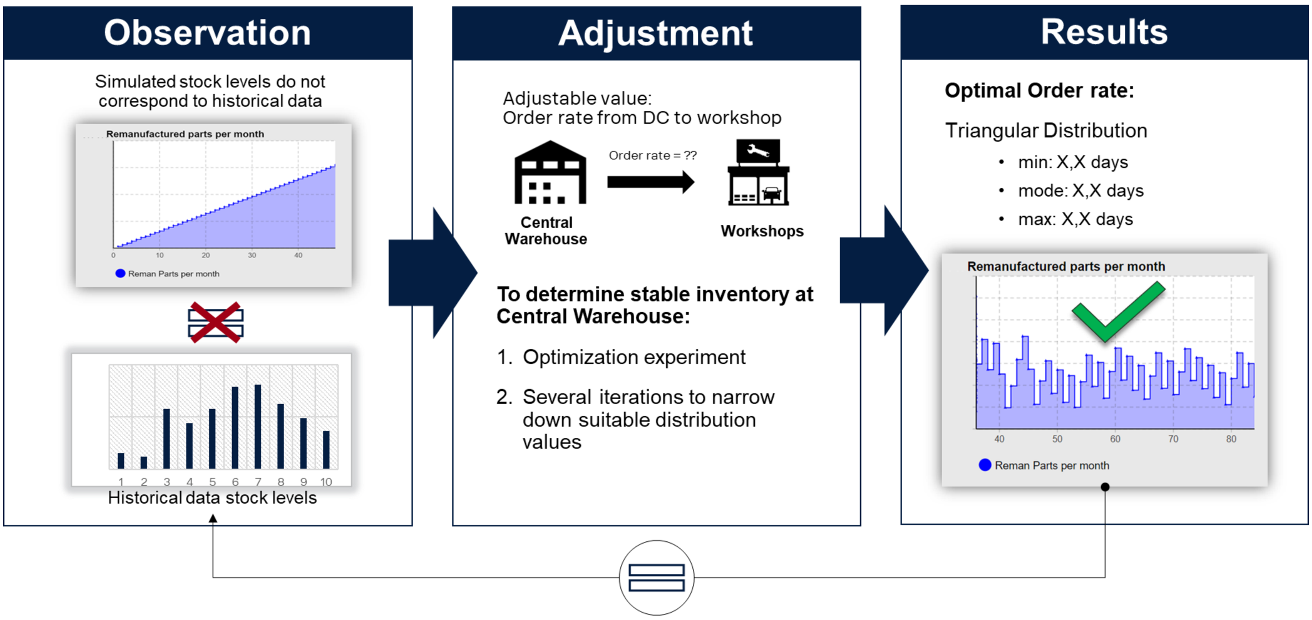


Figure 4. Overview of Model Calibration Approach as a Result of Validation Through Historical Data (Anonymized Result)

4. RESULTS

4.1 Baseline Scenario

The results of the four-year simulation run are summarized in Figure 5. The figure compares the main metrics for both the remanufacturing and new production processes and the delivery of spare parts.

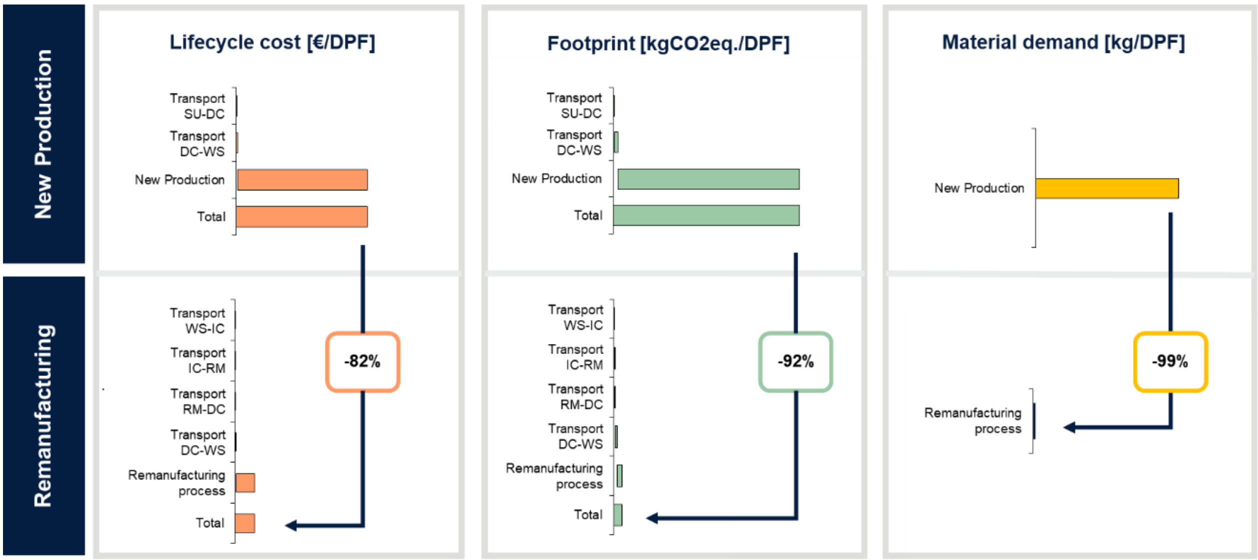


Figure 5. Results from Baseline Scenario Comparing New Production and Remanufacturing Scenario Based on Cost, CO_2-Emissions and Material Demand (SU: Supplier, DC: Distribution Center, WS: Workshops, IS: Inspection Center, RM: Remanufacturer)

The results reveal significant insights into the comparison of using remanufactured spare parts compared to newly produced spare parts. The cost per DPF is 82% lower for the remanufacturing process compared to new production. This is based on the main assumption that the returned cores are remanufactureable and capable of meeting the demand. Thus, as long as this assumption holds true, the results indicate that remanufacturing offers cost advantages in terms of reduced expenses associated to new production. However, in case the returned cores cannot be remanufactured, then the demand needs to be fulfilled with new parts, which leads to greater costs. Furthermore, the CO_2-emissions per DPF, which measures the environmental impact in terms of emissions associated with production and transport, demonstrates a favorable outcome for remanufacturing. The footprint per DPF is 92% lower for the remanufacturing process, indicating its potential for reducing CO_2-emissions compared to new production. Additionally, the material demand per DPF, which quantifies the amount of raw materials required for each unit produced, shows a more efficient utilizations of resources by remanufacturing. Remanufactured DPFs require 99% less material, showcasing its capacity to diminish resource consumption. This significant reduction in material demand is based on the remanufacturing process, which is primarily centered around thorough cleaning with minor (if at all) part replacements. Thus, very often the remanufacturing process eliminates the need for extensive material replacement for DPFs.

4.2 Sensitivity Analysis

The sensitivity analysis aims at exploring how cost and emissions are impacted by varying key parameters. In this study three parameters were explored: transport distance, scrap rate at inspection center and the remanufacturing success rate. Figure 6 illustrates the relationship between the three varying parameters and their respective outcomes for cost and CO_2-emissions.

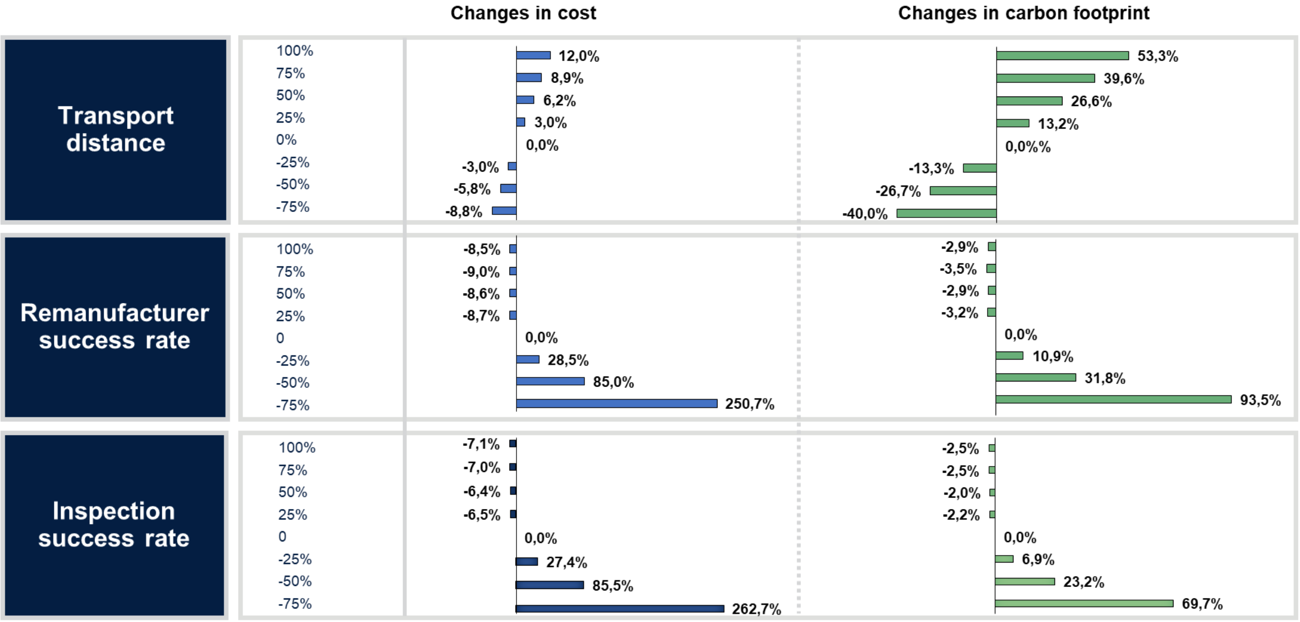


Figure 6. Results of the Sensitivity Analysis

Looking at the results it is evident that the success rate at the remanufacturer and the success rate from inspection play a pivotal role in determining the losses in the given logistics network. The findings indicate that if the success rate at the remanufacturer is decreased by 75% from its current baseline, then there is a substantial increase of approximately 250% in costs and a rise of more than 90% in CO_2-emissions. The success rate from inspection shows similar trends. From a CO_2-emission perspective, transport distance has the greatest reduction potential shown through a potential of -40% achieved by an extreme reduction in transport distance by -75%. Furthermore, it can be observed that there is an expected correlation between cost and CO_2-emissions based on the transport distance. Both, CO_2-emissions and costs increase/decrease proportionally if transport distance increases/decreases, which is logical due to changes in transport distances.

5. DISCUSSION

The simulation approach demonstrates how one entire reverse logistics network of DPFs can be modelled including workshops, intermediate collection hubs and remanufacturing facilities. By using agents as reverse logistics actors and discrete event elements to model processes within each of these actors, it becomes viable to include a large number of workshops and their operations individually. The collection of DPFs from many hundred workshops and aggregation in a hub, followed by their delivery to remanufacturer and redistribution to workshops can be modelled in detail to mirror actual real-world movement and time-behavior of reverse flows. This systemic perspective helps in future optimization and coordination efforts to make the reverse logistics network more efficient and for evaluating reverse logistics performance.

Furthermore, when comparing the conventional production logistics flow with the remanufacturing logistics flow of a DPF, the results strongly indicate that remanufacturing yields superior outcomes in terms of cost, CO_2-emissions and material demand. This outcome is, however, specific to the case study of DPFs and the reverse logistics network at hand and cannot be generalized towards other automotive parts or other (non-Scania) logistics networks. At this point the specific characteristics of DPF remanufacturing need to me mentioned: The remanufacturing process of DPFs compared to remanufacturing processes of other automotive parts requires relatively little intervention in terms of e.g., dismantling, parts replacement and reassembly, and thus lower need for labor. Cleaning and testing are the most crucial remanufacturing activities for DPFs, which are often automated. This results in great material and time savings, and therefore great cost and CO_2-emission savings compared to new production. The potential of savings can furthermore increase if valuable materials are embedded during new production into DPFs. As a consequence of these great savings, there is a large margin for (inefficient) reverse logistics activities i.e., pick-up, collection, sorting and redistribution until reaching cost-parity with new DPFs.

From a managerial point of view, the cost reduction is significant to provide a cost-efficient alternative to newly produced DPFs. Based on the sensitivity analysis, the business case stays positive even with a lower success rate at the remanufacturer and a lower success rate at inspection. To be more specific, with an average cost savings of -82% per DPF the cost could increase with +455% to reach the cost level of a newly produced DPF. Such cost increases occur if the remanufacturing success rate or the inspection success rate drop below -75%. The case is similar for the CO_2-emissions. These considerations highlight how cost-efficient remanufacturing processes compensate for great uncertainty in the reverse supply chain. To provide an answer if remanufactured DPFs are superior to new DPFs, while using the identified savings from the baseline scenario (Figure 5), the potential distance can be calculated that DPFs could be transported until breaking even with new DPF production and delivery. Based on CO_2-emission savings, an additional 63.500 km per DPF would be feasible, while cost savings even indicate an additional 136.000 km per DPF. This means that collecting DPFs from any destination on the globe and remanufacturing them is always economically and environmentally more beneficial than producing new DPFs. For parts with work-intensive remanufacturing cases and a greater share of replaced parts, this type of break-even calculation is supportive to identify trade-offs when deciding whether to remanufacture or produce parts from scratch. One fundamental assumption is that cores (used DPFs) can be successfully obtained from the market and that the remanufacturing process is reliable.

Moreover, the sensitivity analysis highlights that the remanufacturing success rate and inspection success rate at the collection hub are the most influencing factors on the overall performance of the DPF reverse logistics network. The scrap rate along in the reverse supply chain has greater impact on the cost profile than transport distance. The later a DPF is scrapped, the more costly from a total cost perspective, which is why late scrapping of parts should be avoided. These results may change in the light of varying costs e.g., through increasing fuel prices or salaries for working staff. When it comes to CO_2-emissions, the transport distance has the greatest potential when it comes to CO_2-emission savings. However, these effects can be nullified if current inspection and remanufacturing success rates are decreased by -50% and below from its current baseline. As a natural recommendation, it can be stated that it is beneficial to reduce transport distances while increasing and maintaining high inspection and remanufacturing success rates.

The discussion so far has addressed potential improvements based on remanufacturing operations and underlying logistics of spare part transport. Since the vast majority of CO_2-emissions of heavy-duty vehicles are attributed to the use phase, a potential rebound effect needs to be addressed that may result from scaling remanufacturing activities and thus extending the lifetime of older vehicles. Such lifetime extension may delay the adoption of more CO_2-friendly propulsion technologies and lead to an overall increase of emissions on overall transport system level. Such a rebound effect is more likely if the replacement of DPFs happens in the last phase of the vehicle use phase. On the other hand, if the replacement is carried out during earlier stages in the vehicle life, it is challenging to establish causality between DPF renewal and longer use life. Hence, the timing of DPF replacement in relation to other parts is a crucial aspect in improving system effects on transport system level. Since such aspects are not part of the analysis above, this study is limited to operational benefits within Scania's spare part (circular) supply chain.

This model can be reused for other remanufactured spare parts and to quantify systemic effects. The network structure of the workshops in Europe can be reused as these do not change in short-term. However, part and process specific data needs to be gathered and adjusted, such as remanufacturing process modeling (cost and

CO_2-emissions), quota of replaced sub-components as well as transport frequencies and load sizes between the hubs since collection rate and demand may differ from the DPF.

6. CONCLUSIONS

The main objectives of this paper are to develop a reverse logistics simulation model and to test if remanufactured DPFs are more beneficial in terms of cost and CO_2-emission impact compared to new production given an automotive spare part context. For that, a simulation-based decision support tool has been developed that assesses the effectiveness of a European reverse logistics network for remanufactured DPFs and compares outcomes to newly produced spare parts. Through the successful implementation of the modeling and quantification techniques, it has been demonstrated that a comprehensive logistics system, encompassing automotive workshops, intermediate hubs and remanufacturing facilities, can be effectively modelled using a combination of agent-based and discrete event methods. The results of two experiments supported the advantage of remanufacturing DPFs. In the baseline scenario, remanufacturing demonstrates superior outcomes compared to new DPF production in terms of cost savings (-82%), carbon footprint savings (-92%) and material savings (-99%). Such great savings compared to new DPF production demonstrate the possibility to cover global distances to collect DPF, while still maintaining cost and emission levels below newly produced DPFs. The sensitivity analysis identified inspection and remanufacturing success rate as the most influential parameters on overall cost, while reductions in transport distance have the greatest potential to reduce overall CO_2-emissions in the reverse logistics network. This work has laid the foundation for assessing the effectiveness of reverse logistics for remanufactured spare parts and has shown promising results in favor of remanufacturing. Addressing future work, the field of reverse logistics can be further advanced to reach scalable sustainable practices in the industry. Firstly, the simulation model can be expanded to include additional metrics covering further environmental, business-related and social aspects. Such an expansion would provide a more comprehensive structure for metrics and decision-making. Furthermore, to enhance the practicality and usefulness of the developed model, it is essential to investigate the scalability and generalizability of the obtained findings across a wider range of spare part flows. By expanding the scope to include various types of existing spare parts, a more comprehensive understanding of the reverse logistics system can be gained to analyze its effectiveness and identify hindrances with regards to circular business transition. Lastly, the reverse logistics network as a whole can be questioned, which leads to consideration of additional collection hubs, multiple remanufacturers and their locations. A dedicated network analysis including optimization scenarios for locations can guide the way to further reduce cost and CO_2-emissions and inform strategic business decisions.

AUTHOR CONTRIBUTIONS

Michael Lieder: initiation, investigation, funding, methodology design, supervision, debugging, visualization, writing draft, editing, review
Thordis Tryggvadottir: simulation development, data curation, coding, validation, debugging, visualization
Farazee M. A. Asif: conceptualization, supervision, methodology design, review

DECLARATIONS

Competing interests: The authors declare no competing interests.

APPENDIX

1. APPENDIX A1: AGENT-BASED MODEL

This section describes the architectural design of the ABM. As a smaller part of the model uses discrete event approach, the model primarily focuses on the interactions of the agents and their overall system performance. To ensure a clear and standardized communication of the ABM framework, the ODD (Overview, Design Concept, Detail) protocol is followed in detail for the documentation of the model (Grimm et al., 2010).

1.1 Purpose

The purpose of this ABM is to simulate the existing logistics network for Scania's aftermarket operations when it comes to remanufactured parts and compare the effect of reverse logistics flow of a DPF to the effect of forward logistics of a new DPF.

1.2 Entities, State Variables and Scales

Table A1 lists variables and parameter on global modeling level (main). Parameters values are inputs to the model and have been collected through interviews with business units, remanufacturing operators and engineers within the DPF ecosystem.

Table A1. Global Variables and Parameters

Main modeling level

Variable name	Description [Units]	Data type
Total delivered parts	Total number of remanufactured units that have been delivered to a workshop during simulation [count]	integer
Total returned parts	Total number of units that have been returned to workshop during the simulation [count]	integer
Total scrapped parts	Total number of parts that have been scrapped during the simulation [count]	integer
Idle trucks	Number of trucks that are idle / not in use at a time [count]	integer
Lost deliveries	Counts number of times DC is not able to deliver an order due to insufficient stock levels [count]	integer
Total cost	Total cost [Euro]	double
Total CO2	Total CO2 [kgCO2eq.]	double
Total added material	Total added material [kg]	double
Parameter name	Description [Units]	Data type
CO2 emission for truck	A constant for the CO2 from transportations [Kg CO2eq/ton Km]	double
Transortation Cost	A constant for the cost for the transportations [€/Km/count]	double
Part weight	The weight of a single unit [Kg]	double
Remanufacturing Cost	A constant for the cost that comes with remanufacturing [€/count]	double
Remanufacturing CO2	A constant for the CO2 that comes with remanufacturing [Kg/count]	double
Remanufacturing Success rate	A constant for the success rate at the remanufacturer [%]	double
Added Material per unit	A constant for the added material that comes with remanufacturing [Kg/count]	double
Full truck load	A cosntant for the number of units that are in a full truck load [count/truck]	double
Scrap rate	A constant for the scrap rate during the inspection at the inspection center [%]	double
Cost for a new part	A contant for the cost of producing the unit from scratch [€/count]	double
CO2 for a new part	A constant for the CO2 emission that comes with producing a new part [Kg CO2eq/count]	double

The model consists of five key agent types: workshops, inspection center, remanufacturer, distribution center (DC), and a truck agent responsible for transportation between these agents. Each agent is represented as an individual entity, with its own set of state variables and behavior rules. State variables for each agent depend on their role in the system. Some of the state variables are aggregated at the global system level (main) and provide information on the overall system performance. Table A2 summarizes agent-specific variables i.e., used within each agent.

Table A2. Agent-Specific Variables

Workshop

Variable name	Description [Units]	Data type
Location	Latitude & Longitude values for the locations of the workshops, each workshop has its own location [degrees]	double
Returned parts stock	Number of returned parts in inventory at a time [count]	integer
Return rate	The rate at which the customer returnes used units to workshop. Each workshop has its own return rate [count/month]	exponential arrival rate (double)
Stock threshold	The stock level when parts are shipped, all workshops have their own value [count]	integer
Order rate	The rate at which the workshop orders remanufactured parts from DC. Each workshop has its own order rate [count/week]	exponential arrival rate (double)
Order quantity	The number of parts in a workshop order. Each workshop has its own order quantity [count/order]	integer

Inspection center

Variable name	Description [Units]	Data type
Location	Latitude & Longitude values for the location of the inspection center [degrees]	double
Returned parts stock	Number of returned parts in inventory at a time [count]	integer
Stock threshold	The stock level when parts are shipped [count]	integer

Distribution center

Variable name	Description [Units]	Data type
Location	Latitude & Longitude values for the location of DC [degrees]	double
Remanufactured Parts	Number of remanufactured parts in inventory at a time [count]	integer

Remanufacturer

Variable name	Description [Units]	Data type
Location	Latitude & Longitude values for the location of the remanufacturer [degrees]	double
Remanufactures parts	Number of remanufactured parts in inventory at a time [count]	integer

Truck

Variable name	Description [Units]	Data type
Load	Number of parts in the load being transported [count]	integer
Load weight	The weight of the load being transported [kg]	double

Each agent has a state that indicates its current status, such as whether it is idle, processing parts, or waiting for transportation. The statechart of each agent varies depending on its role in the system, but all fixed-location agents (i.e., workshops, inspection center, remanufacturer, and DC) share a similar statechart with minor deviations. To provide a better understanding, Figure A1 shows an example of the statechart for a workshop agent, which includes states such as ”Satisfied”, ”Waiting for Pickup”, ”Waiting for Delivery”, and ”Getting Order”.

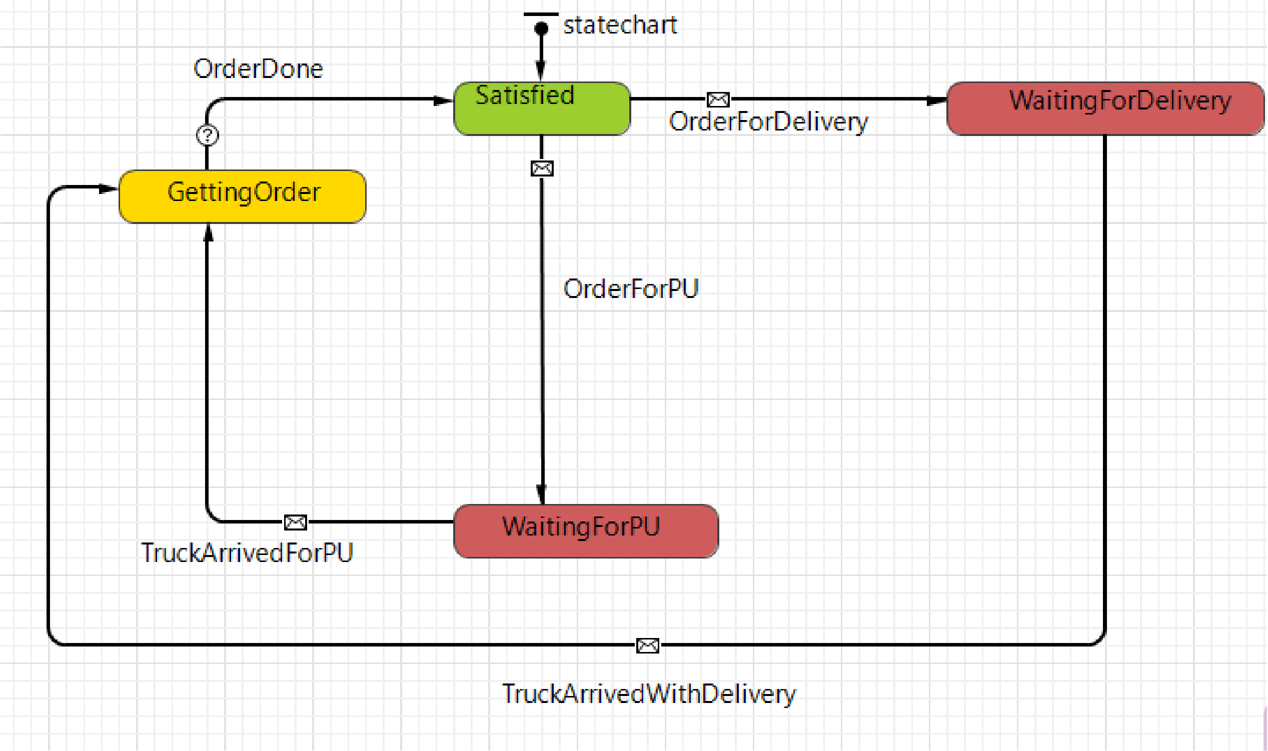


Figure A1. Statechart of Workshop Agent

The workshop agent transitions through these different states in a sequential process. When the parts are waiting for delivery, the arrival of the truck triggers a transition to the ”Getting Order” state. Once the truck unloads all the parts, another message prompts a transition to the ”Satisfied” state, indicating successful order fulfillment. This statechart is representative of the statecharts of all fixed-location agents. In contrast, the statechart for the truck agent includes states such as ”Moving to Pickup Location”, ”Loading Parts”, ”Moving to Delivery Location”, and ”Unloading Parts”. However, the statechart of the truck agent, which is responsible for the transportation of parts between agents, is different as it includes states related to its movement and delivery of parts.

The model uses a GIS map to locate the agents in terms of longitude and latitude and street routes to allow trucks agents to move between locations autonomously. This enables truck agents to take the fastest route between the fixed agents and also allows for the visualization of the geographic distribution of the network as presented in Figure A2. Each agent is placed on the map using its respective longitude and latitude coordinates. This allows for the modeling of spatial units and that are an important aspect of the model, as they impact the transportation of parts and the overall flow of the reverse logistics network.

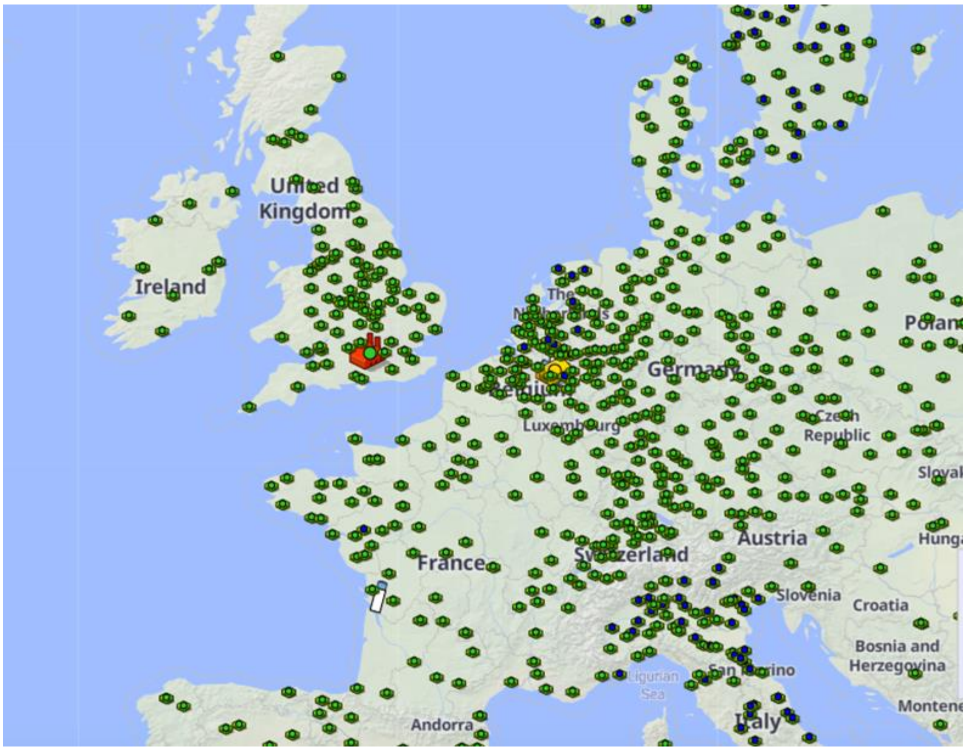


Figure A2. Visualization of the Geographic Distribution of the Network Using GIS Map

1.3 Process Overview and Scheduling

The model is designed to run in discrete time steps of one month each. The model is run for a period of four years, during which various events occur that affect the performance variables. Through the simulation run performance parameters are reported on a monthly basis. To give an overview of the process in question, the workshop agents hold the starting event. These events can be considered as the first point of interaction as that is the place where returned DPFs are dropped off from end customer. Each workshop has its own return rate per month according to historical data. When parts are returned to workshop, they enter a discrete event process to keep track of the inventory level. Once the inventory level reaches the stock threshold for that workshop, the parts are shipped to the inspection center for inspection. If the parts pass inspection, they are sent to the remanufacturer for remanufacturing. At the remanufacturer, the parts undergo a second evaluation to determine if they can be remanufactured or if they need to be scrapped. If the parts pass the evaluation, they undergo remanufacturing. Once remanufactured, the parts are shipped to the DC for storage and then sent to workshops upon demand.

The order of events is mostly imposed, with the scheduling controlled through various discrete event processes. The scheduling of the different entities in the model is primarily determined by the stock levels. When the stock level at a workshop reaches the delivery quantity specified for that workshop, the workshop orders a shipment to the inspection center. Similarly, when the stock level at the inspection center reaches the quantity required for a full truck load, an order is placed to ship the parts to the remanufacturer. In addition to stock levels, events are used to trigger shipments for the forward flow of remanufactured parts for example for the flow of remanufactured parts between the remanufacturer and the DC.

The state variables in the model are updated dynamically over the course of the simulation run. The inventory levels at each agent are adjusted whenever a part is returned or shipped out. Performance variables such as cost or CO_2-emissions are updated in real-time whenever an event occurs that affects them. For instance, when a truck transports parts, the distance, cost and CO_2-emissions associated with that shipment are immediately logged and added to the corresponding performance variable.

1.4 Design Concept

Basic principles: In section 3.1 of the paper, all relevant design items are summarized, including the overall modeling concept (Figure 2).

Emergence: Emergence in the reverse logistics model is characterized by the self-organization of the network and the adaptive routing behavior of the truck agents based on the changing demand for parts and transportation needs. This emergent system behavior results from the interactions and feedback between the agents and the environment so they are not predetermined by the model itself.

Adaption: The main adaptive function in the model is the trucks' ability to dynamically respond to demand changes in the system. Instead of hardcoding truck routes or destinations, focus has been set on modelling the behavior of the truck so that, depending on inventory stock levels in the network, trucks can respond dynamically to changes and adapt their routing accordingly. The truck agent's behavior is classified into four categories where two categories are for forward logistics and two for reverse logistics. This allows for the truck to move to any location without any limitations of a predetermined path or destination. The truck agents' behavior is designed to be flexible, allowing it to adapt to changes in the environment.

Objectives: The objective of the simulation modelling is to develop a comprehensive reverse logistics network model that includes all the key players to simulate the actual system as close to reality as possible. The ultimate goal is to use this model to quantitatively evaluate the impact on cost and CO_2-emissions of the network, to make a comparison between the remanufacturing logistics flow and the new production logistics flow for DPFs.

Sensing: The sensing capabilities of the agents and their interactions with each other have already been mentioned previously. These agents are able to sense and respond to changes in the system, such as changes in inventory levels or the arrival of new parts.

Interaction: The interactions between the various agents in the system are primarily driven by the exchange of orders and the management of order collections. For example, when the stock level at a workshop reaches a certain stock threshold, an order object is created and added to the "OrderRequests" collection. The truck agent is constantly checking this collection for new orders and will move to the appropriate location and carry out the necessary actions in response to each order. The overall aim is that the interactions between the agents are designed to be efficient and streamlined without delays and errors. By using orders and order collections, the system is able to effectively manage the flow of parts between these agents and ensure that each agent is carrying out the appropriate actions at the right time.

Stochasticity: The main source of stochasticity in the model is the rate at which a workshop orders remanufactured parts from the DC. This rate is modeled using a triangular function with predetermined minimum, maximum, and mode values. The use of this function allows for a level of variability in the ordering process, which contributes to the overall stochasticity of the model.

Observation: During the simulation run data is collected. The collected data contains, for example, the total number of delivered parts, total returned parts and total scrapped part throughout the simulation. Additionally, there are aggregated variables that provide important information on the performance of the overall system, such as total cost, total CO_2-emissions and total demanded material. There are more detailed breakdowns of these variables such as CO_2-emissions and cost only for certain transportation sections such as between DC and workshop.

1.5 Initialization

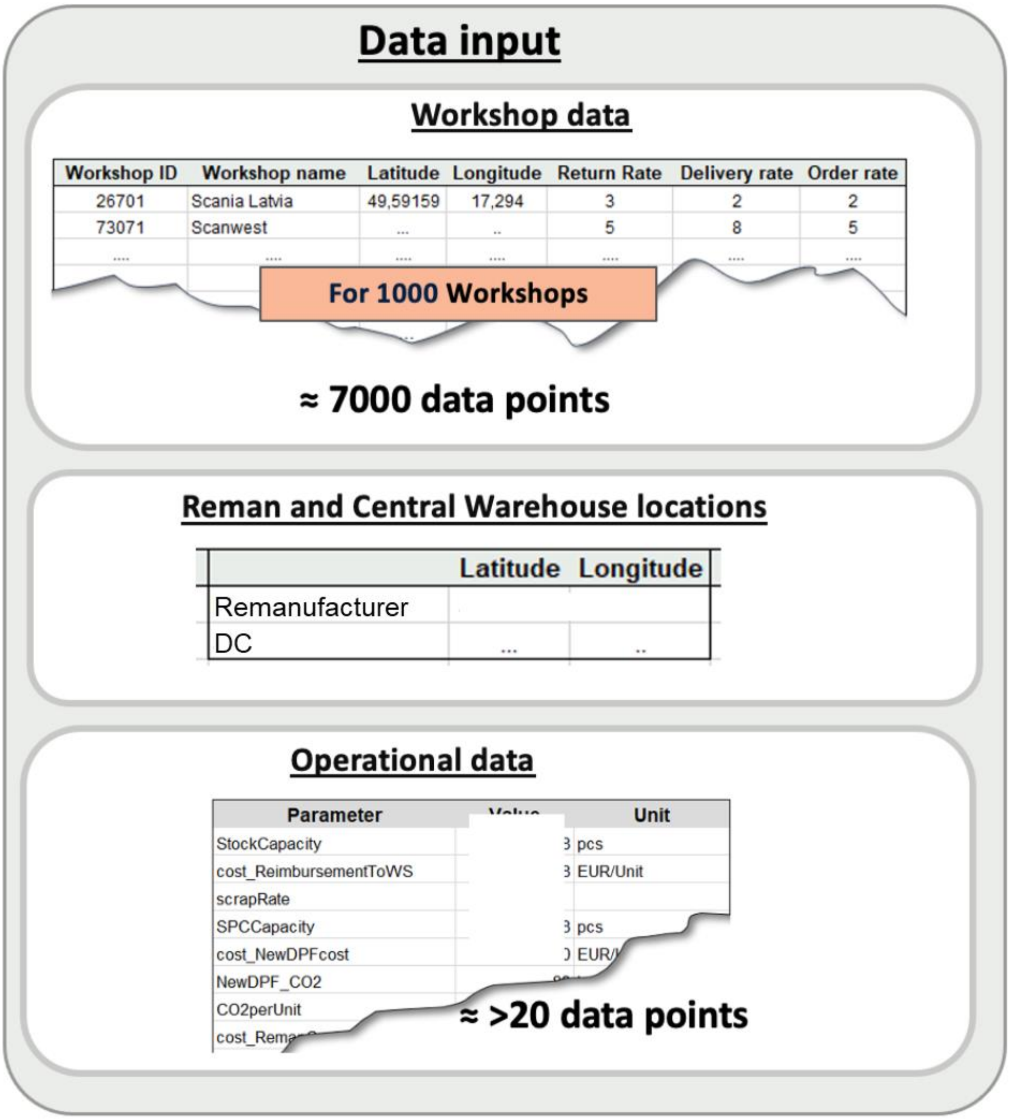
In this study, the initialization process consists of two steps. The first is the creation of the network which is done once in the beginning. The second step is setting the input parameters.

Network creation: the initialization of the reverse logistics network used for this study is crucial to ensure accurate simulation results. To achieve this, a GIS map is used which enables the different agents in the model to be geographically located. Each fixed position agent is initialized with its respective latitude and longitude coordinates obtained from a connected database, which are used to position them on the map. Around 1000 workshops are included in the database analyzed in this study, and their location coordinates are utilized to assign the particular latitude and longitude coordinates to every agent. With the application of this database, a precise representation of the actual logistics network can be created in the simulation model.

Setting global parameters: Before simulation start, a number of global input parameters must be defined. Every time the model runs, its initialization procedure reads values from an excel sheet to set these parameters. These parameters have been gathered from Scania sources.

1.6 Input Data

The model requires two distinct sets of input data as shown in Figure A3. The first data set includes information such as the latitude and longitude coordinates, the drop off rate, the stock level threshold, and the order quantity for each workshop. This dataset is utilized during the initialization phase to create the network and set the corresponding parameters for each workshop. The second input data set is the operational data, which contains constants like costs and CO_2-emissions. This data is used to establish the parameter values at the beginning of a simulation run.



Workshop ID	Workshop name	Latitude	Longitude	Return Rate	Delivery rate	Order rate
26701	Scania Latvia	49,59159	17,294	3	2	2
73071	Scanwest	...	..	5	8	5
....	....	....	....	....	....	....

	Latitude	Longitude
Remanufacturer		
DC	...	..

Parameter	Value	Unit
StockCapacity		pcs
cost_ReimbursementToWS		EUR/Unit
scrapRate		
SPCCapacity		pcs
cost_NewDPFcost		EUR/
NewDPF_CO2		
CO2perUnit		
cost_Rem		

Figure A3. Data Input Overview

1.7 Submodels

The processes that exist within the agents in this model can be considered as the submodels.

Workshops: The workshop agent uses discrete event methods to track the flow of returned and remanufactured parts, shown on Figure A4. When a customer returns a part, the workshop agent receives it at a predefined rate based on the return rate for that specific workshop. As the number of returned parts accumulates and reaches the predefined stock capacity, the workshop agent orders a truck to pick up the returned parts and deliver them to the inspection center. As for the remanufactured parts, the workshop agent orders remanufactured parts at a predetermined order rate from the data sheet.

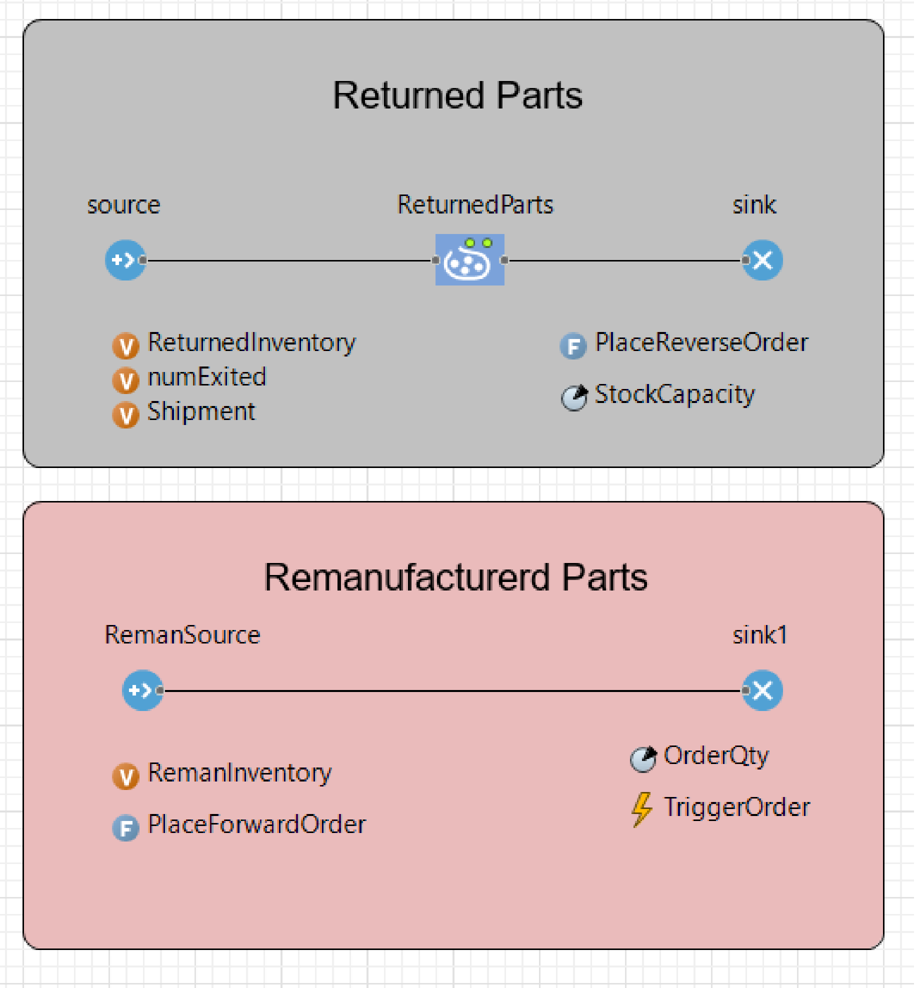


Figure A4. Discrete Event Logic Within Workshop Agents

Inspection Center: The inspection center is responsible for determining which returned parts are eligible for remanufacturing. The inspection process within the inspection center agent is modeled using discrete event features. Parts enter the inspection center through a source block and are then processed through a gate where the ”scrapRate” parameter determines the percentage of parts that should be scrapped. The remaining parts that pass through the gate are temporarily stored until the stock level reaches a certain stock level. Once the stock level, defined in the parameter ”SPCCapacity”, is reached, the parts are then directed to a sink block and shipped to the remanufacturer for further processing.

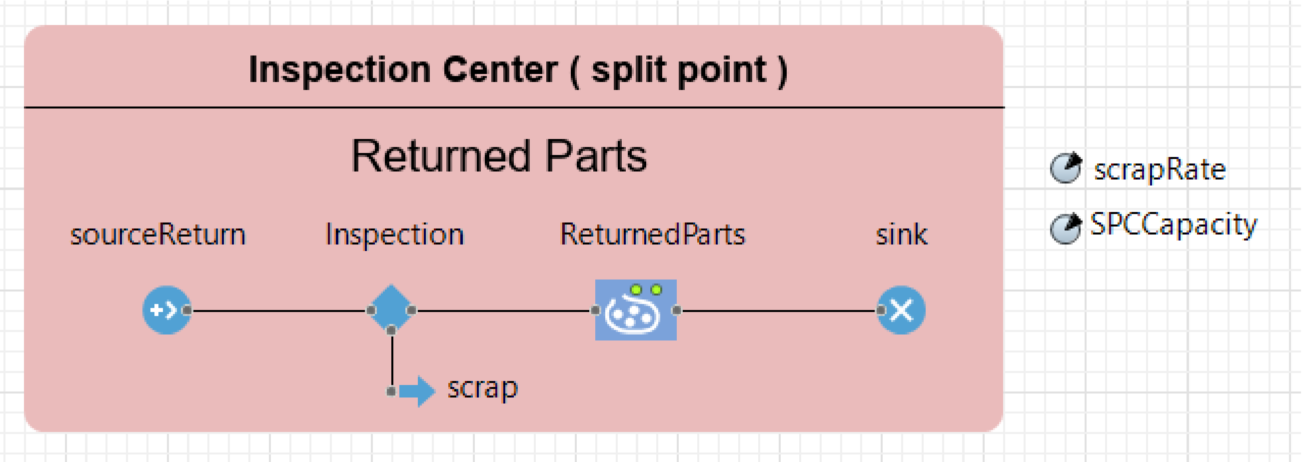


Figure A5. Discrete Event Logic Within Inspection Center Agent

DC: The DC is responsible for storing and managing the inventory of remanufactured parts. The process of storing and shipping the parts within the DC agent is modeled using discrete event features shown in Figure A6. Parts are received at the DC agent through a source block and then processed through a wait block, referred to as ”RemanParts” on Figure A6, where they are temporarily stored until they are requested by a workshop. When an order comes in from a workshop, the number of parts in that order are released from the wait block and directed to a second wait block, referred to as ”RemanParts1” on the figure. There they are stored until the truck arrives for pickup. The number of parts in each order is determined by the workshop and can vary depending on the workshop’s needs. Once the truck arrives for pickup, the parts are released from the second wait block and directed to a sink block, as they are shipped to the workshop for use.

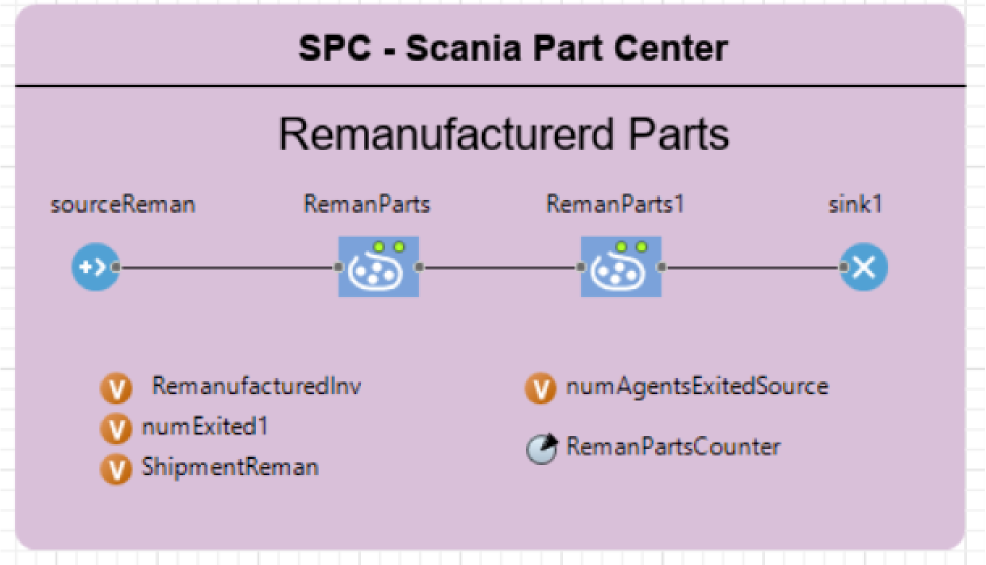


Figure A6. Discrete Event Logic Within Distribution Center Agent

Remanufacturer: The remanufacturer employs discrete event features for its process, beginning with a quality check to assess the part’s suitability for remanufacturing. The process gate employs a similar approach as the inspection center, where the ”SuccessRate” parameter determines the percentage of parts that proceed to remanufacturing. Following remanufacturing, the parts are stored and shipped in full truck loads, which occur a certain number of times on average and are triggered by a specific event.

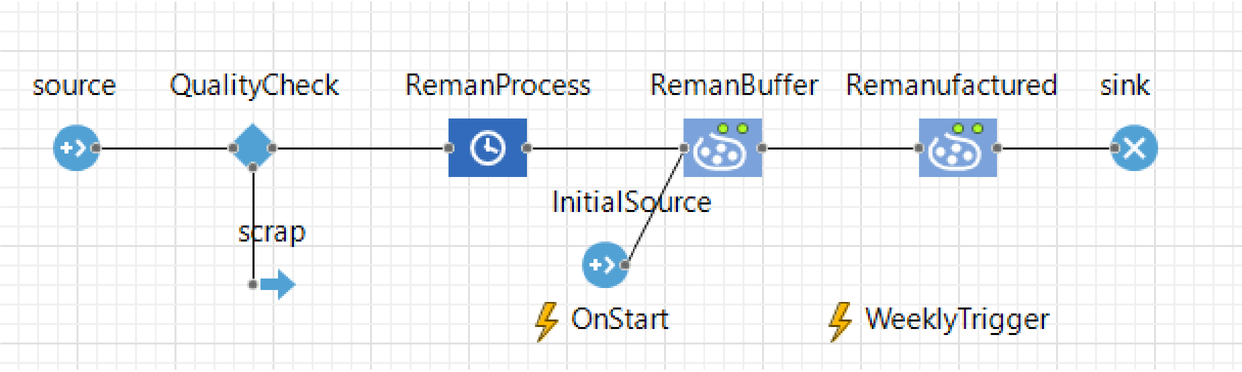


Figure A7: Discrete Event Logic Within Remanufacturing Agent

Truck: The purpose of the truck agent is to transport the parts between the various location agents and log the distances, CO_2-emissions, and costs associated with transportation. The focus of the agent-based approach for the truck is to model its behavior, rather than hardcode its route or destination. This enables the truck to respond dynamically to changes and adapt its behavior accordingly, depending on what else is happening in the system. As mentioned before the interactions between the various agents are primarily driven by the exchange of orders and the management of order collections. The interactions between the truck and the various locations are facilitated using specific branches in the truck agent's statechart making sure the truck is routed correctly. For example, if a reverse order is received from a workshop, the truck will follow the branch that leads to the workshop location, pick up the requested parts, and then proceed to the inspection center to unload them. This allows the truck to drive to any workshop without being constrained by a predetermined route or destination. Figure A8 shows how the statechart for the truck is designed.

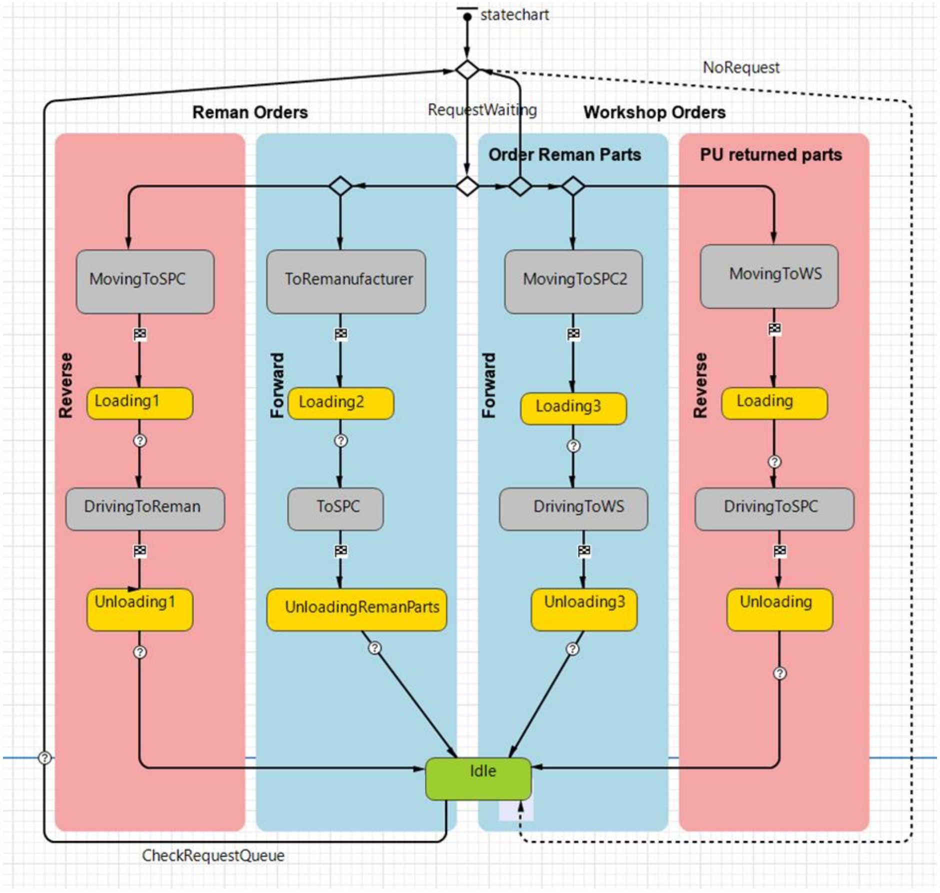


Figure A8. Agent-Based Logic for Truck Routing

SUPPLEMENTARY MATERIAL

For full-sized tables and figures found in this paper, click here or copy the following URL: http://circulareconomyjournal.org/wp-content/uploads/2025/02/Supplementary_Material_Lieder_et_al_Simulation-Models-for-Reverse-Logistics-Decisions-Insights-From-a-Case-Study-of-Diesel-Particulate-Filter-Remanufacturing.pdf

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