Modelling and Analysis of Circular Production Network Structures

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Abstract. Circular business models have the potential to generate value for consumers, benefit producers and positively impact the environment. Despite its potential, designing a circular production network remains a significant challenge. Recognising multiple factors that influence the design of production networks, the proposed approach emphasises the importance of product, process and location attributes in the design and selection of a suitable production network. Five archetypes of reverse networks, specifically tailored to reverse logistics and circular production, are introduced. These network types are analysed and compared in a simulation. The research evaluates the performance of these network types in a case study from the construction machinery industry, taking into account factors such as production volumes, regional-specific transport costs and times, labor costs de-pendent on the country, varying return volumes across the European Union. The research shows how simulation can be used to develop and evaluate suitable network types for circular production.

Keywords: Reverse Logistics · Circular Production · Remanufacturing · Network Configuration · Return Volume

1 Introduction

The circular economy represents an important opportunity to contribute to future climate goals by decoupling the production of goods from the use of resources [1]. This transition is reflected in the growing number of companies integrating circular economy principles into their operations. A critical aspect of achieving these goals is the strategic design of production networks, which remains a significant challenge for globally operating companies [2]. However, the return of a significant number of used products from customers continues to pose considerable difficulties [3]. Therefore, this paper examines these challenges and explores strategies for effective product remanufacturing, aiming to provide insights into circular global production network (GPN) structures and suitable reverse network configurations for the return of cores for remanufacturing and refurbishment.

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2 State of the Art

As GPNs are often the result of historical growth, they are usually not designed to cope with today's requirements in terms of volatility, complexity or new constraints such as increased closed-loop management [4]. Continuous adaptation of the network configuration, i.e. the structuring of GPNs concerning the geographical distribution of their sites and resources (network structure), is therefore of central importance for maintaining the competitiveness of GPNs. In this context, Abele et al. 2008 [5] define network phenotypes - local-for-local, hub-and-spoke, world factory, sequential and web structure - which are differentiated based on allocating production scopes and associated resources and the sequence of production steps. Each phenotype has different characteristics, such as local customisation, transactional costs, economies of scale and scope. This research uses these network configurations in reverse logistics and analyses their impact on costs through discrete event and agent-based simulations, building on Klenk's work in reverse supply chain simulation [3]. Consequently, this article focuses on the following primary research question:

RQ1: How do different network configurations and varying return volumes influence total costs per remanufactured product in reverse logistics operations?

Linear optimisation problems are often used to analyse and optimise reverse logistics. In contrast to linear programming (LP), simulations are particularly valuable for analysing complex systems, especially when dealing with uncertainty, non-linear relationships, and dynamic changes over time. They enable the evaluation of multiple design variants with relatively low effort, making it possible to explore a wide range of configurations [6]. It is crucial to comprehensively analyse the various cost types in reverse logistics in GPNs. These cost types include remanufacturing, transportation, handling and storage costs. Thus, the second research question arises as follows:

RQ2: Which cost components significantly impact total costs per remanufactured product in reverse logistics, and how do these costs vary across network configurations and return volumes?

3 Circular Production Network Structures

The following chapter provides the methodology and detailed description of circular production networks' implementation and structure process.

3.1 Methodology

The methodology of this study is based on the guidelines of VDI 3633, part 1 [6]. The methodological process begins with defining the objectives, followed by a system analysis, whose results are presented as a conceptual model. In this work, the conceptual model includes a system overview diagram, target values, input variables, and control variables. Developing an activity diagram and a mathematical formula describing the calculation of transport costs leads to a formal model. Both models are explained in

Sect. 3.2. Subsequently, the formal model is implemented into a software model in Python using the SimPy library. After implementing the model, experiments are conducted, and the results are analysed. A full factorial design is used in the experiments. Data collection and processing, crucial for accurate simulation input, are conducted case-specifically and in parallel with the other steps. This is detailed in the case study in Sect. 4 [6].

The applied simulation method encompasses several approaches, including discrete event simulation (DES) and agent-based simulation (ABS). DES is a process-oriented method that models events at specific points in time and represents systems as a series of discrete events, including queue modelling. ABS models the behaviour of individual agents and their interactions [7].

The simulation model used in this study is dynamic, stochastic, and discrete. Dynamic simulation models represent systems that change over time and analyse temporal processes. Stochastic simulation models involve random input components that lead to random outputs, allowing the estimation of system properties through exponentially distributed arrival times [8].

3.2 Implementation

This simulation aims to analyse the impact of return volumes in reverse logistics on selecting the economically optimal network type. The conceptual model of this work, shown in Fig. 1, is based on the work of Klenk [3] and forms the basis for the simulation. The modules are general functionality, participants, logistics and procurement, market, and product. The information agent stores all relevant information at discrete points in time in the simulation, which is important for subsequent cost calculations. The market module comprises the generation of cores and demand and matching supply and demand. The product module contains the specific product characteristics. The core arrives at the workshop, is transported to the collection centre, and finally to the remanufacturing plant. New components are also transported to the remanufacturing plant. At the end of the process, remanufactured finished goods are produced.

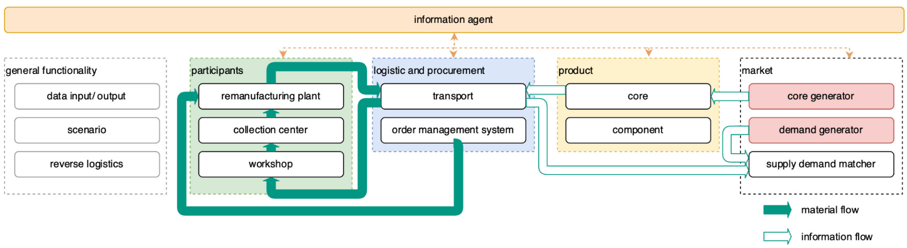

Fig. 1. Conceptual framework of the simulation modules and the material and information flow

The input variables for modelling reverse logistics processes include rejection rates, inventory and procurement parameters, and specific details for workshops, collection centres, and remanufacturing plants. Core-related variables are rejection rates, return parameters, and bills of materials. Component variables include inventory, procurement parameters, and rejection rates. At workshops, collection centres, and remanufacturing plants, variables encompass inspection, handling (loading, unloading, packaging), disassembly, and remanufacturing times, as well as depreciation and headcount. Transport parameters cover core and component capacities per pallet, transportation cost structures, and transport trigger levels. The control variables define the configurable parameters within the model and are detailed in Sect. 4. The target values serve to evaluate the cost-effectiveness of the reverse logistics processes. These include logistics, remanufacturing, and depreciation costs of the remanufacturing plant. Logistics costs cover direct transport from the workshop to the remanufacturing plant, indirect transport via collection centres, and handling and storage costs. Remanufacturing costs encompass inspection, remanufacturing, reassembly, disassembly, and depreciation.

The formal model of the reverse logistics simulation includes demand and core generation, stock checking, and supply-demand matching. Cores are inspected, palletised, and sent directly to the remanufacturing facility or through a collection centre. At the facility, cores are inspected, disassembled, and remanufactured. When all parts are available, reassembly occurs. The order management system monitors stock levels and places orders as needed. Finished products are assigned to customers on a FIFO basis.

4 Case Study and Network Structures

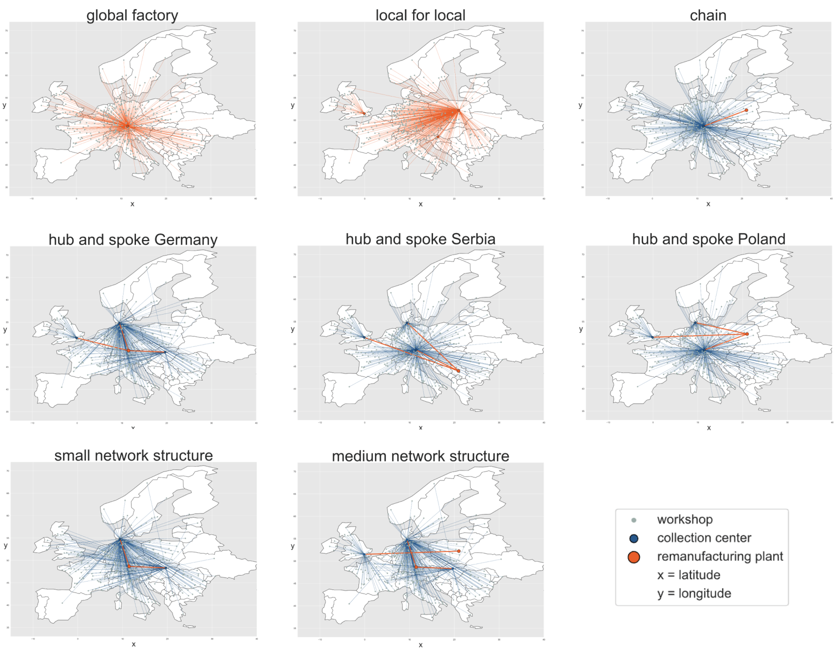

Fig. 2. Network configurations for reverse logistics in the construction equipment industry

The case study examines the potential reverse logistics of a company in the construction equipment industry. It explores variations in network configurations and return volumes for over 400 workshops, as visualised in Fig. 2. These scenarios were selected heuristically on the basis of discussions with industry experts. The network configurations include a “global factory” with a central remanufacturing facility in Germany, “local for local” with three remanufacturing facilities in the UK, Poland, and Croatia, various “hub and spoke (h&s)” scenarios with three collection centres and a remanufacturing facility in Germany, Serbia, or Poland, and a “chain” with a collection centre in Germany and a remanufacturing facility in Poland. The “small network” comprises two collection centres in Denmark and Slovakia and a remanufacturing facility in Germany. The “medium network” includes an additional collection centre in the UK and another remanufacturing facility in Poland. Additionally, return volumes vary from very low (800 cores per year) to low (1100 cores per year), medium (1400 cores per year), high (2000 cores per year), and very high (15000 cores per year).

In this case study, the following costs are considered: transportation costs, remanufacturing costs, storage costs, and depreciation of the remanufacturing plants. Ordering and penalty costs for unserved customers due to a specific scrap rate of cores and components are neglected. The following section explains the data collection and calculation of transportation, storage and processing costs for reverse logistics.

The transportation costs were systematically recorded by submitting price inquiries through a publicly accessible online portal of a logistics service provider [9]. An analysis of the correlation between transportation costs and distance revealed only a weak relationship. However, the cost analysis for varying pallet quantities identified two distinct linear trends: a steeper increase in costs was observed for the first pallets, while a more moderate linear increase was noted for the remaining pallets, up to a quantity of 20. Consequently, the transportation costs for each route are automatically determined via the portal for the first pallet. The costs for additional pallets on the same route are then calculated using a formula that accounts for these two linear trends. When querying the country-specific individual routes, deviations from standard dimensions for load carriers and means of transport are taken into account. The required storage area is increased by a factor of 1.11 to account for additional operational spaces, with rental costs set at 6.75 euros per square meter based on E&G Real Estate GmbH [10]. A five-level high-bay warehouse is assumed. Processing costs are determined based on publicly available labour rates sourced from various sources, including the Federal Statistical Office, Trading Economics, and the Austrian Federal Economic Chamber [11–13]. The following section describes the statistical distributions and model assumptions used, as well as additional specifications of the simulation. This simulation used exponential distributions to model customer demand and arrival processes, with process times following a truncated normal distribution. The maturity phase is simulated, where supply meets demand without direct coupling. Additionally, the t,S-order policy for order management is implemented.

The simulation setup includes a 90-day warm-up period and runs 365 days, with eight-hour workdays. To ensure statistical robustness, each simulation is replicated 20 times. An information agent monitors reverse logistics data. Pseudo-random numbers are consistently generated using a fixed seed value for reliability, and the Numpy random number generator transforms uniformly distributed random numbers to match desired distributions. Experiments employ a full factorial design to test all scenarios systematically. Simulation results are evaluated following VDI 3633, part 3 guidelines, averaging data and calculating confidence intervals. Statistical analysis includes the creation of a heatmap to visualize correlations, bar charts to show cost allocation, and interaction plots to illustrate variable relationships. Additionally, Tukey HSD tests were performed to identify significant differences between scenarios.

5 Results

The network configurations are visualized in terms of total costs per sold product using a heatmap in Fig. 3 and are analyzed with a Tukey HSD test. In response to RQ1: The results indicate that the “global factory,” “hub and spoke Germany,” “medium network structure,” and “small network structure” configurations consistently incur higher costs compared to the “chain” configuration, with mean differences ranging from 235% to 299%. The “hub and spoke Poland” configuration showed higher and lower costs. The “local for local” configuration showed no significant difference compared to the “chain” configuration. “hub and spoke Serbia” proved to be the most cost-effective configuration in all categories, with mean differences ranging from 74% to 374%. The “local for local” scenario without a central hub as well as the “hub and spoke Serbia” scenario with a central hub are among the more cost-effective configurations. Interestingly, “hub and spoke Germany”, despite having a similar configuration to “hub and spoke Serbia,” performs significantly worse, necessitating a closer look at the cost distribution, which is crucial for answering RQ2.

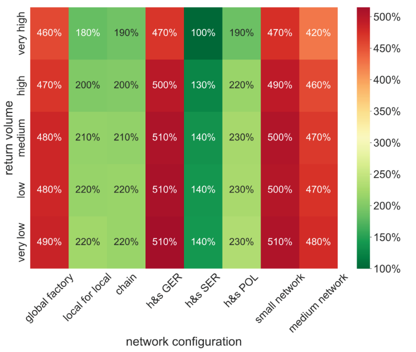

Fig. 3. Heatmap of transport costs per re-manufactured product for reverse logistics

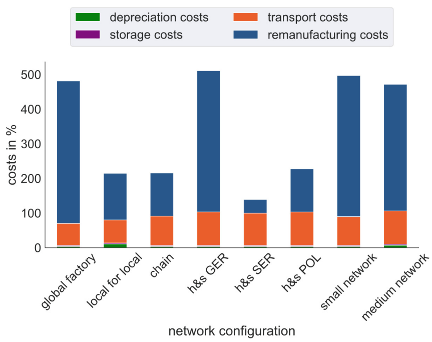

Fig. 4. Cost allocation for low return volume for reverse logistics

The cost distribution is visualised in Fig. 4. The average share of each cost type in the total costs per sold product is as follows: remanufacturing costs share 70%, transport costs share 28%, storage costs share 1%, and depreciation costs share 1%. This distribution indicates that remanufacturing costs constitute the majority of the total costs, followed by transport costs, while storage and depreciation costs have minimal impact. A look at the transportation costs in the interaction plot in Fig. 5 shows that these costs decrease with higher return volumes. This is because a fully loaded pallet can be transported from the workshop, distributing the transportation costs of a pallet over more cores. Additionally, it becomes clear that scenarios without a central hub incur lower transportation costs. This could be due to logistics companies already optimising highly competitive logistic networks. Internal logistic networks might disrupt rather than support them in terms of cost efficiency.

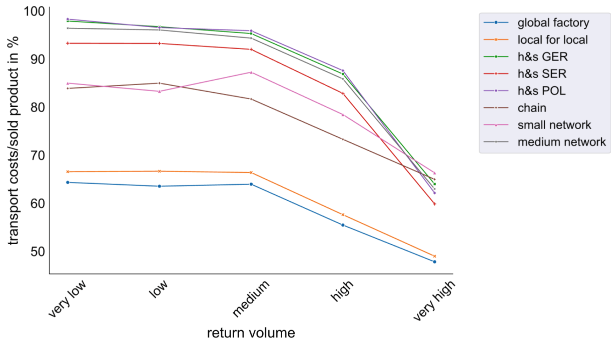

Fig. 5. Interaction plot of total transport costs per remanufactured product

The Tukey HSD test confirms that the "global factory" configuration is more cost-effective than the "local for local" configuration in most cases concerning transportation costs. Additionally, it is more cost-effective in all return volumes compared to all other network configurations. A closer look at remanufacturing costs in Fig. 3 shows that they significantly influence total costs. Since remanufacturing costs are labor-intensive in this case, they are significantly influenced by the labor costs of the respective country. This explains the differences in total costs between the various "hub and spoke" configurations.

6 Summary and Outlook

This study investigates the impact of different network configurations and return volumes on total costs per remanufactured product in reverse logistics (RQ1 and RQ2). It highlights remanufacturing costs as pivotal, particularly influenced by labour wages. The use case demonstrates cost advantages by strategically locating remanufacturing plants in low-cost locations such as Poland, Croatia and Serbia. Direct transportation to remanufacturing sites reduces costs in logistic networks like the "global factory" and "local for local." Higher return volumes mitigate differences in transportation expenses across configurations, underscoring the significance of remanufacturing costs. Future research may focus on optimising facility numbers across locations to enhance scalability and efficiency, particularly in competitive labour markets. Further opportunities lie in refining logistical strategies and inventory management for new components. Investigating the correlation between CO2 emissions and transportation costs, alongside the dynamics of donor and recipient markets within the EU, represents promising directions for future inquiry.

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