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STRATEGIC AND TACTICAL SELECTION OF HUBS FOR RAIL-BASED METAL SCRAP COLLECTION

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ABSTRACT

The steel industry's transformation toward sustainable production leads to an increased use of steel scrap to produce recycled steel. This necessitates a redesign of rail-based supply chains that have been historically designed to serve steel production from coal and iron ore. For a large German rail freight company, our study investigates which shunting yards should potentially be designated as hubs that bundle steel scrap transports. We tackle the complexity of the resulting logistics system with an agent-based simulation model to evaluate the performance of various hub configurations and demand scenarios from a strategic and tactical perspective. Our results show that a smaller number of hubs significantly reduces transport times and operating costs. However, this efficiency comes with increased vulnerability to disruptions, highlighting a trade-off between cost-efficiency and robustness. Our case study offers actionable insights into the efficient and sustainable design of commercial steel scrap transport networks.

1 INTRODUCTION

The steel industry has undergone a significant structural transformation by increasingly substituting primary iron resources with steel scrap, offering more sustainable and resource-efficient production pathways (Suer et al. 2022). As a result, the demand for steel scrap is expected to rise (Lopez et al. 2023). This development necessitates adjustments in existing logistics and transport processes to accommodate growing volumes of steel scrap. In this context, our commercial case study for a German rail freight company examines which existing shunting yards should be designated as hubs for bundling wagonload steel scrap into block trains. Using an agent-based simulation, the rail freight company is enabled to assess the commercial impact of strategic and tactical decisions through systematic "what-if" analyses: Strategically, we explore how hub number and location affect system performance and costs. Tactically, we evaluate resilience to disruptions such as hub outages and capacity constraints. Our study provides actionable recommendations to conduct cost-efficient and robust rail-based commercial steel scrap transport. These recommendations serve as a basis for rail freight companies to ensure economic viability while facing long-term, capital-intensive decisions. We contribute to both practice and literature by complementing existing simulation studies on steel supply chains (e.g., Sandhu et al. 2013) with a real-world commercial focus.

2 MODELING AND SIMULATION STUDY

This study employs an agent-based simulation model, implemented in AnyLogic 8, representing scrap senders (dealers), scrap receivers (steel mills), hubs, and trains. Transport demand is derived from historical data provided by the rail freight company. Agent-based simulation is particularly well-suited, as it captures the stochastic variability in demand and the operational complexity. The detailed modeling of routing decisions, shunting operations and train formation processes exceed the capabilities of closed-form analytical models, while the data scale and granularity make optimization-based methods computationally intractable. In addition, simulation enables time-resolved system analysis, such as tracking individual trains across the network, which allows decision-makers to identify infrastructure bottlenecks - e.g., congested corridors or shunting yards operating at capacity limits. However, for our hub-focused analysis, we assume rail corridors to have unlimited capacity. System behavior is evaluated through systematic parameter variation combining configurations and scenarios: *Configurations* define which of the existing shunting yards are selected as hubs for scrap collection. *Scenarios* capture potential changes in volume and spatial distribution of steel scrap demand (e.g., increased imports via ports). Each simulation run covers a time horizon of one month and is executed with 20 seeds to ensure statistical robustness. The logistics system's performance is evaluated in terms of transported scrap volume and costs, while robustness is assessed through disruption simulations (e.g., failure of single hubs). Note that, since we focus on the tactical and strategical decision level, demand distribution and hub availability remain constant during a run. This is why a simulation time horizon of one month was sufficient for the effects of the variations to materialize in our simulations. Throughout our study, we closely collaborated with the rail freight company to iteratively validate the simulation model. This ensured the practical relevance and real-world validity of our approach. Additionally, we jointly verified the simulation results and conducted sensitivity analyses by varying key assumptions and parameters, to analyze the limits of the system for each configuration. These analyses allow decision-makers to explore trade-offs between cost and service levels across hub configurations to identify configurations with the best performance-to-cost-ratio.

3 RESULTS

The analysis of our simulation runs reveals that a smaller number of hubs within the network offers several advantages. Specifically, travel times, operating costs, and the total number of freight wagons required can be significantly reduced. As a result, overall system efficiency under normal operating conditions (i.e., without disruptions) can be improved. However, this high efficiency under normal operating conditions comes at a cost: during disruption scenarios, such as the temporary failure of a hub, operating costs increase considerably. In a logistics system with four scrap hubs, the failure of a single hub can lead to a rise in operating costs of up to 37%. This increase is primarily due to significantly longer transport routes required to reroute scrap flows. These findings highlight the relevance of our study, that helps to find a viable tradeoff between high economic efficiency under normal conditions and acceptable cost increases during disruptions. Nevertheless, there are additional reasons why fewer hubs can be advantageous: Fewer hubs lead to bundling effects, which facilitate the faster formation of full trains that travel between the scrap hubs, thereby reducing waiting times. This can reduce the total transport time from the scrap sender to the receiver by up to 33%, although the average transport distance increases by approximately 10%. At the same time, transport costs decrease by up to 9%, and the total number of required freight wagons can be reduced by as much as 29%, without compromising transport performance.

4 CONCLUSION

Our study provides actionable insights for a large German rail freight company: The number of scrap hubs should be set as low as possible, but high enough to ensure operational resilience when disruptions occur. Direct delivery to a limited number of hubs and the formation of full trains between hubs are essential levers for reducing the average transport duration and thereby increasing the overall cost-efficiency of the logistics system. Shorter transport times lead to a reduced need for freight wagons, which results in lower investment and maintenance costs. The decisions on scrap hub location and freight wagon fleet size have a long-term impact on the company's business due to their high capital intensity. Our results serve as a basis to support this decision-making process of designing commercial rail-based steel scrap transport in a cost-efficient and environmentally friendly way.

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