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Data-driven management of material flows in circular economy by logistics optimization

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Abstract. The aim of the Circular economy (CE) business models is to reuse materials and decrease the need for virgin materials in the value chains. This, in turn, requires close collaboration and information sharing between the value chain stakeholders. For this, digitalization and data play a crucial role. This paper studies how small and medium sized enterprises (SMEs) operating in CE can utilize digitalization and data in managing and optimizing the material flows that are central to their production processes. The paper focuses on four case companies, all operating in CE business in Finland, and analyses how these companies have been able to enhance their material flow management by means of data-driven logistics optimization in a research-based university-industry collaboration. The solutions range from conceptual solutions to mathematical optimization and a tool supported solution concept.

Keywords: Data-driven decision-making, circular economy, logistics optimization, SMEs.

1 Introduction

Circular economy (CE) represents an emerging alternative for traditional linear models, where virgin materials are being used and disposed [1]. The CE incorporates a regenerative system that minimizes the entry and waste of resources, emissions, and expenditure of energy through slowing down, closing, and straightening the energy circuits [2]. As CE aims to reuse materials and decrease the need for virgin materials, there are challenges in the supply chain implementation and coordination [3]. In this manner, the CE business concepts aim at addressing sustainable development needs by minimizing resource input and waste, emissions, and energy leakage without jeopardizing growth and prosperity [3].

Operational requirements related to material flows are significantly higher in CE business than in many other business areas. This is because the challenges related to logistics are emphasized in the management of material flows in CE. Digitalization provides several kinds of opportunities to make the flow of materials more effective, and thus make the processes of CE profitable for the stakeholders. Hence, it is natural that the CE companies show increasing interest in developing and investing in digital solutions that help them to make their material flows more effective [4]. Currently available data on the material supply and need, as well as logistics capabilities provides opportunities for data-driven planning and optimization of the logistics in the value chains of CE.

This paper aims at improving understanding on the logistics optimization in the value chains of small and medium sized enterprises (SMEs) operating on the area of CE. Thus, this paper presents four individual cases and seeks answers to the following research question: *How circular economy SME's can develop their data-driven material flow management by means of optimization and planning?*

We approach this question by means of a case study containing four cases, each representing CE SMEs in Finland. In each case, this paper presents a company specific challenge to which solution has been found by means of a practical development project conducted in collaboration between the company and university. In this manner, each case illustrates a company-specific solution for data-driven optimization of the material flows in the case companies.

2 Optimizing material flows in circular economy

In the area of CE, SMEs play a key role [5]. They are in the center in the efforts to achieve environmental sustainability and more inclusive growth [6]. However, particularly in the SME domain, new tools and techniques provided by digitalization require education, continuous learning, and innovation. A wide range of technological tools are available to develop digital solutions for circular economy, and data can enable the efficient use of resources and reduce environmental effect. However, there are still challenges in the linear supply chains where data is not adequately shared between the stakeholders [7].

The main challenge in the data-driven management of material flows is the lack of centralized data governance [8]. Data has several owners in the private and public sector with different motives. Currently the platform ecosystem for circular economy in Finland aims to build interoperability between industries and to collect, harmonize and enrich data. The platform ecosystem serves material producers, processors and users, and other partners and platforms [8]. Creating profitable business in circular economy requires data of materials, volumes, qualities, and locations. For example, the target to utilize demolition materials was 70 % on 2020, but the actual utilization rate was only 50 % [9].

The rapid development of digitalization opens possibilities to data-based approaches to planning and optimization of the management of material flows. This, in turn, often requires open interfaces to share the data related to the material supply and demand, as well as transportation. In this paper, we study how data available from the recycled materials can be utilized in the computational optimization of the material flow management

3 Methodology

This paper presents a qualitative case study of four CE SMEs, all located in Finland. As illustrated in Table 1, the case companies focus on waste management, recycling services and biogas production. Research data was collected by interviewing company representatives on two interview rounds, conducted in November 2021 and January 2022. The interviews were based on a semi-structured questionnaire, in which the questions were related to logistics challenges and optimization needs.

Table 1. Case companies.

Case	Role of person interviewed	Data collection	Number of employees	Core business area	Solution concept
A	CEO	November 2021 workshop, company interview November 2021 and January 2022	50	Waste management, recycling services and solutions for households and companies.	Conceptual solution
B	Service Manager	Company interview January 2022	60	Waste management and recycling services for households and companies.	Tool supported solution concept
C	CEO	November 2021 workshop, company interview November 2021 and January 2022	30	Glass recycling services and glass products.	Conceptual solution
D	CDO	November 2021 workshop, company interview November 2021 and January 2022	90	Waste management and recycling services for households and companies.	Mathematical optimization

Information was gathered on logistics challenges and optimization need that are described in the Results section for each case company. In each case, the challenges were analysed in a development project carried out by Häme University of Applied Sciences (HAMK). The solution concepts presented in Results section range from conceptual solutions (case A and case C) to mathematical optimization (case D) and tool supported solution concept (case B).

4 Results

This section summarizes the logistics challenges and needs for optimization in case companies and the conceptual solution for each case. Conceptual solutions developed for the challenges are introduced in the following sub-sections. These challenges relate to the optimization of waste management logistics or the contract areas. The conceptual solutions are based on Internet of Things (IoT), material sharing platform or mathematical modelling.

4.1 Concept Case A: optimizing waste transportation routes

The case company A is interested in how the data alongside the material flow can give value for the company itself and its customers. The question is how to handle raw material acquisition, outgoing products, and deliveries to the end user as efficiently as possible? The specific challenge in this company case is to plan back and forth transportation and try to understand how to utilize data to design sensible routes? The existing data from the vehicles includes spatial information, driving mode and fuel consumption. Sensors installed to the waste containers raise an alarm when the container is getting full. This way, an order is entered into the information system of the company. However, despite the fact that the data is collected, it is not fully utilized. As the objective of the case company is to utilize transportation data to demonstrate and minimize the carbon footprint of individual transport routes, it needs to plan efficient collection route for a certain region. So far, this kind of route planning has been done manually by organizing in the map view either by address or manually drawing a route from one destination to another.

As illustrated in Figure 1, a solution concept for case A consists of monitoring the filling rate of the different kind of containers with the different sensor technologies. The filling rate data and alerts can be visualised in the map and can be used in the route optimization. The concept for case A consists of four types of scenarios for customer orders: 1) industrial actor contacts case company to get rid of waste, 2) households contacts case company to get rid of waste, 3) IoT based service for households where waste containers are monitored and optimally emptied and 4) IoT based service for industry where waste containers are monitored and optimally emptied.

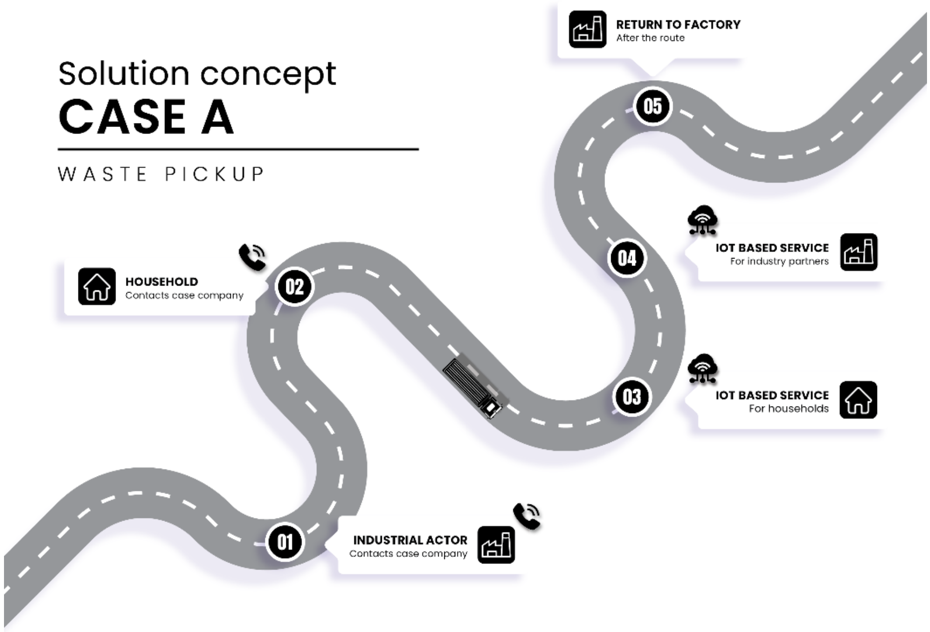

Fig. 1. Case A solution concept.

4.2 Concept Case B: Regional route planning

Case company B needs to be prepared to the changes in law that directs the households waste sorting and their transportation organized by municipalities. It involves publicly procured competition that is to be based on market research and dialogue with prospective service providers. The central questions faced by the company include the following: 1) what kind of collection areas are formed for the contracts, 2) how many vehicles will be needed and 3) how many days the collection takes. There may be multiple contractors by area and by waste, as the law requires the distribution of work. Optimal contract, i.e., collection, areas enable the efficient and flexible collection of waste for the contractor and are accessible for multiple service providers to participate in the tender. Thus, the market mechanism is expected to ensure reasonable pricing for individual households. For the areas of question, there is an existing map-based visualization to support estimations of waste accumulation. Now, company B is interested in quantified indicators of planned routes, waste volume, and capacity in planned contract areas. In addition, company B is interested in route optimization solutions for order-based services without regular routes.

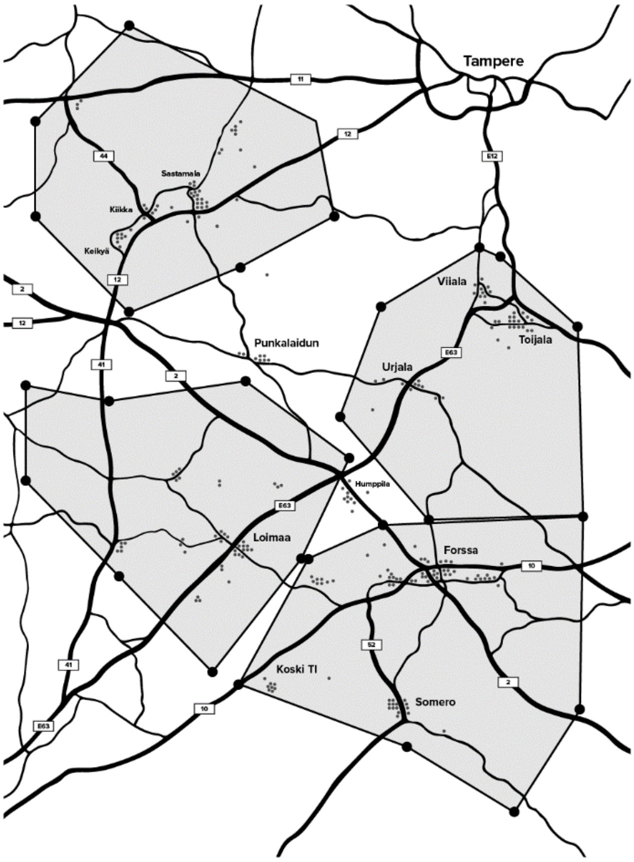

Fig. 2. Illustration of the developed tool in the company case B. Points are shown on the locations where the waste is collected, and polygons are drawn on top of the map to visualize the contract areas.

As a solution for case B, a tool was developed that plots customers, i.e., the collection points, on a map and allows the user to draw polygons to specify the desired contract areas. Then, based on these areas, the following indicator metrics were computed: 1) bins within the area, 2) the total number of bins emptying in a year, and 3) the average density of the bins. Using approximations of the bin contents the indicator metrics are further converted to include an estimation of the absolute amount of waste. Visualization of the tool interface is shown in Figure 2. The tool can be run separately for each contract area and waste variety.

4.3 Concept Case C: Glass waste sourcing

Case company C is interested in making a new business concept relying on transportation optimization. The company is making CE business with recycling glass. It transports large quantities and wants to expand operations on the raw material sourcing and export operations. A central question is how to make a long-distance material transport profitable by using sensors, optimization, and smart packaging? In addition, the company is interested in the waste management in construction sites, as there is a lot of glass that is not circulated. Thus, the company is trying to make a solution, where the whole concept competitive in the long run and on the other hand improve their customer service in the raw material procurement.

The solution concept for case C consists of four types of scenarios for glass waste sourcing (Figure 3): 1) industrial actor generates plate glass as a side stream and contacts case company to get rid of waste, 2) the pre-demolition audit done in construction demolition sites that inform when glass waste is available in demolition sites, 3) waste material availability announcement on the Materiaalitori material sharing platform, 4) IoT based service where waste containers are monitored and optimally emptied (containers that are filled 75 % or more).

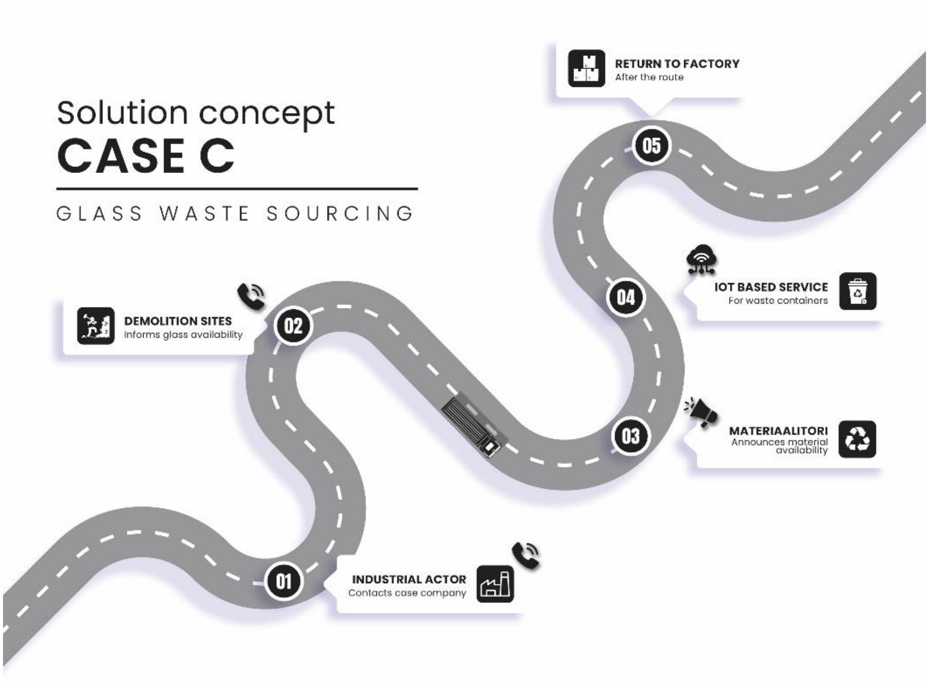

Fig. 3. Case C solution concept.

4.4 Concept case D: Optimizing locations for waste receiving stations

Company case D explored location options for several new small waste stations in their operating area. Due to a change in the collection of waste management fees from the citizens in a Finnish region, certain waste varieties may now be brought to waste management stations free of charge and their further processing is covered with a mandatory yearly fee. Due to the compulsive nature of waste sorting, the waste receiving stations need to be placed close to the citizens.

In this case, options for possible locations of new waste stations were evaluated based on their average and median distances to the citizens' addresses. In addition, the standard deviation and number of citizens that were considered to be "far away" were used in the estimation. The threshold for "far away" was set to 30 km. The distance was Euclidean, i.e., as the crow flies. Initial situation contained the locations of the current waste stations and the addresses of the citizens in the region. The objective was to create a network of waste stations so that inhabitants have a short distance to the waste stations.

The concept for case D was to explore optimal locations for waste stations by placing potential locations in the operating area and calculating the distances for every resident to the nearest waste station. Locations for new stations were proposed so that all residents would have the shortest possible distance to their nearest station. The analysis showed that, in addition to decreasing the distance to the nearest waste station, well placed new waste stations decreased the amount of "far away" citizens from the initial several thousand to a thousand or even only few hundred depending on the scenario. The concept for the case D is illustrated in Figure 4.

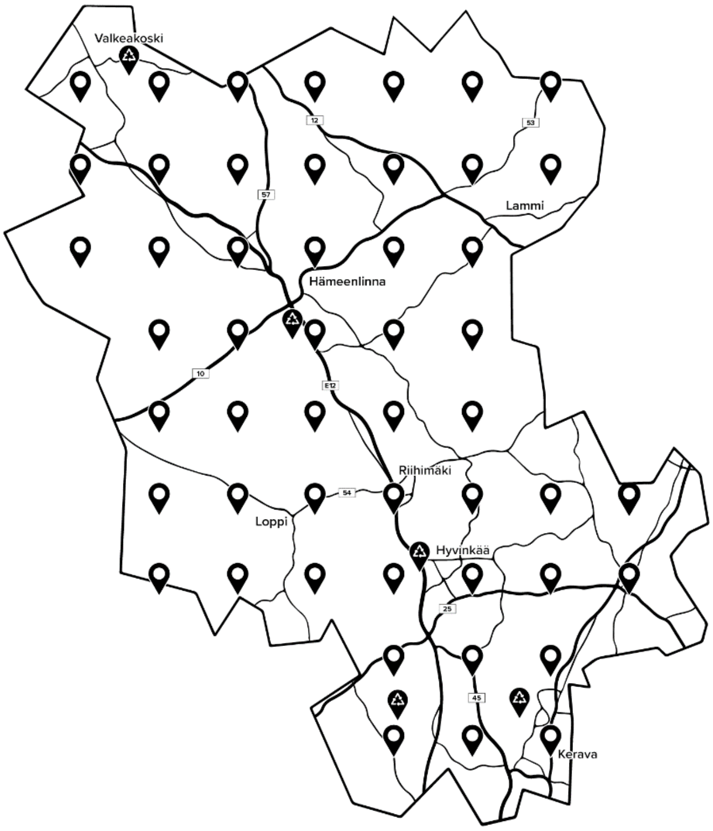

Fig. 4. Case D solution concept.

5 Discussion

The applied research at Häme University of Applied Sciences (HAMK) aims to produce new and creative solutions to increase the vitality, wellbeing and sustainability of businesses and society. Long term goals 2035 outlined in the Road Map for Circular Economy in Kanta-Häme [10], Finland, include material efficient operations and minimizing waste generation. On regional level waste management, recycling services and biogas production are key circular economy actors that can significantly enhance waste material flows from households and industry to reuse in production of new products or as energy. In Finland, many CE actors are SMEs and do not have sophisticated logistics optimization solutions in-house or resources to develop them internally. University-industry collaboration is one means to develop logistics optimization in CE SMEs. The four case studies introduced in the study present solution concepts to regional challenges, however, the way of developing the solutions and the solution concepts themselves can be applied more broadly to CE SMEs in other regions and countries with similar challenges.

Advanced and continuous logistics optimization requires that data is readily available in a scope that makes optimization possible. For instance, in case B, a tool was developed that plots collection points of material on a map and allows the user to draw polygons to specify desired areas of interest for which all relevant data is computed to support decision-making of company expert. Case D presented a solution concept for determining the optimal placement of new waste stations based on existing data about households. Whereas case A and case C are examples of conceptual solutions that support CE SMEs in sense-making what kind of system can be built to optimize their logistics. As a result of the sense-making process in case A it was decided to launch a student project, where students investigate how historical data of contacts from industrial actors and households could be used to predict new orders for route planning. Case C helped to understand that the case company needs to explore more the available data and opportunities for optimization inside the company, which resulted in recruiting a thesis worker from the university to support the process.

Investigation of CE SMEs problem space also revealed that many CE SMEs in Finland share the same information systems and some of them are based on open source platforms. This clearly indicates opportunities for pooling resources related to logistics information systems and logistics optimization.

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