Waste Management 156 (2023) 159–167

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Optimizing environmental and economic aspects of collaborative transportation and logistics related to infrastructure projects – A case study from Norway

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ARTICLE INFO

Keywords:
Collaborative Logistics
Waste Management
Mathematical Programming
Operations Research

ABSTRACT

The main challenge addressed in this paper is how to handle and recycle the large amount of C&D waste that is generated from infrastructure projects. The study is motivated by Bærum Ressursbank in Norway and their aim of finding logistical solutions to an expected surplus of 15 million m^3 of waste from infrastructure projects in the next decade. We identify the key decisions as the design of the distribution network for both surplus waste materials and new construction materials and the investments in processing machinery at each recycling facility, and we call the problem representing this situation the Infrastructure Waste Management Problem (IWMP). The methodologies used are mathematical programming and operations research. We formulate the IWMP as a mixed integer linear program and identify two objectives; to minimize transportation costs and to minimize the environmental impact of the operations. The description of the problem, assumptions, and data are based on cases that represent the situation of Bærum Ressursbank. A special emphasis in the analysis is to quantify the gains from collaboration. Comparing individual planning of each project with an ideal situation of complete collaboration gives a cost reduction of more than 29% and a reduction in emissions of more than 14%. The study supports the conjecture by Bærum Ressursbank that large cost savings and considerable reductions in environmental impact are possible through collaboration.

1. Introduction

Economic growth, along with increasing populations, leads to an increase in construction activities in many regions of the world. As a consequence, construction and demolition (C&D) projects such as infrastructure construction and remediation demand increasingly more raw materials such as rock and crushed stone. Traditionally, demands have been met by extracting virgin materials from quarries and then transporting them to the project sites where they are demanded. These are nonrenewable resources, and extraction leads to a strain on local society, as the excavation of soil is noisy, dusty, and area demanding. On the other hand, C&D projects today generally generate a net surplus of waste materials that need to be handled. These waste materials have traditionally been disposed of as landfills, although most of them are high quality materials that potentially could be reused or recycled. The environmental drawbacks of landfills, i.e., toxins, leachate and greenhouse gases, and the economic benefits of reusing and recycling are a clear motivation for decision-makers in the C&D industry to analyze material flows.

When analyzing waste materials and demanded products, it is clear that the potentials for the recycling and reuse of materials in the C&D sector are massive. Waste materials from one project can often coincide with demand from another project, either directly or after some degree of processing. Therefore, the recycling and reuse of waste materials from C&D projects may be used as good sources of construction materials, substituting natural virgin resources (Jendia and Besaiso, 2011).

Furthermore, the C&D sector is one of the main contributors to CO_2 emissions in fast-growing cities (Peters et al., 2007). These emissions are derived from resource extraction, earthwork machines, material processing, and transportation requirements. In 2018, 153 million tonnes of rock, stone, asphalt, concrete, and other construction material and waste were transported in Norway. This accounts for 60% of all domestic goods transportation by lorries (Statistisk Sentralbyrå, 2019). Some studies have found that recycling of C&D waste actually contributes negatively to the environment if the transportation distances required to transport material to and from recycling facilities are long (Mercante

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https://doi.org/10.1016/j.wasman.2022.11.019
Received 10 June 2022; Received in revised form 11 November 2022; Accepted 14 November 2022

et al., 2012). Therefore, good management and planning are required to obtain the desired benefits.

In Norway, several participants in the C&D industry begin to see the importance of material recovery and reuse. Nevertheless, the C&D sector generates the majority of total waste in the country (25% in 2016), which is still increasing (Skjerpen, 2018). Additionally, the amount of recycling has decreased in recent years, as more concrete, soil, stone, and gravel are sent to landfills instead of material recovery (Skjerpen, 2018).

The management of C&D waste falls under reverse logistics management with the objective of capturing the value of the waste, reducing the amount of waste that ends up in landfills, reducing the environmental impact, and reducing costs. Relevant reviews on reverse logistics management can be found in Fleischmann et al. (1997) (focusing on quantitative methods), Pokharel and Mutha (2009) (using content analysis for classification), Govindan et al. (2015) (using content analysis and including closed-loop supply chain issues), Govindan and Soleimani (2017) (focusing on publications in the Journal of Cleaner Production), and Prajapati et al. (2019) (using content analysis and an abductive research approach). There are also reviews specifically targeting reverse logistics in the construction industry; see, for example, Vargas et al. (2021) and Hosseini et al. (2015), but none of these have an operations research perspective. Van Engeland et al. (2020) argue in their excellent review that the scientific areas of reverse logistics and waste management have a clear overlap and define a waste reverse supply chain as a network consisting of all entities involved in the flow of disposed products leaving the point of consumption. They focus on strategic network optimization models in waste reverse supply chains. Of more than 200 articles, only three deal with C&D waste. Xu and Wei (2012) study a location-allocation problem and analyze a case from China. The results show that the proposed model can be an important tool for strategic decision-making within C&D waste management. Galán et al. (2013) analyze the location of recycling facilities in Cantabria, Spain, under economical and environmental criteria. Cases with and without administrative constraints are tested and large differences in objective values are reported. This study was later extended by Dosal et al. (2013) by introducing social criteria in the objective. Fu et al. (2017) study the location of classification processing centers and study the effect of government subsidies on a Chinese case.

Ghiani et al. (2014) discuss strategic and tactical issues in solid waste management. The authors point out that planning at the tactical level typically includes allocating flow among the given facilities and give Mitropoulos et al. (2009),Yeomans (2011), and Ghiani et al. (2012) as examples of studies where this is important. More recent studies in this area are (Ghiani et al., 2021), focusing on the usage of transfer stations in a waste collection system, (Saif et al., 2022), dealing with sustainability targets for a municipal solid waste supply chain, and (Allevi et al., 2021), proposing a waste management model in a circular economy framework, among others.

The main challenge addressed in this paper is how to handle and recycle the large amount of C&D waste that is generated from infrastructure projects in the coming years, in an environmentally and economically optimal way. We denote this problem by the infrastructure waste management problem (IWMP). The problem combines strategic decisions about the technology to be used in recycling facilities with tactical decisions about the allocation of waste and the production of products from the waste. The hypothesis is that better planning of mass transport and recycling across projects will facilitate greater reuse of waste materials and reduced transportation needs, resulting in both economic and environmental benefits.

The case we study is the work of Bærum Ressursbank, a collaborative forum initiated by the Norwegian municipality of Bærum between numerous participants in the C&D industry. Bærum Ressursbank aims to find logistical solutions to an expected surplus of 15 million m^3 of waste from infrastructure projects in the next decade. The current situation within the C&D industry where Bærum Ressursbank operates is characterized by a very low level of collaboration, uncertainty about the risk and possible gains with collaboration and suspicion between the actors. This has led to very myopic planning in which each project seeks to minimize its own costs. By promoting, incentivizing, or even forcing collaboration, Bærum Ressursbank conjectures that large cost savings and considerable reductions in environmental impact are possible.

In this case study, we include infrastructure projects such as road and railway constructions and not other C&D projects. Thus, the by far largest quantities of both supplied and demanded materials are stone, soil, asphalt, and concrete. Other materials, e.g. building waste, are outside the scope of the case study. To quantify the value of a holistic planning perspective and collaboration between the actors in the C&D industry, we use operations research and formulate the optimization problem mathematically. Given data from Bærum Ressursbank, we can adjust the mathematical model to different scenarios and solve it. By comparing the objective values of the scenarios and their solutions, we can quantitatively assess the effect of collaboration and other important aspects of the problem.

The paper extends the current literature on infrastructure waste management by including the processes at the recycling facilities and by allocating the costs and environmental effects to the different actors in a consistent way. This enables a study of different ways to collaborate. The IWMP can also be seen from a collaborative logistics perspective, where strategic decisions regarding technology investments and production aspects are not well studied. We also introduce strategic decisions regarding technology investments and production aspects in the collaborative logistics literature. These are aspects that are not often discussed.

The main contributions of this paper are: (1) A formal description of the IWMP based on the work of Bærum Ressursbank, (2) A mixed integer linear formulation of the problem, and (3) A comprehensive case study based on the work of Bærum Ressursbank.

The paper is organized as follows. Section 2 gives a formal description of the problem, and Section 3 presents the mathematical formulation. Section 4 is the computational study, and Section 6 concludes the paper.

2. Problem description

The infrastructure waste management problem (IWMP) is to find the distribution network for both surplus waste materials and new construction materials and to identify the need for certain processing machines at each recycling facility. The problem is defined over a geographical area. Within the system boundaries, there are several locations categorized into four different types; project sites, recycling facilities, filling locations, and disposal locations. There are multiple instances of each type, distributed over the system area. The planning horizon covers many years or even decades and is divided into years as time periods.

Project sites are locations where construction and demolition work related to infrastructure projects occurs. The project sites generate surplus materials that must be transported away and demand new materials and products that are transported to the site. For convenience, all these masses, both waste, surplus materials, new materials, and new products, are denoted products. The project sites correspond to the geographical location where surplus products are generated and new products are needed.

The project sites are groups in projects, and one project may consist of several project sites, e.g. representing different outlets from a railway tunnel. The project owner owns the project and is responsible for its completion. Outlet locations are predefined for each project. The project sites do not have any storage capacity (products that can be reused within the same project and stored intermediately at the project sites are excluded from the problem). Therefore, surplus products must be transported away from the project sites when they are generated. These can be sent to a recycling facility, a filling location, a disposal site, or directly to other project sites demanding the products.

Recycling facilities can transform one or several products received from project sites into one or more new products through different processes. The new products can then be delivered to project sites according to demand. Some processes generate surplus (waste) products not usable by any project site (e.g. small fractions of useless sand from crushing stone processes), and these may be delivered to either a filling location or a disposal site. The machines used for the processes have a fixed setup cost and a time-dependent usage cost. Furthermore, recycling facilities have a finite temporary storage capacity, which can be used to store incoming products before they are processed or outgoing products before they are sent out.

Filling locations can accept certain surplus products for socially beneficial purposes. This could typically be the construction of a recreational area, expansion of land, or creation of an island. Nothing is transported from a filling location, and the amount of masses received cannot exceed a finite permanent storage capacity.

Disposal locations are conceptually similar to filling locations. They can receive waste products and store them permanently. Nothing is transported from a disposal location. The difference between a filling location and a disposal location is that the masses used at the filling locations serve socially beneficial purposes, whereas the disposal sites are only used to remove unwanted masses. Therefore, the disposal prices paid by the projects and the products that are acceptable are different for the filling locations and disposal sites.

Some locations may have the properties of several types of location. Typically, this is the case for recycling facilities, which have both temporary storage capacity and areas designated for permanent disposal.

In addition to the product flows mentioned above, flows across the system boundaries are possible. These are limited to either transportation from recycling facilities (e.g. surplus products from processes sold or disposed outside the system), out from project sites (e.g. waste products sold or disposed outside the system), or into project sites (e.g. products not possible to find or produce anywhere inside the system). Fig. 1 shows the system, its boundary and the flows between different location types. The green dashed flows represent principally favorable flows, and increasing these will have a positive effect on both system costs and emissions.

All transportation is done with a homogeneous fleet of vehicles. Due to large quantities, the transportation cost can be seen as a flow cost depending on the distance. There are additional costs for transporting products from external quarries to the project sites, representing the cost of producing the products from virgin material. The cost of disposal and recycling depends on the products. Some products are defined as quality products, and a fraction of these can be sold externally, while the other products cannot be sold.

The objective focusing on emissions has the same components as the cost-based objective function, except that there are no emissions associated with setting up a machine at a recycling facility. Emissions related to recycling plant processes are allocated to project sites based on relative product flows. This is important when the different projects are analyzed.

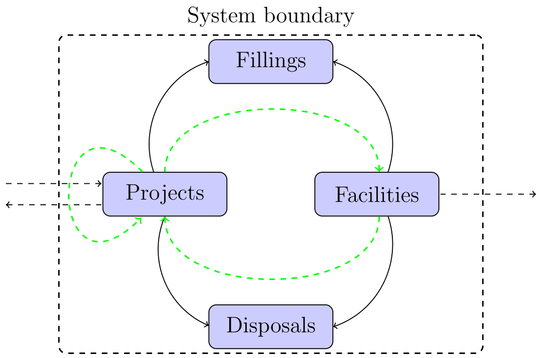

Fig. 1. Transportation flows within and across system boundaries. Green arrows represent principally favorable flows.

A given amount of surplus products will be transported away from each project site in each time period of the planning horizon. Furthermore, the demand for new products at each project site must be met in the specified time period.

The goal of the IWMP is to minimize environmental impacts and costs for different projects and for the entire system.

3. Mathematical formulation

We assume that the IWMP is static and deterministic and propose a mixed integer linear programming formulation. The set of project sites, $\mathscr{N}^S$, recycling facilities, $\mathscr{N}^F$, disposal locations, $\mathscr{N}^D$, filling locations, $\mathscr{N}^U$, and externals, $\mathscr{N}^E$, comprise all nodes, $\mathscr{N}$, between which it is possible to transport a set of products, $\mathscr{P}$. Each node represents a geographical location with inbound and/or outbound transports. Each project in the set of projects $\mathscr{S}$ is a collection of one or several project sites, one for each outlet. Furthermore, each recycling facility can set up a set of processing machines, $\mathscr{M}$, with which a set of processes, $\mathscr{R}$, can be run. These processes transform surplus products into demanded products. Subsets of these sets, as well as parameters and variables, are introduced as they become relevant. The set $\mathscr{T}$ of years defines the planning horizon. The constraints are presented in groups to ease the presentation.

3.0.1. *Product flows*

We base our modeling approach regarding product flows and roundtrips on Carlsson and Rönnqvist (2007) and introduce two flow variables, f_{ijpt} denotes the quantity of product p transported from node i to node j in time period t, while g_{ijklt} is the artificial quantity transported on roundtrip $i \rightarrow j \rightarrow k \rightarrow l \rightarrow i$ in time period t. The flow balance for the project sites can now be formulated

$$\sum_{j \in \mathscr{N}} f_{ijpt} = S_{ipt} \quad i \in \mathscr{N}^S, p \in \mathscr{P}, t \in \mathscr{T} \tag{1}$$

$$\sum_{j \in \mathscr{N}} f_{jipt} = D_{ipt} \quad i \in \mathscr{N}^S, p \in \mathscr{P}, t \in \mathscr{T} \tag{2}$$

where S_{ipt} and D_{ipt} are the demand and supply of product p at node i in time period t, respectively. For disposal locations and filling locations, we introduce a variable s_{ipt} that denotes the inventory level of product p at location i at the beginning of time period t. This gives

$$s_{ipt} + \sum_{j \in \mathscr{N}} f_{jipt} = s_{ip,t+1} \quad i \in \mathscr{N}^U \cup \mathscr{N}^D, p \in \mathscr{P}, t \in \mathscr{T} \tag{3}$$

Recycling facilities also have inventory level variables, and in addition we introduce B_{pmr} denoting the quantity of product p produced/consumed if process r is run by machine m one time and the variable h_{imrt} representing the number of times process r is run with machine m at node i in time period t. This gives

$$s_{ipt} + \sum_{j \in \mathscr{N}} f_{jipt} + \sum_{m \in \mathscr{M}} \sum_{r \in \mathscr{R}} B_{pmr} h_{imrt} - \sum_{j \in \mathscr{N}} f_{ijpt} = s_{ip,t+1} \quad i \in \mathscr{N}^F, p \in \mathscr{P}, t \in \mathscr{T} \tag{4}$$

The artificial quantity transported on a roundtrip is linked to the flow on single arcs through

$$\sum_{k \in \mathscr{N}} \sum_{l \in \mathscr{N}} g_{ijklt} \leqslant \sum_{p \in \mathscr{P}} f_{ijpt} \quad i, j \in \mathscr{N}, t \in \mathscr{T} \tag{5}$$

$$\sum_{i \in \mathscr{N}} \sum_{j \in \mathscr{N}} g_{ijklt} \leqslant \sum_{p \in \mathscr{P}} f_{klpt} \quad k, l \in \mathscr{N}, t \in \mathscr{T} \tag{6}$$

Constraints (5) ensure that the total artificial quantity on arc (i,j) is less than the product flow, meaning that the same quantity cannot be transported on two roundtrips. Constraints (6) state the same, but for arc (k,l).

Finally, the storage capacities at filling and disposal locations and at recycling facilities are handled in the following constraints

$$\sum_{p\in\mathscr{P}} s_{ipt} \leqslant Q_i \quad i \in \mathscr{N}^U \cup \mathscr{N}^D \cup \mathscr{N}^F, t \in \mathscr{T} \tag{7}$$

where Q_i denote the storage capacity of node i.

3.0.2. Process constraints

To model the processes at the recycling facilities, we introduce T^R_{mr} as the duration of one run of process r with machine m and T^P as the time available in one time period. The variable y_{imt} is 1 if machine m is used at node i in time period t, and 0 otherwise, and y^S_{imt} is 1 if machine m is used at node i in time period t but was not used in time period $t-1$, and 0 otherwise. The process constraints at the recycling facilities can now be formulated as follows

$$\sum_{r\in\mathscr{R}_m} T^R_{mr} h_{imrt} \leqslant T^P y_{imt} \quad i \in \mathscr{N}^F, m \in \mathscr{M}, t \in \mathscr{T} \tag{8}$$

$$y_{im,t+1} \leqslant y_{imt} + y^S_{im,t+1} \quad i \in \mathscr{N}^F, m \in \mathscr{M}, t \in \mathscr{T} \tag{9}$$

3.0.3. Allocation of process emissions

To model the allocation of process emissions to project sites according to the assumption that emissions are allocated based on the relative flows, we introduce e_{ijp} as process emissions allocated to the flow from i to j from producing product p and state the assumption in the following equation

$$\frac{\sum\limits_{t\in\mathscr{T}} f_{ijpt}}{\sum\limits_{k\in\mathscr{N}^S}\sum\limits_{t\in\mathscr{T}} f_{ikpt}} = \frac{e_{ijp}}{\sum\limits_{k\in\mathscr{N}^S} e_{ikp}} \quad i \in \mathscr{N}^F, j \in \mathscr{N}^S, p \in \mathscr{P} \tag{10}$$

To linearize this, we start with a set $\mathscr{Q}$ of overestimation weights $W_q \in [0,1]$ and the associated variable l_{qijp} which is 1 if weight q is used as an overestimation of the flow from i to j of product p. We introduce $\mathscr{P}^{\mathscr{D}}$ as the set of products that are demanded at project sites and define the relative production output $B^D_{pmr} = B_{pmr}/\sum_{\rho\in\mathscr{P}^{\mathscr{D}}} B_{\rho mr}$ stating product p's part of the total production of the products demanded from machine m running process r. The linearization of (10) is formulated as

$$\sum_{j\in\mathscr{N}^S} e_{ijp} = \sum_{m\in\mathscr{M}}\sum_{r\in\mathscr{R}}\sum_{t\in\mathscr{T}} B^D_{pmr} E^R_r h_{imrt} \quad i \in \mathscr{N}^F, p \in \mathscr{P}^D \tag{11}$$

$$\sum_{k\in\mathscr{N}^S}\sum_{t\in\mathscr{T}} W_q f_{ikpt} - \sum_{t\in\mathscr{T}} f_{ijpt} \geqslant -M\left(1 - l_{qijp}\right) \quad q \in \mathscr{Q}, i \in \mathscr{N}^F, j \in \mathscr{N}^S, p \in \mathscr{P}^D \tag{12}$$

$$\sum_{k\in\mathscr{N}^S} W_{(q-1)} e_{ikp} - e_{ijp} \leqslant M\left(1 - l_{qijp}\right) \quad q \in \mathscr{Q}, i \in \mathscr{N}^F, j \in \mathscr{N}^S, p \in \mathscr{P}^D \tag{13}$$

$$e_{ijp} \leqslant M \sum_{t\in\mathscr{T}} f_{ijpt} \quad i \in \mathscr{N}^F, j \in \mathscr{N}^S, p \in \mathscr{P}^D \tag{14}$$

$$\sum_{q\in\mathscr{Q}} l_{qijp} = 1 \quad i \in \mathscr{N}^F, j \in \mathscr{N}^S, p \in \mathscr{P}^D \tag{15}$$

In constraints (11), E^R_r are the emissions generated by one run of process r and they state that all emissions from a recycling facility must be distributed. Constraints (12) and (13) ensure that the chosen weight is the smallest overestimation of flow ratios and that the allocated emissions are greater than the largest underestimate. Constraints (14) make sure that no emissions are distributed unless there is flow, and constraints (15) state that exactly one weight must be chosen.

3.0.4. Variable definitions

All variables are defined according to

$$s_{ipt} \geqslant 0 \quad i \in \mathscr{N}^U \cup \mathscr{N}^D \cup \mathscr{N}^F, p \in \mathscr{P}, t \in \mathscr{T} \tag{16}$$

$$f_{ijpt} \geqslant 0 \quad i,j \in \mathscr{N}, p \in \mathscr{P}, t \in \mathscr{T} \tag{17}$$

$$g_{ijklt} \geqslant 0 \quad i,j,k,l \in \mathscr{N}, t \in \mathscr{T} \tag{18}$$

$$h_{imrt} \geqslant 0 \quad i \in \mathscr{N}^F, m \in \mathscr{M}, r \in \mathscr{R}, t \in \mathscr{T} \tag{19}$$

$$e_{ijp} \geqslant 0 \quad i \in \mathscr{N}^F, j \in \mathscr{N}^S, p \in \mathscr{P} \tag{20}$$

$$y_{imt} \in \{0,1\} \quad i \in \mathscr{N}^F, m \in \mathscr{M}, t \in \mathscr{T} \tag{21}$$

$$l_{qijp} \in \{0,1\} \quad q \in \mathscr{Q}, i \in \mathscr{N}^F, j \in \mathscr{N}^S, p \in \mathscr{P}^D \tag{22}$$

When generating the flow variables f_{ijpt} we make sure that no variables representing infeasible flows are generated. Starting from the arcs in Fig. 1, we remove flows of products without supply and demand. The artificial quantities g_{ijklt} are generated given that there are corresponding flow variables and that the reduction in empty driving is at least 20%.

3.0.5. Objective functions

The proposed model is used to perform economic and environmental analyses on a system level as well as for individual projects. Therefore, different objective functions are used for the analyses. We present the economic and environmental objective functions for the system level and then describe how the individual objective functions are derived from these. To facilitate the presentation, we discuss each part of the objective functions separately.

3.0.6. Transportation

The unit monetary costs, C^T_{ij}, and the unit environmental impacts, E^T_{ij}, of transport are modelled to represent the cost and impact per unit of transported product from i to j. Therefore, they must consider both the total weight of a vehicle, the empty weight of the vehicle, and the distance from node i to node j. These characteristics lead to the following expression for unit monetary costs and environmental impacts, respectively

$$C^T_{ij} = C^T \frac{W^F D_{ij} + W^E D_{ji}}{W^F - W^E} \quad i,j \in \mathscr{N} \tag{23}$$

$$E^T_{ij} = E^T \frac{W^F D_{ij} + W^E D_{ji}}{W^F - W^E} \quad i,j \in \mathscr{N} \tag{24}$$

where C^T and E^T are the cost and environmental impact per tonne-kilometer, W^F and W^E the weight of a full and empty vehicle, and D_{ij} the distance between node i and j. Instead of back-and-forth routes, roundtrips can be used to reduce transportation cost and environmental impact. With one flow from i to j and one from k to l, a roundtrip $i \rightarrow j \rightarrow k \rightarrow l \rightarrow i$ can be created. In Fig. 2, two back-and-forth routes and a roundtrip are illustrated. The monetary savings, R^C_{ijkl}, and reductions in environmental impact, R^E_{ijkl}, are calculated according to

$$R^C_{ijkl} = C^T \frac{W^E\left(\left(D_{ji} + D_{lk}\right) - \left(D_{jk} + D_{li}\right)\right)}{W^F - W^E} \quad i,j,k,l \in \mathscr{N} \tag{25}$$

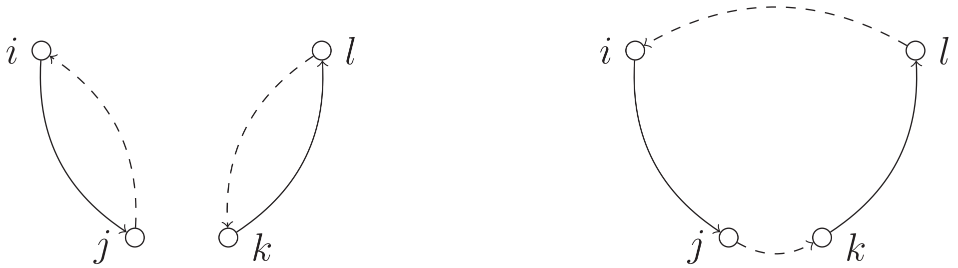

Fig. 2. The figure shows two back-and-forth routes [left] and a roundtrip [right]. Solid lines represent fully loaded vehicles and dashed lines empty vehicles.

$$R^E_{ijkl} = E^T \frac{W^E\left(\left(D_{ji} + D_{lk}\right) - \left(D_{jk} + D_{li}\right)\right)}{W^F - W^E} \quad i, j, k, l \in \mathcal{N} \tag{26}$$

Two things should be noted. Connecting two flows into a roundtrip does not necessarily give a benefit, and it is only the distance for the empty vehicle that is saved. Given this, the costs and emissions related to transportation can be formulated as

$$TC^T = \sum_{i\in\mathcal{N}}\sum_{j\in\mathcal{N}}\sum_{p\in\mathcal{P}}\sum_{t\in\mathcal{T}} C^T_{ij} f_{ijpt} - \sum_{i\in\mathcal{N}}\sum_{j\in\mathcal{N}}\sum_{k\in\mathcal{N}}\sum_{l\in\mathcal{N}}\sum_{t\in\mathcal{T}} R^C_{ijkl} g_{ijklt} \tag{27}$$

$$TE^T = \sum_{i\in\mathcal{N}}\sum_{j\in\mathcal{N}}\sum_{p\in\mathcal{P}}\sum_{t\in\mathcal{T}} C^E_{ij} f_{ijpt} - \sum_{i\in\mathcal{N}}\sum_{j\in\mathcal{N}}\sum_{k\in\mathcal{N}}\sum_{l\in\mathcal{N}}\sum_{t\in\mathcal{T}} R^E_{ijkl} g_{ijklt} \tag{28}$$

3.0.7. *Use of virgin products*

Production costs and emissions from virgin products brought into the project sites from external quarries are modelled using C^V_p and E^V_p as costs and emissions from the production of product p from virgin materials, respectively. This gives

$$TC^V = \sum_{i\in\mathcal{N}^E}\sum_{j\in\mathcal{N}^S}\sum_{p\in\mathcal{P}}\sum_{t\in\mathcal{T}} C^V_p f_{ijpt} \tag{29}$$

$$TE^V = \sum_{i\in\mathcal{N}^E}\sum_{j\in\mathcal{N}^S}\sum_{p\in\mathcal{P}}\sum_{t\in\mathcal{T}} E^V_p f_{ijpt} \tag{30}$$

3.0.8. *Recycling processes*

We assume a fixed cost, C^R_r, and an amount of emissions, E^R_r, per time process r is run. In addition, there is a fixed cost, C^M_m, for using machine m in a time period if it was not used the previous time period. This gives

$$TC^R = \sum_{i\in\mathcal{N}^F}\sum_{m\in\mathcal{M}}\sum_{r\in\mathcal{R}}\sum_{t\in\mathcal{T}} C^R_r h_{imrt} + \sum_{i\in\mathcal{N}^F}\sum_{m\in\mathcal{M}}\sum_{t\in\mathcal{T}} C^M_m y^S_{imt} \tag{31}$$

$$TE^R = \sum_{i\in\mathcal{N}^F}\sum_{m\in\mathcal{M}}\sum_{r\in\mathcal{R}}\sum_{t\in\mathcal{T}} E^R_r h_{imrt} \tag{32}$$

3.0.9. *Disposal and filling*

To model the costs and emissions associated with disposal and filling, we define a set of quality products, $\mathcal{P}^Q \subseteq \mathcal{P}$, i.e., products that from a societal perspective are better to sell outside the system boundary than dispose inside the system. For these, there is an external demand and only a fraction γ of the total flow is disposed. The emissions produced by the disposal of these products are the emissions of producing the products from virgin material, while the cost is denoted C^D_p. The cost of sending product p to the filling locations is C^U_p. Disposal of non-quality products does not induce any decision-relevant emissions. This gives

$$\begin{aligned} TC^D = {} & \sum_{i\in\mathcal{N}}\sum_{j\in\mathcal{N}^D}\sum_{p\in\mathcal{P}}\sum_{t\in\mathcal{T}} C^D_p f_{ijpt} + \sum_{i\in\mathcal{N}^S\cup\mathcal{N}^F}\sum_{j\in\mathcal{N}^E}\sum_{p\in\mathcal{P}^Q}\sum_{t\in\mathcal{T}} \gamma C^D_p f_{ijpt} + \\ & \sum_{i\in\mathcal{N}^S\cup\mathcal{N}^F}\sum_{j\in\mathcal{N}^E}\sum_{p\in\mathcal{P}\setminus\mathcal{P}^Q}\sum_{t\in\mathcal{T}} C^D_p f_{ijpt} + \sum_{i\in\mathcal{N}}\sum_{j\in\mathcal{N}^U}\sum_{p\in\mathcal{P}}\sum_{t\in\mathcal{T}} C^U_p f_{ijpt} \end{aligned} \tag{33}$$

$$\begin{aligned} TE^D = {} & \sum_{i\in\mathcal{N}}\sum_{i\in\mathcal{N}^D\cup\mathcal{N}^U}\sum_{p\in\mathcal{P}}\sum_{t\in\mathcal{T}} E^V_p f_{ijpt} + \sum_{i\in\mathcal{N}^S\cup\mathcal{N}^F}\sum_{i\in\mathcal{N}^E}\sum_{p\in\mathcal{P}^Q}\sum_{t\in\mathcal{T}} \gamma E^V_p f_{ijpt} + \\ & \sum_{i\in\mathcal{N}^S\cup\mathcal{N}^F}\sum_{j\in\mathcal{N}^E}\sum_{p\in\mathcal{P}\setminus\mathcal{P}^Q}\sum_{t\in\mathcal{T}} E^V_p f_{ijpt} \end{aligned} \tag{34}$$

3.0.10. *Total system emissions and costs*

The resulting objective functions for minimizing system costs and emissions are

$$\min z^C = TC^T + TC^V + TC^R + TC^D \tag{35}$$

$$\min z^E = TE^T + TE^V + TE^R + TE^D \tag{36}$$

3.0.11. *Perspective of the project owners*

There are two main reasons why objective functions have been derived from the perspective of project owners. First, project owners have a major influence on how logistics are organized and how much collaboration is applied. Therefore, it is important to be able to quantify how different scenarios affect the respective projects for project owners. Second, optimizing from the perspective of individual projects makes a relevant base case, because this represents a scenario without the collaboration enabled by Bærum Ressursbank. Other (better) solutions can then be compared with the base case.

Cost and emissions related to transport and product flows to and from the project sites are allocated to the owner of the project sites. For flows from one project site to another project site, the receiver pays the cost. If a roundtrip includes project sites with different owners, the savings are allocated based on the relative distance with fully loaded vehicles.

4. Computational study

The focus of the computational study is on the practical implications and managerial insights that can be gained by analyzing the results of the model for different scenarios. The model is implemented in Mosel Xpress-IVE 8.12 optimization software from FICO, run on a Hewlett–Packard Elitebook with an Intel(R) Core(TM) i7-7600U CPU @ 2.80 GHz and 16 GB RAM. The runtime was less than 15 min for all instances and hence no time limit on the computations was set. The analyses are made by defining a number of different instances with desired characteristics, solving these to optimality, and comparing the solutions. The differences in objective values and solution structure are inherit from the characteristics of the instances and are thoroughly analyzed. The data collection has been done by the authors in close collaboration with the partners of Bærum Ressursbank and other participants in the C&D

sector in Norway. The amount of data needed for the computational study is not large, and therefore a data pipeline was not set up. All data have been thoroughly examined and validated by C&D waste management experts within Bærum Ressursbank. All costs are measured in Norwegian krone (NOK) and emissions are counted in CO_2 equivalents. We use tonnes for weight measures, kilometers (km) for distances and tonne-kilometers (tkm) for transportation work, i.e., moving two tonnes a distance of three kilometers is equivalent to six tkm.

4.1. Case data

Five infrastructure projects are included in the system considered in the computational study. These are different in size with respect to both supply and demand and the number of project sites. The key specifications for each project are presented in Table 1.

There are 13 Project sites, five Recycling facilities, four Filling locations, and four Disposal locations. As mentioned above, a geographical location can be modelled with two different nodes if the location has allocated areas for both disposal and recycling.

The planning horizon is 11 years, with a yearly given supply from and demand to each project site. These are assumed to be evenly spread over the respective years. Supply exceeds demand to a great extent. Fig. 3 shows the net supply and demand and the accumulation of supply throughout all years. As we can see, most of the supply is concentrated around 2022–2024, while demand is highest towards the end of the planning horizon.

The supply and demand of masses are divided into 21 different products, presented in relative quantities in Tables 5 and 6 in Appendix A. Additionally, seven intermediate products are involved in one or several of the 19 different recycling processes.

4.2. Multiobjective optimization of costs and emissions

To analyze the trade-off between costs and emissions, we have used the weighted objective function

$$\min z^{MO} = \omega z^C + (1-\omega) z^E \tag{37}$$

where z^C and z^E are defined in Eqs. (35) and (36) respectively. The values (z^E, z^C) for different ω are shown in Fig. 4. Here, we have assumed that there is no transportation collaboration between the different projects. This is implemented by only including roundtrip variables where the sites visited belong to the same project.

Even though the weighted sum method for multiobjective optimization does not guarantee that all Pareto efficient solutions are found, the number of different solutions found and their spread give a solid ground for the analysis (Antunes et al., 2016). The difference in total emissions is approximately 1%, while total costs vary around 4% between an entirely economic objective function, point A in the figure, and an entirely environmental objective function, point B. A reason for this is that transportation and processes drive both costs and emissions relatively similarly. However, within these ranges, the Pareto front is relatively steep at both ends and a solution around the point C seems as a reasonable trade-off.

Table 1
Key specifications for the projects.

	Project 1	Project 2	Project 3	Project 4	Project 5
Number of project sites	7	1	1	1	3
Fraction of total supply	58.7%	0.8%	17.2%	14.6%	8.7%
Fraction of total demand	92.6%	0.1%	5.3%	2.0%	0.0%

4.3. Levels of cooperation

Bærum Ressursbank is an enabler of collaboration and can also explicitly state that cooperation is a condition for the C&D industry within the municipality. It is therefore of interest to analyze the effect of collaboration on the system level as well as for each project. The current situation within the C&D industry where Bærum Ressursbank operates is driven by uncertainty about the risks and gains with collaboration and suspicion between the actors. This has led to very myopic planning where each project seeks to minimize its own costs. Using the objective function (37) with weights such that point C in Fig. 4 gives the system optimum and hence the lowest objective value, we contrast this with situations with less collaboration. We have analyzed four levels of collaboration; (1) Individual projects without roundtrips, (2) Trading between projects without roundtrips, (3) Trading between projects with roundtrips, and (4) System collaboration.

The first level of cooperation is planning transportation and logistics individually for each project. Each project chooses optimal transportation routes without taking into account the demand and supply of other projects. The only roundtrips that are allowed are backhauls, that is, $i \rightarrow j \rightarrow i$. First, we solve the problem for each project individually by removing the demand and supply of all other projects. Then, we fix the flows to and from each project site based on these solutions. Finally, we optimize at the system level with the fixed flows. The system solution based on the solutions for the individual projects may be infeasible due to the inventory capacity restrictions at the facilities and locations and we therefore relax these constraints. This mimics the current situation, but underestimates the costs and emissions due to the relaxations.

The second level of cooperation allows trade of products between different projects, but excludes the possibility of roundtrip collaboration. Therefore, the demand of a project can be met by supplies from other projects either directly or through processing. We minimize the sum of the objective function values directly associated with the projects, fix the flows to and from each project site based on this solution, and then optimize at the system level. The third level has the same assumptions as the second, but we allow roundtrips including project sites belonging to the same project.

The most comprehensive form of cooperation is called system collaboration. Here, all participating projects consider the supply and demand of other projects, and the total costs and total system emissions are minimized. Additionally, projects collaborate on transportation, with the possibility to utilize roundtrips.

The four levels of cooperation are evaluated with the objective function (37) weighted so that the point C in Fig. 4 is the system optimum. For the objective functions for individual projects, the same weights are used. Table 2 shows a comparison of key results for the four scenarios. The first two rows show the system emissions and the system costs. The next three rows show the tonne-kilometers, the kilometers driven in total, and the kilometers driven by empty vehicles. Roundtrip is the savings in kilometers driven by empty vehicles by allowing transportation collaboration. External show the percentage of the total demand and supply that are fulfilled by externals.

The first thing to note is that the values from Individual projects are not directly comparable with the other values due to the relaxation of the capacities. The two most attractive filling locations receive more than 170% of their total capacity, indicating that the costs and emissions presented in Table 2 are lower than the true values. The most important takeaway from this column is that considerable quantities are handled by externals, around 8% of the demand and 28% of the supply. The other scenarios are easier to compare. We see a clear improvement in all aspects as the level of collaboration increases. Including the possibilities for roundtrips between project sites clearly decreases the empty kilometers, but is not able to decrease the quantity of supply that is transported from outside the system boundary. With a holistic view of the system, the optimal objective function value is reduced by 16%. This translates into a reduction in costs by almost 15% and in emissions by

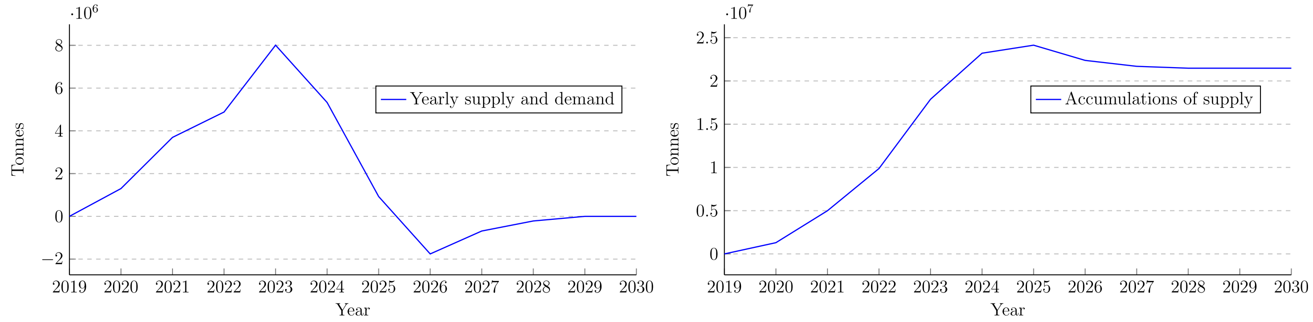

Fig. 3. Net sum of supply (positive numbers) and demand (negative numbers) [left] and accumulated sum of supply and demand [right] from all projects included in Bærum Ressursbank.

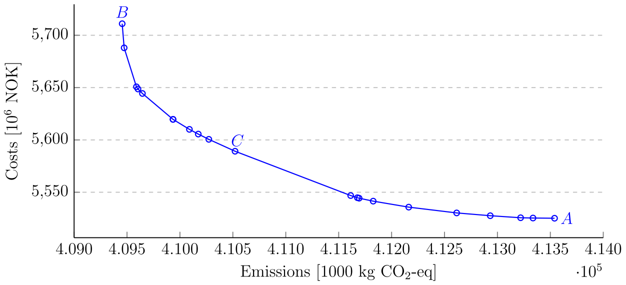

Fig. 4. The Pareto efficient solutions $z^{MO} = (z^E, z^C)$ generated by changing ω in (37). Each circle marks a solution and the line is an outer approximation of the Pareto front.

almost 20%. We also see a clear saving in empty kilometers and in the quantity of supply that is transported from outside the system boundary.

4.4. Specific analysis for Bærum Ressursbank

One of the main goals of this study is to help Bærum Ressursbank with analyzing the viability of the project. More specifically, the following tasks where given; (A) Quantifying the effects of cooperation in a collaborative initiative such as Bærum Ressursbank, compared with individual managing of logistics for each project, and (B) Show the consequences of different political and operational decisions. The effects of task A are divided in two categories; (1) Commercial effect concentrating on costs and emissions, and (2) Political effect focusing on emissions and inconvenience for local residents. Task B is exemplified by analyzing how emissions and costs are influenced if a major project rejects participation in the collaboration.

4.4.1. Commercial and political effects of cooperation

Project owners and politicians are two stakeholders that are important to influence when trying to make any practical changes to logistics and transportation in the C&D sector. Bærum Ressursbank must be able to show specific results that demonstrate the advantages for each respective stakeholder.

Environmental issues are of great concern to governments and municipalities. This includes both the local environment and global climate, ranging from resident inconvenience to global warming. Therefore, the following results are compared considering political effects: Total system emissions, Total number of tonne-kilometers, Total number of kilometers driven without cargo, Total number of vehicle-kilometers, and Amount of material recycled.

Economic benefits are in general most important for project owners and other commercial parties, as they depend on their businesses being profitable in the long run. However, the recent focus on climate and global warming has made it significant for commercial parties to show environmental care. Therefore, the following results are compared considering commercial effects: Costs for each individual project, Emissions from each individual project, and Total system costs.

In all analyses, we compare the system collaboration case with the case where the transportation and logistics is planned individually for each project. As said before, this mimics the current situation but underestimates the costs and emissions due to the possible overuse of nearby filling locations. This corresponds to the cases System collaboration and Individual projects in Table 2. Assuming that the main driver of the projects is cost, we minimize cost in this analysis.

As Table 3 shows, there are economical as well as environmental benefits from a collaboration based on optimizing the whole system. The main reason for the decrease in both costs and emissions on the system level is a reduction in the transportation to and from the system, i.e., the external transportation, and in the usage of the recycling facilities. The

Table 3
Comparison of system and project emissions and costs by the introduction of Bærum Ressursbank.

Cost/Emission	Unit	Individual projects	System collaboration	Change
System Emissions	[10^6 kg CO_2-eq]	483.2	411.3	−14.9%
Project Emissions	[10^6 kg CO_2-eq]	371.1	400.4	7.9%
System Cost	[10^6 NOK]	7775.0	5464.4	−29.7%
Project Cost	[10^6 NOK]	5679.5	5207.9	−8.3%

Table 2
Comparison of key figures for four levels of cooperation.

Cost/Emission	Unit	Individual projects	Trading no roundtrips	Trading roundtrips	System collaboration
Emissions	[10^6 kg CO_2-eq]	471.8	486.0	478.7	408.7
Costs	[10^6 NOK]	7058.6	7144.3	6897.5	5536.0
Tonne-kilometers	[10^6 tkm]	1783.5	1913.8	1835.0	1383.3
Vehicle-kilometers	[10^6 km]	79.8	84.7	78.0	56.8
Empty kilometers	[10^6 km]	23.6	25.8	15.7	13.4
Roundtrip	[% empty saved]	18.1	18.3	40.0	52.0
External	[% of demand]	8.7	0.0	0.0	0.0
External	[% of supply]	27.4	32.1	31.6	15.3

emissions allocated to the projects increase, mainly because the overuse of nearby filling locations in the Individual projects case underestimates the emissions in this case. In contrast, the costs allocated to the projects decrease as a result of less supply transported from outside the system boundary. This has a larger impact on costs than on emissions. Since the savings of the system are greater than the savings for the projects, the total savings of the system must be allocated to the project owners and other participants in a fair way. Several sharing mechanisms have been developed for these costs and savings distributions to deal with these issues. Among others, Frisk et al. (2010) discuss different methods applied to collaborative forest transport in Sweden, a conceptually related problem to the IWMP. They provide an optimization-based allocation method that tries to make the relative savings of each participant as equal as possible.

4.4.2. Effects of major projects excluded from collaboration

An important characteristic of the system of Bærum Ressursbank is the fact that one project is significantly larger than the other projects. Potentially, this participant might consider it more beneficial not to cooperate with other projects because they themselves might be able to organize transportation and reuse as efficiently alone as together with the collaboration. Therefore, it is interesting to compare total system emissions and costs for a case where the largest project is included and a case where it is excluded. We solved the model for only the largest project, then fixed the flows in this solution and reoptimized the model with all projects. This gives the total costs and emissions in the case when the largest project is not part of the collaboration. The results are presented in Table 4.

Total system emissions and costs are higher when organizing the largest project outside the collaboration. This is mainly due to the reduced possibilities of reuse and recycling and limited roundtrip cooperation between the projects. When the largest project does its own planning, it does not collaborate with the other projects. This results in a 10% increase in costs for the largest project, showing that it is much worse off not being part of the collaboration. The tonne-kilometers are drastically reduced when all projects collaborate, meaning that more of the waste produced within Bærum Ressursbank can be reused or recycled, the percentage of demand/supply handled by externals is 15/22 when the largest project is excluded from collaboration and 0/16 when it is collaborating. This, together with a reduction in system costs of more than 16% should really be an incentive for project owners to collaborate within Bærum Ressursbank.

Table 4
Comparison of when all projects collaborate and when the largest project is excluded.

Cost/ Emission	Unit	All projects collaborate	Largest project excluded	Change
Emissions	[10^6 kg CO_2-eq]	411.3	434.3	5.6%
Costs	[10^6 NOK]	5464.4	6376.8	16.7%
Tonne-kilometers	[10^6 tkm]	1389.2	1580.0	13.7%

5. Discussion

The analysis in Section 4 shows that there is great potential to reduce costs and environmental impact by getting actors in the C&D industry where Bærum resursbank operates to collaborate. To exploit this potential, there are many issues to deal with, as discussed in (Basso et al., 2019). They categorize the challenges related to horizontal collaboration in logistics into four groups related to design, planning and operations, market/business, and behavior.

Unlike situations where fairly equal actors collaborate to better realize logistics activities, here there is a strong partner, Bærum resursbank, that can establish the framework for collaboration. This means that challenges related to design, such as the number of actors in the collaboration, who should be part of the collaboration, and who will lead the collaboration, can be handled by Bærum resursbank in a satisfactory way. Allocating economic savings among the actors is also an important issue and a clear and transparent method of allocation is necessary for good working collaboration. The fact that the project portfolio and the actors in the C&D industry change over time is another important challenge, but we see potential in the work of Bærum resursbank to mitigate this.

More technical issues, such as systems for data collection, communication, and information sharing, are aspects that need to be in place for collaboration to work. The role of Bærum resursbank is very important when it comes to specifying, designing, and managing the systems needed. This, together with incomplete, inaccurate logistics information, and inefficient information flow and updates, is highlighted as barriers for horizontal collaboration related to information sharing by Karam et al. (2021).

We do not see that collusion is an issue in this case. The municipality of Bærum is a strong partner in Bærum resursbank and can act as an independent third party, guaranteeing that the decisions implemented align with the strategy to reach an optimal solution for the system.

6. Conclusions

In this paper we studied the infrastructure waste management problem (IWMP) and the gains from collaborating in the construction and demolition (C&D) industry. The IWMP combines strategic decisions on the choice of technology at recycling facilities and tactical decisions on the allocation of waste and the production of products from the waste. The case is the work of Bærum Ressursbank, a collaborative forum initiated by the Norwegian municipality of Bærum between numerous participants in the C&D industry with the aim of finding logistic solutions to an expected surplus of 15 million m^3 of waste from infrastructure projects in the next decade. The IWMP was formulated as a mixed integer linear program and solved using commercial software.

The current situation within the C&D industry where Bærum Ressursbank operates is characterized by a very low level of collaboration, uncertainty about the risk and possible gains with collaboration and suspicion between the actors. This has led to very myopic planning in which each project seeks to minimize its own costs. By promoting, incentivizing, or even forcing collaboration, Bærum Ressursbank is convinced that large cost savings and considerable reductions in environmental impact are possible.

The key findings from the computational study can be summarized as follows.

- Although the model is complex, it is computationally tractable with computational times less than 15 min for all instances we tested.
- Total emissions and costs are well aligned with respect to the objective functions used, and the differences resulting from different weighting schemes are relatively small.
- There are challenges in modeling the current situation in the municipality of Bærum. Even with an underestimation of the current situation with respect to emissions and costs, the results show the potential to reduce both dimensions through collaboration.

The results of the computational study support the conjecture by Bærum Ressursbank. Comparing a situation in which transportation planning is done individually for each project with the ideal situation of complete collaboration gives a cost reduction of more than 29% and a reduction in emissions of more than 14%. We also show that if the largest project is outside the collaboration, the total system cost is increased by more than 15%, further highlighting the importance of collaboration.

There are limitations with this study. The system boundary and the flow to and from external sources is generalized with the same unit cost for all nodes. A more thorough data collection could have given better estimates of these costs, but this would not change the key findings or conclusions. The current situation is hard to model exactly using the methodology chosen, but the adopted practice of formulating an underestimation with respect to costs and emissions is considered sound given the comparisons made.

Unlike most cases of horizontal collaboration in the freight transport sector, the IWMP also includes the processes of transforming waste at some projects to valuable products at other. There are many unanswered questions related to design and management, especially with respect to information uncertainty, which are interesting avenues for further research.

The Norwegian National Transport Plan is a 10-year investment plan for all modes of transport in Norway. The plan coordinates the investments carried out by the Norwegian Transportation Administrations. Coordination between different projects regarding infrastructure waste management has not been a major priority, but it is an interesting path for further research. By shifting projects in time, synergies between supply generated at one project and demand at another can be exploited.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank Ida Nilsson of Norconsult AS and Tore Gulli of Bærum kommune for a good partnership providing industrial advice and the necessary data. Finally, we thank Lasse Johansen from Sprint Consulting for helpful conversations. This work was partly supported by the Research Council of Norway through the AXIOM project. This support is gratefully acknowledged.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.wasman.2022.11.019.

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