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# Optimizing environmental and economic aspects of collaborative transportation and logistics related to construction and demolition projects

Master's thesis in Industrial Economics and Technology  
Management

Supervisor: Henrik Andersson

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# Preface

This master thesis is written as part of my Master of Science degree in Industrial Economics and Technology Management at the Norwegian University of Science and Technology (NTNU). The thesis is made for the master course TIØ4905 Applied Economics and Operations Research. The problem statement considered in this thesis is developed together with Bærum kommune who has acted as an industry partner through their initiative Bærum Ressursbank. This thesis is not a continuation of a master project, but of the previous work of Bærum Ressursbank, providing me with necessary prerequisite knowledge to the subject.

I would like to thank my supervisor Henrik Andersson for being patient with invaluable guidance and thorough discussions. Furthermore, I would like to thank Ida Andersson from Norconsult AS and Tore Gulli from Bærum kommune for a good partnership providing me with industrial advisory, helping me finding necessary data and including me in the parallel work of Bærum Ressursbank. Finally, I would like to thank Lasse Johansen from Sprint Consulting for helpful conversations.

# Abstract

The largest waste types in many regions throughout the world are represented by surplus rock, stone fractions and other construction- and demolition waste, with a large potential for reuse and recycling. In order to fulfil national and international goals of 70 % material recovery from construction and demolition projects it is necessary to facilitate adequate management of these wastes. On the other hand, there is an increased demand and scarcity of natural occurring material. Thus, recycling and reuse of construction and demolition waste are of both environmental and economic importance, as it can reduce landfill, transportation and resource extraction. The municipality of Bærum wants to facilitate an optimal use of such masses through the collaborative project Bærum Ressursbank. This initiative is the origin of this master thesis.

The aim of this paper is to provide decision support for planning of recycling and handling of surplus material from construction and demolition projects. The hypothesis is that a better planning of mass transportation and recycling collaboratively across projects will facilitate increased reuse of waste materials and reduced transportation needs, resulting in both economic and environmental benefits.

This is done by finding the distribution network of construction masses and which processing machines that are needed at different recycling facilities. The problem is solved by the means of a deterministic Mixed Integer Linear Programming (MILP) optimization model that combine a supply chain network problem formulation with a formulation of transportation backhauling (in this thesis denoted roundtrip). The model considers both environmental (CO<sub>2</sub> emissions) and economic criteria, from the perspectives of individual project owners and the overall system/society. Using this model, different scenarios are analysed based on a real-life case in the municipality of Bærum in Norway.

The main contribution of this thesis is a developed model which can be used as a decision support tool for both government agencies and commercial participants in the construction and demolition sector when planning transportation and logistics around construction wastes. The

paper shows that if trade and transportation of masses are planned cooperatively across projects, close to all demand is possible to get from recycled and reused construction waste. Furthermore, the analysis show that emissions and costs can be reduced at least 20 % and 34 %, respectively, compared to individually optimizing each respective project. However, the results indicate that not all environmental impacts are reflected by only considering CO<sub>2</sub> emissions. In the case study carried out in this thesis, benefits for local inhabitants surpass the reductions in carbon emissions, as a transportation collaboration could reduce kilometres empty driving of trucks by as much as 55 %.

The model proposed in this master thesis is ready to be implemented in real world applications. Several industry participants have already shown interest for the model with positive feedbacks. By increasing the quality of input data even more, the produced results become increasingly accurate, and can be used as decision support for governmental agencies, project owners, entrepreneurs and other parties in the construction and demolition sector.

# Sammendrag

Overskuddsmasser fra bygg- og anleggsprosjekter representerer den største avfallskategorien i mange regioner rundt omkring i verden. Slike masser har et stort, uutnyttet resirkuleringspotensial. For å imøtekomme nasjonale og internasjonale mål om minst 70 % gjenvinning av overskuddsmasser er det nødvendig å legge til rette for bærekraftig massehåndtering i bransjen. På en annen side er det et økende behov for byggemasser, samtidig som mange av overskuddsmassene er verdifulle, ikke-fornybare ressurser som bør utnyttes til det fulle for å unngå knapphet på ressurser. Resirkulering og gjenbruk av overskuddsmasser er derfor viktig både miljømessig og økonomisk, for å redusere deponering, transport og utvinning av jomfruelige råvarer. Dette ønsker Bærum kommune å legge til rette for gjennom samarbeidsprosjektet Bærum Ressursbank, som også er utgangspunktet for masteroppgaven.

Formålet med denne masteroppgaven er å gi beslutningsstøtte til planlegging av gjenvinning og håndtering av overskuddsmasse fra utbyggingsprosjekter. Hensikten er å se på økonomiske og miljømessige effekter av transport, behandling og gjenbruk. Hypotesen er at samarbeid mellom aktører i bransjen og bedre planlegging av gjenvinning og massetransport vil gjøre det mulig å gjenbruke mer av overskuddsmassene og redusere transportbehov. Dette vil i så fall gi både miljømessige og økonomiske besparelser.

For å løse disse problemstillingene, er det utarbeidet en modell for å finne distribusjonsnettverket av overskuddsmasser og hvilke anlegg som behøver ulike gjenvinningsmaskiner. Modellen er en Mixed Integer Linear Programming (MILP) optimeringsmodell som kombinerer formuleringer fra problemer som tar for seg forsyningskjedenettverk (supply chain network problems) og returtransport (backhauling). Modellen ser på både miljømessige og økonomiske kriterier, fra både prosjekteieres og samfunnets ståsted. Modellen har blitt brukt med reelle data for å optimere og analysere transport og logistikk i Bærum kommune.

Hovedbidraget fra masteroppgaven er en modell som kan benyttes som beslutningsstøtte for både private og offentlige aktører for å planlegge transport og logistikk rundt overskuddsmasser. Resultater fra analysene som er gjort viser både økonomiske og miljømessige besparelser av å koordinere massetransporten mellom prosjektene. Ved å få alle

aktørene til å samarbeide kan så mye som 99 % av behovene for byggemasser hentes fra overskuddsmasse fra andre prosjekter. Analysen viser også en reduksjon i utslipp og kostnader på henholdsvis 20 % og 34 % ved samarbeid, sammenliknet med et tilfelle hvor alle enkeltaktører optimerer transport og logistikk individuelt. Et viktig aspekt som blir avdekket er at det kan være vanskelig å vise alle miljømessige konsekvenser kun ved å se på utslipp av CO<sub>2</sub>. I studien som er gjort her, er et eksempel på dette at besparelsen i antall kilometer tomkjøring er så mye som 55 % hvis prosjekter samarbeider om transport, noe som er betydelig mer enn besparelsene i rene karbonutslipp. Dette er likevel et viktig mål på hvordan lokalbefolkningen påvirkes.

Modellen som er utviklet i denne masteroppgaven er klar til å bli tatt i bruk til industrielle formål, noe flere aktører i bransjen har vist interesse for. Med kvalitetssikring av input-data vil resultatene bli enda mer nøyaktige, og brukes til beslutningsstøtte for både kommunale og statlige aktører, prosjekteiere, entreprenører og andre i bygg- og anleggsbransjen.

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# Chapter 1 Introduction

Together with economic growth and increasing populations, construction activities increase in many regions throughout the world. Accordingly, construction and demolition projects such as construction and remediation of infrastructure demand increasingly more raw materials as rock and crushed stone. Traditionally, demands have been met by extracting virgin materials from quarries. These are non-renewable resources, and the extraction leads to strain on the local society as excavation of soil is noisy, dusty and area demanding. On the other hand, construction and demolition projects today generally generate a net surplus of waste materials needing to be handled. These waste materials have traditionally been disposed of as landfill, even though much of it is high quality materials.

However, the potentials for recycling and reuse of materials in the construction and demolition sector are massive. Waste materials from one project may often coincide with demand from another project, either directly or after some degree of processing. Thus, recycling and reusing waste materials from construction and demolition projects may be used as good sources of construction materials, substituting natural virgin resources (Jendia & Besaiso, 2011).

Furthermore, the construction and demolition sector is one of the major contributors to CO<sub>2</sub> emission in fast growing cities (Peters, Weber, Guan, & Hubacek, 2007). These emissions are derived from both 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 counts for 60 % of all domestic goods transportation by lorries (Statistisk sentralbyrå, 2019). Some studies have found that recycling of construction and demolition waste actually contribute negatively to the environment if the transportation distances required to carry material to and from recycling facilities are long (Mercante, Bovea, Ibáñez-Foré, & Arena, 2012). Therefore, good management and planning is required to obtain the desired benefits.

In Norway, several participants in the construction and demolition industry begin to see the importance of material recovery and reuse. Nevertheless, the construction and demolition sector generate the majority of total waste in the country (25 % in 2016), which still is increasing (Skjerpen, 2018). Also, the amount of recycling has fallen the recent years, as more than ever

concrete, soil, stone and gravel is being sent to disposal instead of material recovery (Skjerpen, 2018).

The main challenge addressed in this master thesis is how to handle and recycle the massive amounts of construction and demolition wastes that are generated from infrastructure projects the following years, in both an environmental and economic optimal way. The hypothesis is that a better planning of mass transportation and recycling across projects will facilitate increased reuse of waste materials and reduced transportation needs, resulting in both economic and environmental benefits.

The motivation for this thesis is the work of Bærum Ressursbank, a collaborative forum initiated by the Norwegian municipality of Bærum between numerous participants in the construction and demolition industry. The aim of Bærum Ressursbank is to find logistical solutions to an expected surplus of 15 million m<sup>3</sup> of construction waste during the coming decade:

*“Practical and organizational solutions are to be pursued to handle the masses at the most efficient, economical and environmentally and climate-friendly way” (Nilsson, 2018)*

This thesis is a continuation of the preliminary work done by Bærum Ressursbank and the model is developed around the needs and circumstances of the construction and demolition sector in Bærum.

The construction and demolition projects included in the thesis are mostly infrastructure projects as road and railway constructions. Thus, the by far biggest quantities of both surplus and demanded materials are stone, soil, asphalt and concrete. These materials along with specific variations of these are considered in this thesis. Other materials as e.g. building waste are outside the scopes of the thesis. Throughout the thesis several terms are used when referring to construction material in different settings. Terms include *masses*, *construction masses*, *new materials*, *waste materials*, *virgin materials*, *materials* and *products*. All these refer to the materials inside the scope of this thesis, as described above. *Products* is used as a more general term in the mathematical model description, as the model might be expanded to other areas and sectors.

Because of limited sites available, we consider only pre-defined locations of recycling facilities, disposal sites and filling locations. Thus, identifying where each facility should be located is outside the scope of this thesis, even though these questions affect long-term costs and emissions (Queiruga, Walther, Gonzalez-Benito, & Spengler, 2008).

The main contributions of this thesis are a model that can be used to find the distribution network for both surplus waste materials and new, demanded construction materials and to identify the need for certain processing machines at each recycling facility. This is done by the means of a Mixed Integer Linear Programming (MILP) optimization model minimizing environmental impacts (CO<sub>2</sub> emissions) and costs for different participants and for the whole system. This model is then used to analyse different scenarios, applied to a real-life case in the municipality of Bærum in Norway.

The paper is organized as follows. Chapter 2 covers background information about the scopes of this thesis, presenting Bærum Ressursbank and industry specifics as the waste types included, recycling processes, stakeholders, environmental goals and how things are practiced in the sector today. Chapter 3 presents a review of literature used as inspiration for the model developed in this thesis, divided into papers about waste supply chain network optimization and backhauling formulations. Chapter 4 describes the problem considered in this thesis, while the mathematical model which is proposed to solve this problem is presented in detail in Chapter 5. A computational study of the mathematical model is carried out in Chapter 6, first looking at conceptual aspects of the model, before showing an analysis tailored the needs of Bærum Ressursbank. Finally, Chapter 7 conclude the findings, discussing some of the most important results from this master thesis.

## Chapter 2      **Background**

In order to understand the mechanisms of transportation and logistics of surplus material in the construction and demolition industry, it is beneficial to look at the underlying needs, possibilities and restrictions. Section 2.1 presents Bærum Ressursbank and their purpose, as this is what this master thesis tries to address. Section 2.2 presents different alternatives of waste handling, prioritizing different measures and describing processing methods for each waste type. Section 2.3 present the different stakeholders involved, while Section 2.4 describes how industry participants plan and organize transportation and logistics today. Finally, climate goals for the construction and demolition waste sector are presented in Section 2.5.

### **2.1      Bærum Ressursbank**

Bærum Ressursbank is a collaborative initiative between different participants involved in the construction and demolition sector. Project owners, entrepreneurs, landowners, transportation providers, developers, research institutions and public authorities among others are represented. The purpose of Bærum Ressursbank is to find ways to handle and exploit the enormous amount of surplus construction masses that will be generated from several big infrastructure projects the coming decade. Approximately 15 million m<sup>3</sup> of material must be handled, finding useful purposes and preventing environmental damage. The biggest quantities expected are stone, asphalt, concrete and soil, constituting the main focus of Bærum Ressursbank.

### **2.2      Waste handling and product types**

To increase reuse and recycling, it is important to utilize high quality products to high-value purposes and only dispose products that are not suitable for useful purposes. The following section present prioritizing of waste handling measures, before describing the recycling

processes needed to recover the different waste products. The information below is obtained by earlier works by Bærum Ressursbank and personal conversations with experienced people from the industry.

### 2.2.1 The Resource Pyramid

In order to facilitate decision-making related to construction and demolition waste handling, a Resource Pyramid has been developed by Rogaland fylkeskommune (2017), presented in Figure 2.1. This shows the prioritizing of measures and the relationships between different waste handling strategies. The objective is to keep as much as possible of raw materials in the value chain, in order to prevent resource depletion and reducing environmental impacts.

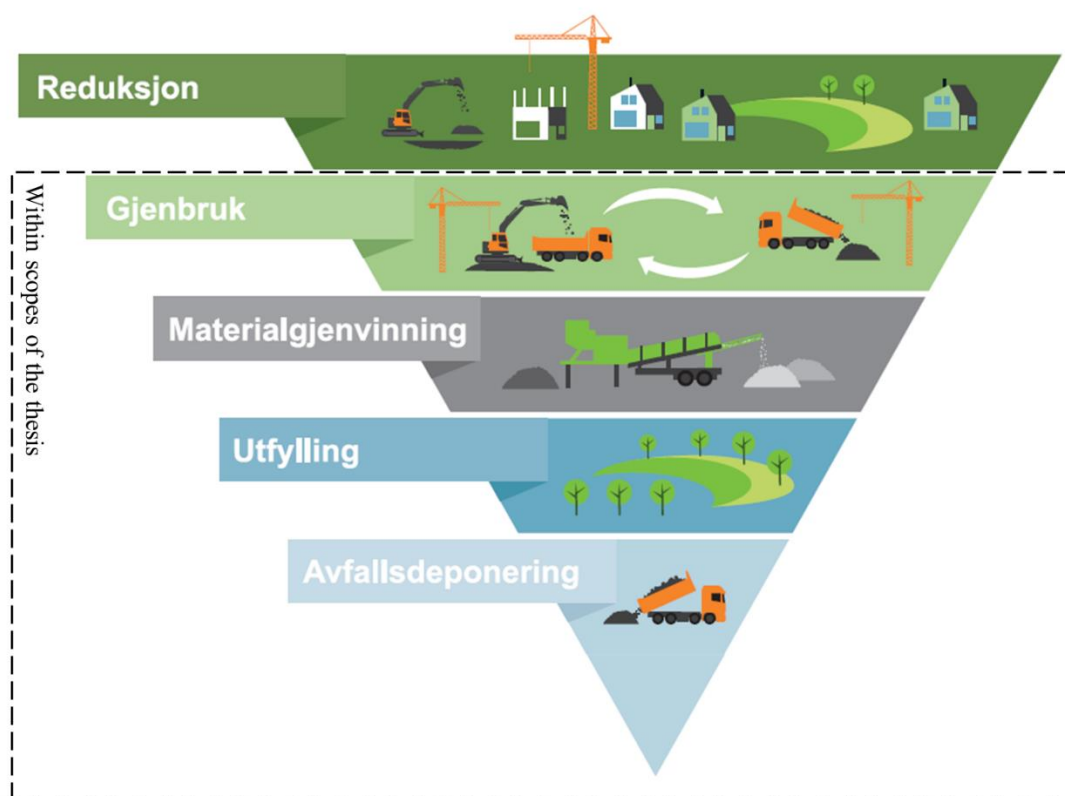


Figure 2.1: The Resource Pyramid developed by Rogaland fylkeskommune. Reduction of waste generation is beyond the scope of this thesis.

The first step of the Resource Pyramid is reducing waste generated from projects, including reuse or recycling within the same project. This prevents need for transportation to and from

the project site. Secondly, reuse without the need for comprehensive processing should be aimed for. This often requires areas for intermediate storage, since supply and demand of a product rarely matches in time. If materials can neither be reused on site nor at another project site, material recycling is desired. This includes various processes at a recycling facility, or directly on site. These processes are further discussed in Section XX. The first three steps of the Resource Pyramid follow the principle that as much raw material as possible should remain circulating in the value chain. However, some materials are not suitable for reuse nor recycling. These materials may be used for useful purposes, in what we will refer to as filling locations throughout the thesis. Here, waste materials substitute the use of virgin materials on locations where there already is a demand for masses. This includes e.g. constructing recreational areas or covering contaminated seafloor. Lastly, some waste materials are not desired to circulate in nature because of contamination. These masses must be disposed of at isolated disposals. However, since permanently disposed materials exit the value chain, disposal should be the last solution for other materials.

### **2.2.2 Stone**

Surplus stone masses from infrastructure projects may be categorized based on quality and fraction size. Quality depends on the geological composition of the bedrock where the stone is excavated from. Since different end purposes require different stone qualities, it is undesirable to use high quality stone for purposes where quality is irrelevant. Most part of the surplus stone from infrastructure projects are excavations and thus come in large fractions, but some excess may as well be of smaller fractions. Waste stone is possible to reuse after one or a combination of several processes, including (1) crushing into smaller fractions, (2) washing to separate different fractions, soils and contaminations, (3) blended as aggregates in asphalt or (4) blended as aggregates in concrete.

The finest stone fractions (e.g. machine sand) have traditionally been treated as unusable waste, as there have been limited possible purposes of reuse. These fractions occur as secondary products from rock excavation or stone crushing processes. Using measures as e.g. washing or sieving separation, these fractions may be utilized in a broader extent, as ingredients producing concrete or asphalt.



### **2.2.3 Asphalt**

Waste asphalt from project sites are either milled or broken up in flakes. A common practice is to mill the upper asphalt layers if there are found any tar in the bottom layers and break it into flakes if all layers are free of tar. However, milled asphalt is much easier to reuse in new asphalt. Traditionally, waste asphalt in flakes has been crushed and used as filling material, reinforcement layers or as a form of cover on roads and other surfaces. As production of new bitumen is both expensive and implies a massive climate footprint, recycling waste asphalt as input in new asphalt is considered much more sustainable than the traditional purposes. In Norway, regulations still prevent using more than 10 % - 20 % recycled asphalt as aggregate in new asphalt, with the possibility to extend this portion with comprehensive documentation (Statens vegvesen, 2014). Some producers operate with a share of recycled asphalt of up to 50 % - 80 % (Nilsson, 2018).

### **2.2.4 Concrete**

Concrete can be recycled in different ways, including direct reuse, crushing to aggregates or as input to production of new concrete. Crushed concrete with low shares of contamination can be used as an alternative to stone aggregates. This practice is growing, even though it is difficult to change long industry traditions. Washing the waste concrete may improve quality of the crushed concrete. Producing new concrete require cement, water, sand and stone aggregate. Traditionally, both sand and stone aggregate are excavated, virgin materials from quarry. However, more sustainable concrete production has been tried the recent years, replacing stone or sand or both with recycled materials. Virgin sand can easily be replaced by machine sand which there generally is a large surplus of. Substituting stone aggregate with crushed concrete is also possible if the highest quality is not required.

### **2.2.5 Soils and other construction waste**

Construction soil can be composed with several compositions of input material. Many secondary products from other processes are usable, as e.g. machine sand, clay, sludge, food soil, woodwork, stumps and roots. Woodwork can also be energy recycled through the use of woodchips in bio fuel.

## 2.3 Stakeholders

The construction and demolition industry involve several different stakeholders, with multiple preferences and point of views. The most important stakeholders for the problem considered in this thesis are presented in figure 2.2, with the organizational and juridical links connecting them. The figure is a generalization of the structures presented by Halvorsen et al. (2005), applicable for most contract forms, where the transport provider act as an subcontractor.

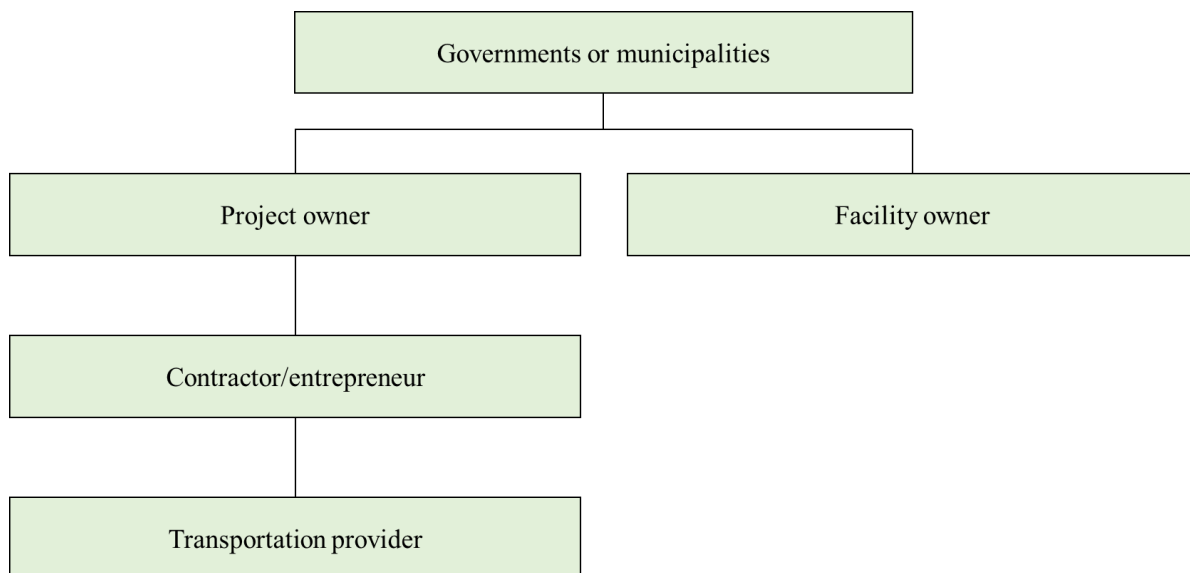


Figure 2.2: Generalized hierarchy of stakeholders involved in construction and demolition projects based on different contract forms.

Project owners usually decide where and what to do with the surplus waste materials generated. They are responsible for engineering, project planning and production documentations, as well as the coordination with one or several contractors (Kjøbli, 2013). Governments and municipalities, however, are able to influence project owners' decisions with economic incentives or regulations. The contractor or entrepreneur is responsible for the actual production. If a project needs transportation of material, the contractor hires a transport provider for the job. Thus, it is up to the transport provider to organize the transport. Assuming that a

transport provider often can optimize their own fleet across several client projects (some contract forms limit subcontractors not to operate between two different projects), the degree of transportation cooperation today very much depends on the number of transport providers.

The last category of stakeholders relevant to the problem in this thesis is owners of recycling facilities. Often, these are owned by contractors or other private participants, but during the work of Bærum Ressursbank it has been discussed whether also the municipality should enter the owner's side. Regardless of owner structure, it has been agreed upon that recycling facilities should be run by commercial, private participants (Nilsson, 2018). The owner invest in certain processing machines, allocate areas to different materials and trade products with project owners. Since these investments often are relatively costly, many facility owners are risk averse when considering new investments or methods to reduce emissions, demanding certainty of return on investment.

## **2.4 Common industry practice**

Traditionally, different participants in the construction and demolition sector have been optimizing their own business independent of each other. Furthermore, few parties collaborate on transportation, as information of material flow often is considered as trade secrets. Thus, construction masses are today transported more or less randomly (Rogaland fylkeskommune, 2017). In Norway, construction materials as rock and stone fractions are in average transported 18,6 kilometres from a quarry to a project site (Søyland, 2019). Mainly, this is still done driving the vehicle back to the quarry empty without goods.

Historically, the fact that projects work for individual optimums has not been an issue because of relatively few construction projects and less demolition wastes. Today, however, individual planning result in poor recycling, widespread extraction of virgin materials and quality masses being disposed of instead of reused. Increasing amounts of projects make the benefits of cooperation across projects more significant.

Globally, there are large differences in recycling and environmental considerations in the construction and demolition sector. In Turkey, the first recycling facility for such wastes wasn't established before 2010 (Jendia & Besaiso, 2011). In Norway, construction and demolition

wastes make the largest share of all waste types, and the amount of wastes that are disposed of actually increases (Skjerpen, 2018). In the Netherlands, Germany, Belgium, and Switzerland, however, there are landfill bans for the unsorted waste and recyclable materials (Ulubeyli, Kazaz, & Arslan, 2017). Already in 2010, all these countries recycled more than 80 % of the construction and demolition wastes, with the Netherlands recycling as much as 98 % (Tojo & Fischer, 2011).

## 2.5 Climate and recycling goals

Several governments have already recognized that reducing emissions from the construction and demolition industry will have large impacts on the environmental challenges we face. Therefore, EU has stated that a minimum of 70 % of construction and demolition waste, *excluding* naturally occurring material (e.g. rock and stone fractions) shall be reused or recycled by 2020 (The European Parliament, 2008). This include concrete, asphalt and bricks. In Norway, these goals have been adapted by the government, proposing several specific measures. In addition, several municipalities have gone one step further, making regional goals of reaching 70 % recycling of all construction and demolition waste, *including* rock, stone fractions, sand, clay and other soils (Rogaland fylkeskommune, 2017).

In Norway, increasingly more people find environmental issues as important. Several industry participants have invested in environmental purposes, among others Velde Pukk, who recently invested in the world's largest recycling facility and several parties researching possibilities for more recycled construction products. These trends have started to reflect in statistics. During the past five years, the amount of domestic transported construction materials has decreased with 12 % (Statistisk sentralbyrå, 2019).

## **Chapter 3      Literature review**

This chapter summarize a literature review consisting of earlier work done on related topics to the problem studied in this thesis. The papers are divided into two categories covering the two optimization topics that are combined in the mathematical problem described in Chapter 5, as no papers found include both of these features. The mathematical model described in Chapter 5 is inspired by the literature below. Section 3.1 present papers studying optimization problems on logistics of waste management, discussing different perspectives to the problem, choices of objective functions and how they deal with multi-objectives. Section 3.2 involve optimization of backhauling and transportation collaboration, focusing on model description.

### **3.1      Optimization of waste supply chain networks**

Management of construction and demolition waste has been studied increasingly more the recent years as the emphasis on the environmental aspects around waste handling has increased. Much work concentrates around management issues of the recycling facilities themselves. These papers investigate performance, economic viability and life cycle analysis of recycling plants (Ulubeylia, Kazazb, & Arslana, 2017). Optimization problems in the construction and demolition waste sector mostly aim to find optimal locations for one or several recycling plants in different regions, on a strategic level (Baniyas, Achillas, Vlachokostas, Moussiopoulos, & Tarsenis, 2010), (Xu & Wei, 2012) and (Dosal, Coronado, Muñoz, Viguri, & Andrés, 2012). Optimization models focusing on such supply chain network designs have, in other fields than the construction and demolition sector as well, lacked a broad scope of environmental and social measures (Eskandarpour, Dejax, Miemczyk, & Péton, 2015). Thus, the following review aims to include papers that regard environmental aspects in a relatively high degree, discussing how these, together with economical perspectives are handled. All papers presented include linear, deterministic problems, even though one of the papers introduce fuzzy variables to deal with uncertain fuel prices and multi-period optimization to handle uncertainties regarding supply and demand. The comprehensively reviewed articles are summarized in Table 3.1.

Galan et al. (2013) develop an optimization model aiming to identify locations and capacities of construction and demolition recycling facilities and intermediate transfer stations as well as the corresponding distribution network. Binary variables decide whether facilities are installed at pre-defined potential locations or not. They propose two objective functions minimizing (1) medium transportation distance and (2) total costs for facility installation and operation and landfill. The model is solved separately for each of the two objectives and applied to a real case in northern Spain. The final proposal is a manually analyzed combination between the two solutions, minimizing distance and costs, respectively. Galan et al. (2013) find that minimizing costs result in a low number of facilities, while minimizing transportation distance result in an increased number of recycling facilities. Finally, they suggest a compromise between the two solutions for their specific case in Spain. Dosal et al. (2013) extend the model of Galan et al. (2013) by introducing social criteria in the objective. As social criteria they consider among others industrialization ratios, level of tourism and vacant land for the potential locations for recycling facilities. Dosal et al. (2013) find that including these social aspects change the optimal location to some degree.

De Andrade (2017) develop a new optimization approach aiming to plan a network for construction and demolition waste, based on the methodology of Processes and Systems Engineering modelling the processing paths for each individual waste type. The optimization is done from two different point of views, minimizing overall network costs including transportation, recycling processes and landfilling and maximizing revenue from recycling facilities selling recycled products. This last perspective makes de Andrade's (2017) work distinguish from other related optimization models for construction and demolition waste. This is an interesting approach, as commercial forces have significant industry power affecting how logistics are planned. The two different perspectives are compared through several scenario analyses optimizing with different input data and different objectives. De Andrade (2017) concludes that economically, direct disposal to landfill actually is preferred over recycling, as the former implies lower costs than the latter. He also finds that increased disposal costs, legal enforcement stating a minimum proportion of wastes being recycled, or a combination of these measures show promising results to be considered in order to meet environmental goals in the future.

Xu et al. (2019) apply methodology from reverse logistics developing an optimization problem for construction and demolition waste recycling and disposal. The decision variables include recycling processes and corresponding volumes as well as transportation volumes. The problem

is modelled as a multi-period optimization problem with multistage decision making for each time period. This approach is chosen because of the high operational costs and uncertainties regarding supply and demand of masses. Six objectives are combined in the objective function, including fixed costs of facilities, transportation costs, process costs, storage costs, green tax and government subsidies. Uncertainties regarding fuel prices are handled by fuzzy variables. As only monetary costs are included in the objective function, no conversion factors nor weighting factors are used. Instead, the model is solved using all cost objectives together, and environmental factors are handled as parameters. The economic influence of varying the environmental parameters such as recycling ratio and collection ratio are then analyzed. Xu, et al. (2019) find that optimizing the disposal network provide a strong political instrument both environmentally and economically, showing reduced environmental damage, reduced resource consumption and economic benefits from converting wastes to new construction materials.

Santibañez-Aguilar et al. (2015) present an optimization model aimed at planning of the reuse of municipal solid waste. Even though this study does not include construction and demolition waste, the paper is included in this literature review due to the model's applicability to other fields as the focus is on transportation to and from recycling facilities and disposal sites more than the incremental collection of waste. Santibañez-Aguilar et al. (2015) look at the problem from a government's point of view, trying to match supply of waste and demand for recycled products and with an economic objective considering the net profit for the entire implementation of the waste management system proposed. They develop a multi-objective problem formulation simultaneously considering economic, environmental and social aspects. Economic costs included are revenue from sales, operating and capital costs for recycling facilities, transportation costs, disposal costs and separation costs. The environmental objective minimizes the fraction of recycled waste. Social aspects include leakage and toxic emissions. The material flow is assumed to follow one specific path, from waste producers, via disposal centers, to recycling facilities, ending at demanding consumers. The way non-recycled waste is handled in the mathematical model is by assuming that it ends up at the disposal centers. Santibañez-Aguilar et al. (2015) generate three different Pareto fronts, each by solving the model for only two of the three respective objectives and discussing the trade-offs between each. Several other optimization models are developed for routing and management of solid waste collection and recycling. These problems are slightly different in nature than construction and demolition waste problems because of the large number of collection nodes and vehicles collecting waste at several locations before returning to a recycling facility. Therefore, only the

work by Santibañez-Aguilar et al. (2015) is included in this literature review. However, the interested reader is encouraged to see the paper of Noche, et al. (2010) for an overview of solid waste management optimization problems.

Table 3.1: Comparison of the reviewed articles on optimization of waste logistics.

Author	Sector	Objectives	Multicriteria method	Case study
Xu, et al. (2019)	CDW	C & R*	Scenario analysis, solved separately	China
de Andrade (2017)	CDW	C & RR	Scenario analysis	Portugal
Santibañez-Aguilar, et al. (2015)	MSW	C & R & S	Pareto-optimality	Mexico
Galan, et al. (2013)	CDW	C & E & S	Solved separately, analysed manually	Spain

MSW = Municipal Solid Waste (from households), CDW = Construction and Demolition Waste, C = Costs, R = Reuse, RR = Revenue for recycling facilities, E = Emissions, S = Social. \*) Excluded from objective function, but covered through scenario analysis

In addition to the papers described above, some inspiration is gathered from supply chain network design problems from other industry fields. These are not explicitly presented here, but an extensive overview is found in the article by Eskandarpour, et al. (2015), covering mathematical models that include both economic and environmental factors. The way the objectives are included in the models vary. Some models treat both economic and environmental objectives in the objective function, either by solving the model for each respective objective, or by applying a multi-objective solution method such as a weighted sum of objectives or the  $\varepsilon$ -constrained method. These papers often use a conversion factor to convert emissions or other environmental measures to monetary units. Examples of this approach is multiplying the emission objective with a cost of carbon credit (Abdallah, Farhat, Diabat, & Kennedy, 2012), (Kannana, Diabatb, Alrefaeic, Govindand, & Yonge, 2012). Other papers optimize costs, while considering environmental factors as constraints, e.g. a maximum allowed greenhouse gas emission.

A common issue for models considering both economic and environmental objectives is that trade-offs between the two objectives always must be considered thoroughly. Galan, et al. (2013) solve the different objectives separately before manually interpreting the solutions and choosing a final solution compromising costs, emissions and social factors rather subjectively.



Santibañez-Aguilar, et al. (2015) analyze different Pareto-curves more mathematically to find the best compromise among their three objective functions. Finally, both de Andrade (2017) and Xu, et al. (2019) analyze results through several scenarios, varying both objective functions and input parameters.

## **3.2 Backhauling in transportation**

The model proposed in Chapter 5 combine formulations from supply chain network problems with transportation backhauling to develop the feature of roundtrip transport collaboration between different projects. This section presents the work used as inspiration for that part of the model.

The paper of Carlsson and Rönnqvist (2007) develop a linear programming problem introducing backhauling variables. They base their model on a tactical transportation problem in forestry, aiming to find the optimal network of flows from supply points to demand points. As they emphasise, this traditional approach can be improved using what they call backhauling. In traditional forestry transportation vehicles return empty after delivering a load of logs. The use of backhauling means, however, that the vehicles find logs that are going in opposite directions so that it is possible to travel loaded in both directions. To include this in their problem formulation, they use additional backhauling variables in addition to the traditional direct flow variables. A backhaul route is defined by a set of direct tours, and it is a “feasible” backhaul route if the distance driving empty is reduced compared with making the same haulage task with direct tours. Furthermore, the benefits of a backhaul route is calculated as the saved empty distance. The cost of a backhaul route is defined as the sum of transportation costs for all direct tours included in the backhaul route minus the calculated benefits of the backhaul route.





What Carlsson and Rönnqvist (2007) identify as the main challenge with the model, is the large number of potential backhaul routes. To cope with this, they suggest several methods. One method is a described column generation solution method. Another is pre-generating a pool of backhaul routes, which they state can be very efficient for industrial applications. The column generation approach divides the problem into a master problem and a sub-problem. The master

problem includes all direct tours and is first optimized without any backhaul routes. Then, the dual solution is used in the sub-problem, identifying the backhaul route with the most negative reduced cost. This route is included in the master problem, before optimizing again. This procedure is then repeated until a convergence criterion is met.

Finally, Carlsson and Rönnqvist (2007) conclude that several case studies testing their model indicate potentially large economic and environmental savings from coordinating transportation with backhauling routes.

## Chapter 4 Problem description

The problem considered in this thesis consists of a system representing a geographical area. Within the system boundaries, there are several locations categorized into four different types of nodes:

-  Project sites
-  Recycling facilities
-  Filling locations
-  Disposal locations

There are multiple instances of each node type, distributed over the system area, e.g. as shown in Figure 4.1.

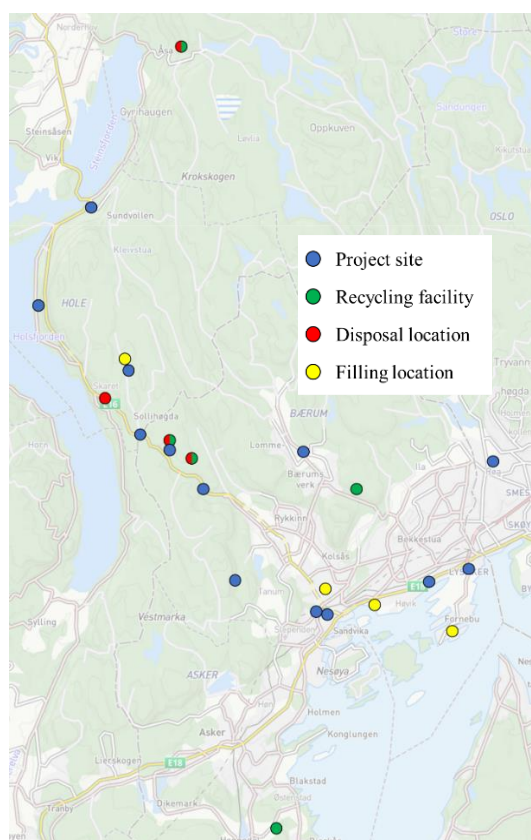


Figure 4.1: Example of distribution of multiple node types within the system boundaries

Project sites are locations where construction and demolition work occur, typically infrastructure projects as road or railway construction. Project sites both generate surplus materials which must be transported away and demand for new materials and products into the site. For convenience, all these masses, both waste, surplus materials, new materials and new products are named *products* in this thesis. Project site nodes correspond to the geographical location where surplus products are generated and new products are needed. Thus, one project may consist of several project site nodes, e.g. representing different outlets from a railway tunnel. In this thesis, outlet locations are pre-defined for each project. Interested readers are, however, encouraged to look at the model by de Lima et al. (2013), proposing a mathematical programming approach for deciding locations of outlet for an individual project. Project sites are assumed not to have any storage capacity (products that can be reused within the same project and stored intermediately at project sites are excluded from the problem). Thus, surplus products must be transported away from project sites at the same time period when they are generated. These can be sent to either a recycling facility, a filling location, a disposal site, or directly to another, demanding project site.

Recycling facilities have, through several processes, the possibility to transform one or several products received from project sites, into one or several new products. These new products can thereafter be delivered to project sites according to demand. Since some processes generate surplus (waste) products not usable by any project site (e.g. small fraction useless sand from crushing stone processes), these may be delivered to either a filling location or a disposal site. 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 construction of a recreational area, expansion of land or creation of an island. Nothing is transported out from a filling location, and the amount of masses received cannot surpass a finite permanent storage capacity.

Disposal locations are conceptually quite similar to filling locations. They can receive waste products, storing them permanently. Nothing is transported out from a disposal location. The difference between a filling location and a disposal site is that the masses used at filling

locations serve socially beneficial purposes, while disposal sites are only used to get rid of unwanted masses. Thus, disposal prices paid by projects and which products that are acceptable are different for filling locations and disposal sites.

Some locations may have the properties of several node types. Typically, this is the case for recycling facilities, which have both temporary storage capacity, as well as 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). Figure 4.2 shows all possible product flows between different types of nodes.

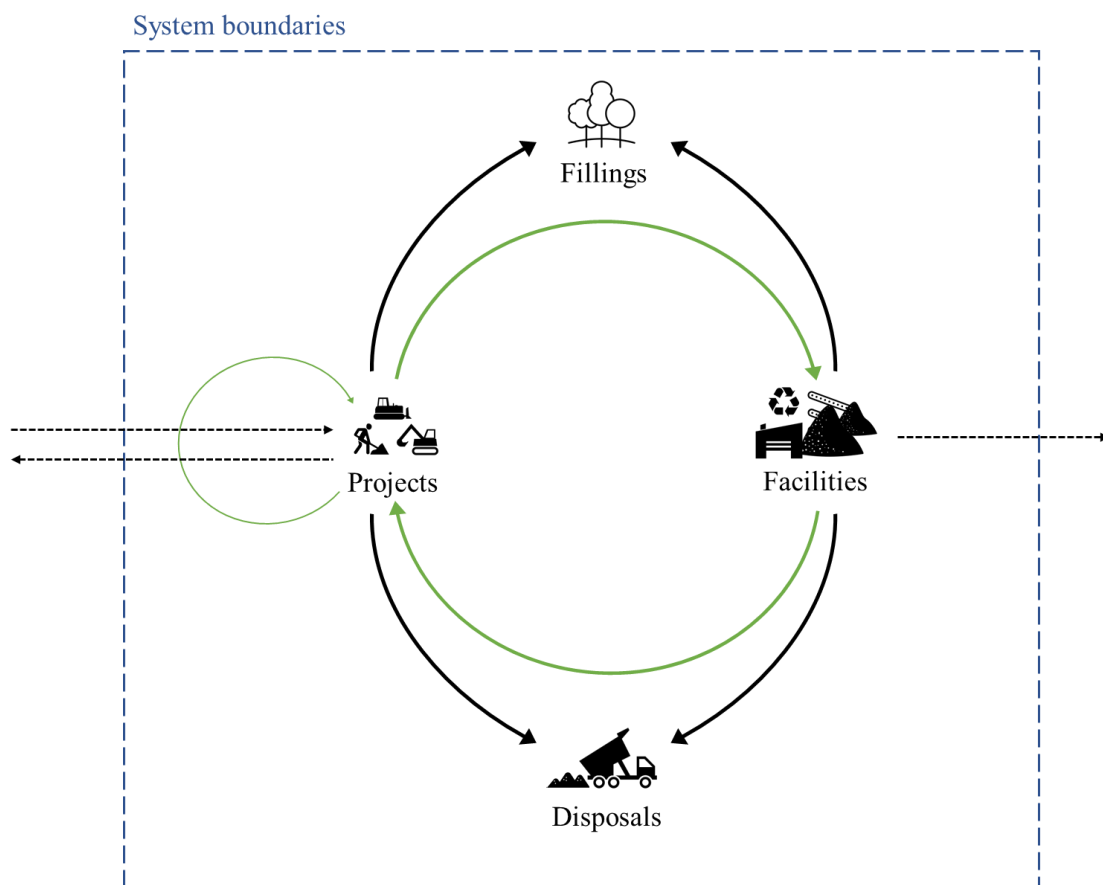


Figure 4.2: Transportation flows within and across system boundaries. Green arrows represent principally favorable flows, according to the Resource Pyramid discussed in Section 2.2.1

A given amount of surplus products are to be transported away from each project site, each time period of the planning horizon. Furthermore, a given demand of new products at each project site are to be met at the specified time period. The problem may be divided into three conceptually different parts:

- Vehicle routing
- Roundtrip cooperation
- Machine investments and usage

First, routing of material transportation between all nodes are to be decided, aiming to reduce the total distance required to transport the masses. Secondly, application of roundtrips and backhauling are to be decided. Roundtrips can reduce empty driving distance and may be organized internally for a project or cooperatively across different projects. Finally, logistics related to recycling processes are to be decided. This includes deciding location of processing machines and amount of usage.

## Chapter 5      Mathematical model

The following chapter presents the proposed mathematical model. Section 5.1 describe assumptions and how the model has been developed to address the conditions presented in Chapter 4. Notations for sets, indices, variables and parameters are shown in Section 5.2. Section 5.3 describe the model constraints, while Section 5.4 present different objective functions. Pre-processing of variables are described in Section 5.5. Finally, extensions to the model is presented in Section 5.6.

### 5.1      Assumptions and modelling choices

The model proposed in this section is a deterministic static, mixed integer linear programming problem. The problem does not include any stochastic variables, even though many aspects covered incur some degree of uncertainty in real life applications. Many of the uncertainties, however, are of such character that they are possible to analyse through scenarios, varying input parameters to the model. This is done in Chapter 6. Nevertheless, extended formulations beyond the one presented here, could include aspects as stochastic fuel prices or supply/demand. Furthermore, further extensions could include multi-period optimization. However, this way of modelling is chosen because complex parameters such as supply and demand are assumed to be relatively well known for the entire planning horizon. Other uncertainties are handled by scenario analysis. The following sections describe modelling choices for each respective part of the model, which in turn is presented in Sections 5.2 - 5.4.

#### 5.1.1    System geography

The set of project sites,  $N^S$ , recycling facilities,  $N^F$ , disposal locations,  $N^D$  and filling locations,  $N^U$  comprise all nodes,  $N$  between which it is possible to transport a set of products,  $P$  within the system. Each node represents the geographical location where products are either transported to or from. Each project in the set of projects  $S$  are represented by one or several

project sites, one for each outlet. Each pair of nodes  $i$  and  $j$  are connected by two arcs, one arc representing the driving distance from  $i$  to  $j$ , while the other represent the driving distance from  $j$  to  $i$ . Of the set of all products, certain products,  $P^D$  are materials demanded by project sites. These must be delivered to project sites either from recycling facilities, other project sites or from an external location. External locations are not represented by a node. Instead, each node  $N^S$  is given a distance from an arbitrary external quarry, which in turn decides transportation costs and emissions when a project receives products from an external location. Similarly, for products transported out from a project site or a recycling facility to an external location, transportation costs and emissions are based on the distance from the node to an arbitrary external disposal site. This distance is assigned to each node  $N^S$  and  $N^F$ . Furthermore, each recycling facility,  $N^F$ , can invest in a set of processing machines,  $M$ , with which a set of processes,  $R$ , can be run. These processes then may transform surplus products to demanded products,  $P^D$ .

### 5.1.2 Product flow

The model consists of two practically different parts, transportation with backhauling and processing of products for reuse, respectively. The transportation problem is formulated as a linear programming problem involving both direct flow variables and additional roundtrip variables, based on the model of Carlsson and Rönnqvist (2007). The direct flow variables,  $f$ , represent real flow of products from supplying project sites to demanding project sites, while the additional roundtrip variables,  $g$ , are used to model flow in roundtrip routes. To keep the number of variables as low as possible, direct flow variables are restricted to represent the arrows shown in Figure 4.2 only. Thus, e.g. no flow variables from a filling or a disposal location are made.

At each time period,  $t$ , for each pair of nodes, indexed  $i$  and  $j$ , variable  $f_{ijpt}$  decide the quantity (typically in tonnes) of a product,  $p$ , that is transported on the arc from  $i$  to  $j$ . As mentioned in Section 2.4, we assume that the common industry practice is to transport products from one location to another before returning the same vehicle empty back to the first location. The empty vehicle-kilometres resulting from this must be included in the transportation costs linked to  $f$ . Because all quantities considered (demands and surpluses) are much larger than the capacity of one lorry, it is further assumed that all vehicles are fully loaded for the first leg of the journey.



Thus, for each pair of nodes, indexed  $i, j$ , for which there will be transported an amount  $f_{ijpt}$  of product  $p$  in time period  $t$ , there will incur transportation costs and transportation emissions which include both driving with full capacity from  $i$  to  $j$ , and empty driving back from  $j$  to  $i$ . Therefore, both unit monetary costs,  $C_{ij}^T$ , and unit environmental impacts,  $E_{ij}^T$ , of transportation are modelled to represent both these costs or impacts, respectively, *per unit (tonnes) transported products from  $i$  to  $j$* . Thus,  $C_{ij}^T$  and  $E_{ij}^T$  must consider both the full 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:

$$C_{ij}^T = C^T \frac{W^{full}D_{ij} + W^{empty}D_{ji}}{W^{cargo}} \quad (5.1)$$

$$E_{ij}^T = \mathcal{E}^T \frac{W^{full}D_{ij} + W^{empty}D_{ji}}{W^{cargo}} \quad (5.2)$$

$C_{ij}^T$  represent the monetary costs for transporting one tonne of goods from node  $i$  to node  $j$ . Similarly,  $E_{ij}^T$  represent CO<sub>2</sub> emissions from transporting one tonne of goods from node  $i$  to node  $j$ . For both equations,  $D_{ij}$  is the driving distance from node  $i$  to node  $j$ ,  $W^{full}$  is the weight of a fully loaded vehicle (cargo plus vehicle weight),  $W^{empty}$  is the weight of an empty vehicle and  $W^{cargo}$  is the weight of the cargo when a vehicle is fully loaded. In Equation (5.1),  $C^T$  represents transportation costs per ton-kilometer, as  $\mathcal{E}^T$  represents environmental impacts per ton-kilometer in Equation (5.2). The two equations have been derived the following way, illustrated by Figure 5.1.

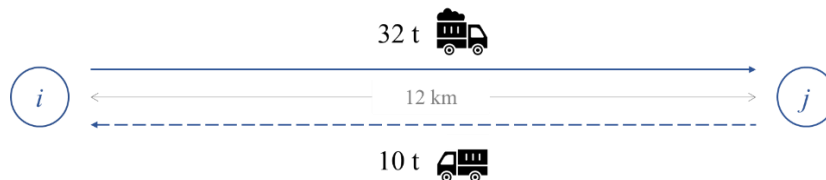


Figure 5.1: Weight of vehicles when transporting goods from node  $i$  to node  $j$

Let  $i$  and  $j$  be two different locations, where an amount of cargo,  $W^{cargo} = 22$  tons is being transported from  $i$  to  $j$  by a vehicle with capacity  $W^{cargo} = 22$  tons and a vehicle weight of  $W^{empty} = 10$  tons. When driving the cargo from  $i$  to  $j$ , total weight may be expressed as  $W^{full} = W^{empty} + W^{cargo} = 32$  tons. This weight is being transported a distance  $\mathcal{D}_{ij} = 12$  km. Returning empty, total weight is 10 tons, travelling the distance  $\mathcal{D}_{ji} = 12$  km. Thus, total ton-kilometers are

$$W^{full}\mathcal{D}_{ij} + W^{empty}\mathcal{D}_{ji} = 32 \text{ t} \cdot 12 \text{ km} + 10 \text{ t} \cdot 12 \text{ km} = 504 \text{ t}\cdot\text{km} \quad (5.3)$$

This represent the total ton-kilometres required for each  $W^{cargo}$  that is being transported with a vehicle driving the total distance  $\mathcal{D}_{ij} + \mathcal{D}_{ji}$ . Thus, dividing by the amount of cargo and total distance travelled, a more general, unitless *vehicle weight factor* is derived, representing the average weight of the vehicle throughout the full journey per unit transported cargo (tonnes):

$$\frac{W^{full}\mathcal{D}_{ij} + W^{empty}\mathcal{D}_{ji}}{(\mathcal{D}_{ij} + \mathcal{D}_{ji})W^{cargo}} = \frac{32 \text{ t} \cdot 12 \text{ km} + 10 \text{ t} \cdot 12 \text{ km}}{(12 \text{ km} + 12 \text{ km})22 \text{ t}} = 0,955 \quad (5.4)$$

The vehicle weight factor tells that for each ton-kilometre of products (cargo) *transported*, in average 0,955 ton-kilometers are *driven* (including cargo weight and vehicle weight). Hence, we can now use the parameters  $\mathcal{C}^T$  and  $\mathcal{E}^T$  in order to derive the expression for unit transportation costs per ton of transported cargo, including the return journey. Multiplying with cost per ton-kilometer,  $\mathcal{C}^T$  and the total distance travelled,  $\mathcal{D}_{ij} + \mathcal{D}_{ji}$ , we can express transportation costs per ton of cargo shipped from  $i$  to  $j$ ,  $\mathcal{C}_{ij}^T$ . The very same procedure applies for environmental costs per ton,  $\mathcal{E}_{ij}^T$ :

$$C_{ij}^T = (\mathcal{D}_{ij} + \mathcal{D}_{ji}) \mathcal{C}^T \frac{W^{full} \mathcal{D}_{ij} + W^{empty} \mathcal{D}_{ji}}{(\mathcal{D}_{ij} + \mathcal{D}_{ji}) W^{cargo}} \quad (5.5)$$

$$E_{ij}^T = (\mathcal{D}_{ij} + \mathcal{D}_{ji}) \mathcal{E}^T \frac{W^{full} \mathcal{D}_{ij} + W^{empty} \mathcal{D}_{ji}}{(\mathcal{D}_{ij} + \mathcal{D}_{ji}) W^{cargo}} \quad (5.6)$$

Note that both (5.5) and (5.6) may be simplified to expressions (5.1) and (5.2). Thus, in the example above using  $\mathcal{C}^T = 3,0$  NOK/t · km, costs per ton become

$$C_{ij}^T = 3,0 \text{ NOK/t} \cdot \text{km} \frac{32 \text{ t} \cdot 12 \text{ km} + 10 \text{ t} \cdot 12 \text{ km}}{22 \text{ t}} = 68,7 \text{ NOK/t} \quad (5.7)$$

If, e.g. the amount of crushed stone to be transported from location  $i$  to location  $j$  is  $f = 100\,000$  tons, transportation costs are calculated as

$$C_{ij}^T \cdot f = 68,7 \text{ NOK/t} \cdot 100\,000 \text{ t} = 687\,300 \text{ NOK} \quad (5.8)$$

### 5.1.3 Roundtrips

However, the model makes use of roundtrips in order to reduce the need of transportation. Roundtrips are modelled based on the work of Carlsson and Rönnqvist (2007). Consider two pairs of nodes, where one pair represents origin and destination of the flow of one product, while the other pair represents origin and destination of the flow of another product, both occurring at the same time period. The common practice is, particularly if these flows are connected to two different projects, to transport each product with different trucks, while returning both empty to their respective origins, as shown in Figure 5.2a. If, however, these two flows are cooperating, one truck may pick up the first product from its origin node, transport it to its destination node, drive empty to the origin node of the second product, transport it to the second destination node, before returning empty to the origin node of the first product, as shown

in Figure 5.3b. Among the set of roundtrip applicable products  $P^R$ , this kind of roundtrips are possible even though the two flows concern different product types. Products that are not possible to include in roundtrips, however, are e.g. asphalt and concrete which both have to be transported in specific vehicles.

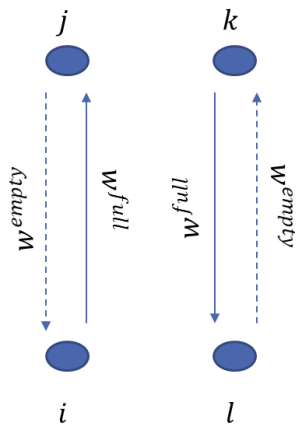


Figure 5.2a: Transportation between two pairs of nodes without roundtrips

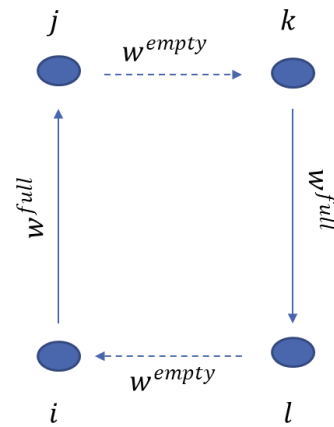


Figure 5.3b: Cooperative transportation between two pairs of nodes using roundtrips

If the distance driving the roundtrip as illustrated in Figure 5.3b, is smaller than the distance driving back and forth between each pair of nodes as illustrated in Figure 5.2a, there will be both monetary and environmental benefits of using the roundtrip. As there are some practical issues outside the scope of this model, e.g. to some degree easier planning without roundtrips, there is a buffer restricting how much a roundtrip has to reduce distance driven in order to be considered. Here, the buffer is set to at least 20 % reduction in distance. As becomes evident looking at Figures 5.2a and 5.3b, the reduction in distance is always empty driving – the products have to be transported between the two original nodes whether the flows are included in a roundtrip or not. Furthermore, in order to express roundtrip savings per unit of the roundtrip variable,  $g$  (tonnes), a roundtrip saving parameter is introduced for both monetary costs and environmental emissions,  $R^C$  and  $R^E$ , respectively, modelled as follows:

$$R_{ijkl}^C = C^T \frac{W^{empty} \Delta \mathcal{D}_{ijkl}^{empty}}{W^{cargo}} \quad (5.9)$$

$$R_{ijkl}^E = \mathcal{E}^T \frac{W^{empty} \Delta \mathcal{D}_{ijkl}^{empty}}{W^{cargo}} \quad (5.10)$$

$R_{ijkl}^C$  represent the monetary savings from using a roundtrip between nodes  $i$ ,  $j$ ,  $k$  and  $l$ , while  $R_{ijkl}^E$  represent the reduction in CO<sub>2</sub> emissions resulting from using the roundtrip. Both savings are relative to the case where nodes  $i$  and  $j$  are operated completely independent of nodes  $k$  and  $l$ .  $\Delta \mathcal{D}_{ijkl}^{empty}$  represent the reduced empty driving when using the roundtrip from  $i$  to  $j$  to  $k$  to  $l$ , and may be expressed as

$$\Delta \mathcal{D}_{ijkl}^{empty} = (\mathcal{D}_{ji} + \mathcal{D}_{lk}) - (\mathcal{D}_{jk} + \mathcal{D}_{li}) \quad (5.11)$$

Equation (5.11) becomes evident when looking at an extension of the last example, as shown in Figures 5.4 and 5.5.

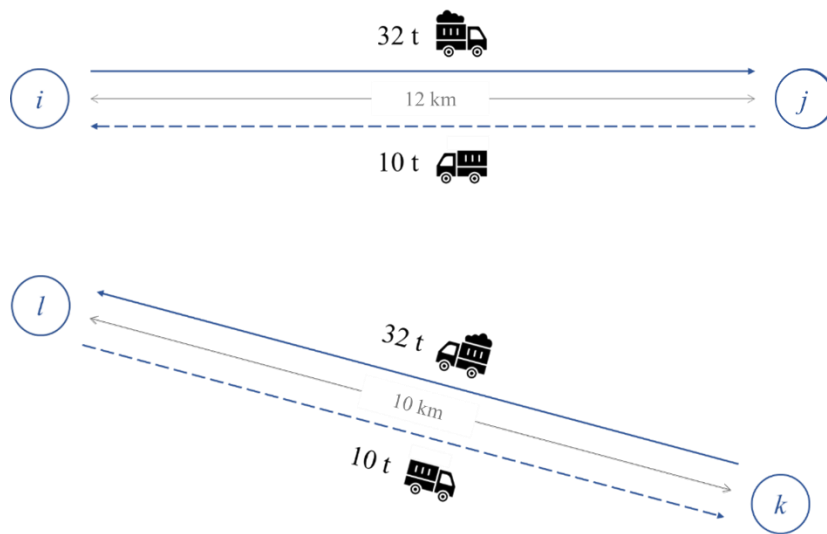


Figure 5.4: Weight of vehicles when operating two pairs of nodes independent from each other

Let  $i, j, k$  and  $l$  be two sets of nodes, where some products must be transported from  $i$  to  $j$ , while some other products must be transported from  $k$  to  $l$ . As mentioned, the base case is driving vehicles full from  $i$  to  $j$  and from  $k$  to  $l$ , and empty back from  $j$  to  $i$  and from  $l$  to  $k$ . The costs of doing this are included in the transportation costs,  $C_{ij}^T$  and  $C_{kl}^T$ , described in Section 5.1.2. Total ton-kilometres for both trips are calculated as

$$\begin{aligned} W^{full}\mathcal{D}_{ij} + W^{empty}\mathcal{D}_{ji} + W^{full}\mathcal{D}_{kl} + W^{empty}\mathcal{D}_{lk} = \\ 32 \text{ t} \cdot 12 \text{ km} + 10 \text{ t} \cdot 12 \text{ km} + 32 \text{ t} \cdot 10 \text{ km} + 10 \text{ t} \cdot 10 \text{ km} = 924 \text{ t}\cdot\text{km} \end{aligned} \quad (5.12)$$

Each vehicle transports the amount  $W^{cargo}$  on each of these trips. Thus, total tonne-kilometres driven per tonne-kilometre of transported products are found dividing by cargo weight and total kilometres as

$$\frac{W^{full}\mathcal{D}_{ij} + W^{empty}\mathcal{D}_{ji} + W^{full}\mathcal{D}_{kl} + W^{empty}\mathcal{D}_{lk}}{W^{cargo}(\mathcal{D}_{ij} + \mathcal{D}_{ji} + \mathcal{D}_{kl} + \mathcal{D}_{lk})} \quad (5.13)$$

Expressed in numbers from the example gives the unitless vehicle weight factor

$$\frac{32 \text{ t} \cdot 12 \text{ km} + 10 \text{ t} \cdot 12 \text{ km} + 32 \text{ t} \cdot 10 \text{ km} + 10 \text{ t} \cdot 10 \text{ km}}{22 \text{ t} (12 \text{ km} + 12 \text{ km} + 10 \text{ km} + 10 \text{ km})} = 0,955 \quad (5.14)$$

However, including these flows in a roundtrip reduces empty driving as shown in Figure 5.5.

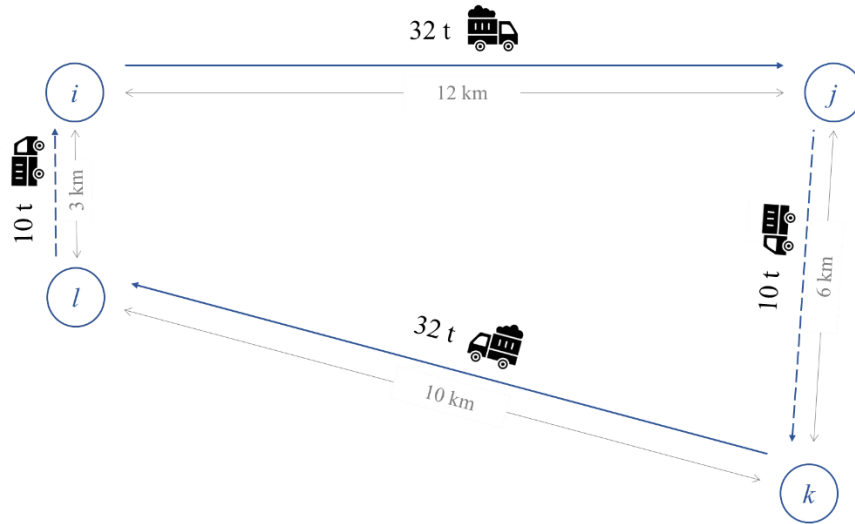


Figure 5.5: Weight of vehicles when including two pairs of nodes in a roundtrip

Total tonne-kilometres for the roundtrip are now calculated as

$$\begin{aligned}
 W^{full}D_{ij} + W^{empty}D_{jk} + W^{full}D_{kl} + W^{empty}D_{li} = \\
 32 \text{ t} \cdot 12 \text{ km} + 10 \text{ t} \cdot 6 \text{ km} + 32 \text{ t} \cdot 10 \text{ km} + 10 \text{ t} \cdot 3 \text{ km} = 794 \text{ t}\cdot\text{km}
 \end{aligned}
 \tag{5.15}$$

Compared to the case shown in Figure 5.4 and according to Equation (5.11), total reduced tonne-kilometres are expressed as

$$\begin{aligned}
 (W^{empty}D_{ji} + W^{empty}D_{lk}) - (W^{empty}D_{jk} + W^{empty}D_{li}) \\
 = W^{empty}\Delta D_{ijkl}^{empty}
 \end{aligned}
 \tag{5.16}$$

Implementing numbers from the example gives the reduction in tonne-kilometres:

$$10 \text{ t} \left( (12 \text{ km} + 10 \text{ km}) - (6 \text{ km} + 3 \text{ km}) \right) = 130 \text{ t}\cdot\text{km} \quad (5.17)$$

This is equal to the difference of total tonne-kilometres calculated in Equations (5.12) and (5.15):

$$924 \text{ t}\cdot\text{km} - 794 \text{ t}\cdot\text{km} = 130 \text{ t}\cdot\text{km} \quad (5.18)$$

The backhaul variable  $g$  decides the amount of products (in tonnes) included in a roundtrip. Therefore, it is desired to express Equation (5.16) per tonne-kilometre of cargo included in the roundtrip:

$$\frac{W^{empty} \Delta \mathcal{D}_{ijkl}^{empty}}{W^{cargo} (\mathcal{D}_{ij} + \mathcal{D}_{jk} + \mathcal{D}_{kl} + \mathcal{D}_{li})} \quad (5.19)$$

Multiplying Equation (5.19) with cost per tonne-kilometre,  $\mathcal{C}^T$  and the total distance of the roundtrip, one derive the general expression for roundtrip savings per ton of cargo included in the roundtrip:

$$\begin{aligned} R_{ijkl}^c &= \mathcal{C}^T (\mathcal{D}_{ij} + \mathcal{D}_{jk} + \mathcal{D}_{kl} + \mathcal{D}_{li}) \frac{W^{empty} \Delta \mathcal{D}_{ijkl}^{empty}}{W^{cargo} (\mathcal{D}_{ij} + \mathcal{D}_{jk} + \mathcal{D}_{kl} + \mathcal{D}_{li})} \\ &= \mathcal{C}^T \frac{W^{empty} \Delta \mathcal{D}_{ijkl}^{empty}}{W^{cargo}} \end{aligned} \quad (5.20)$$

Applying numbers from the example gives roundtrip savings per tonne of products included in the roundtrip of



$$\begin{aligned}
R_{ijkl}^C &= 3,0 \text{ NOK/t}\cdot\text{km} \frac{10 \text{ t} ((12 \text{ km} + 10 \text{ km}) - (6 \text{ km} + 3 \text{ km}))}{22 \text{ t}} \\
&= 17,7 \text{ NOK/t}
\end{aligned} \tag{5.21}$$

The original costs of the two trips done without roundtrips are

$$\begin{aligned}
C_{ij}^C + C_{kl}^C &= 3,0 \text{ NOK/t}\cdot\text{km} \frac{32 \text{ t} \cdot 12 \text{ km} + 10 \text{ t} \cdot 12 \text{ km}}{22 \text{ t}} \\
&\quad + 3,0 \text{ NOK/t}\cdot\text{km} \frac{32 \text{ t} \cdot 10 \text{ km} + 10 \text{ t} \cdot 10 \text{ km}}{22 \text{ t}} \\
&= 68,7 \text{ NOK/t} + 57,3 \text{ NOK/t} \\
&= 126,0 \text{ NOK/t}
\end{aligned} \tag{5.22}$$

Thus, relative savings are about 14 %, resulting in an actual cost per tonne transported goods of  $126,0 \text{ NOK/t} - 17,7 \text{ NOK/t} = 108,3 \text{ NOK/t}$ .

The very same procedure applies for environmental savings per ton of products included in a roundtrip, resulting in the following general expression:

$$R_{ijkl}^E = \varepsilon^T \frac{W^{empty} \Delta D_{ijkl}^{empty}}{W^{cargo}} \tag{5.23}$$

As a final notice, the monetary (and similarly environmental) benefits of using the roundtrip from our example might be considered relatively small. This is because the fact that empty driving consumes less fuel than full driving. Nevertheless, one could argue that the reduced vehicle-kilometres needed give a much bigger social impact for the local community, not reflected by fuel consumption.

### 5.1.4 Relationship between product flow and roundtrip flow

For each set of nodes  $i, j, k$  and  $l$  included in a roundtrip, product flows are present from  $i$  to  $j$  and from  $k$  to  $l$ . These product flows are, as mentioned in Section 5.1.2, represented by the product flow variable  $f$ . Looking back at the example in Figures 5.4 and 5.5, possible flows could be e.g.  $f_{ij} = 100\,000$  t and  $f_{kl} = 60\,000$  t. Obviously, a roundtrip from  $i$  to  $j$  to  $k$  to  $l$  will only be beneficial to use for the minimum of these two product flows. E.g. transporting all of the  $f_{kl} = 60\,000$  t, it is unnecessary to drive the whole loop transporting the last  $f_{ij} = 100\,000$  t –  $60\,000$  t =  $40\,000$  t. Thus, the roundtrip variable,  $g$ , must be restricted to the minimum of the product flows included in the roundtrip, in this case  $g_{ijkl} \leq 60\,000$  t. The remaining  $40\,000$  t that has to be transported from  $i$  to  $j$  could potentially be included in another roundtrip, say from  $i$  to  $j$  to  $m$  to  $n$ . The relationship between variables  $f$  and  $g$  are illustrated with Figure 5.6.

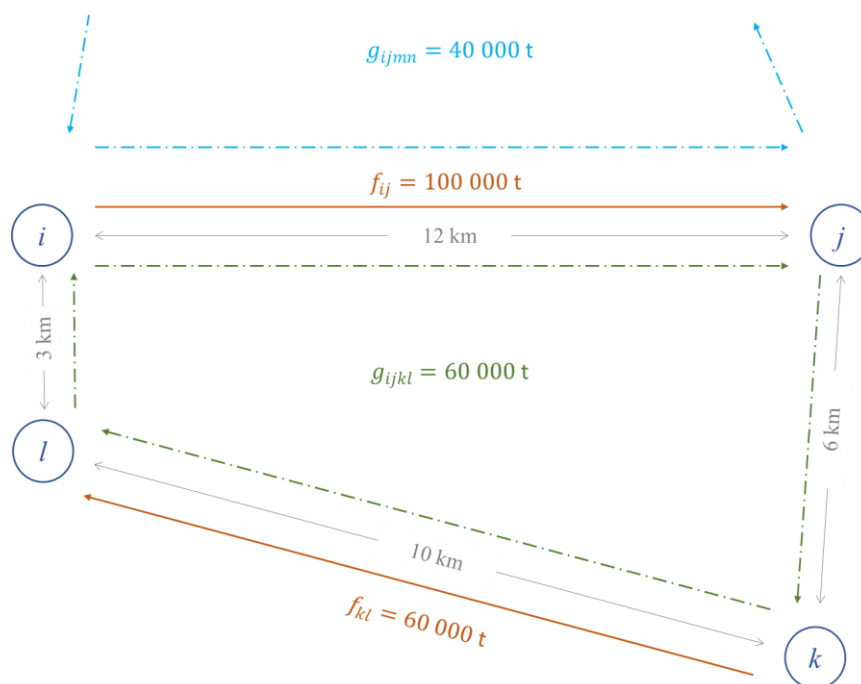


Figure 5.6: Relationship between flow variable  $f$  and roundtrip variable  $g$

In order to show the practical implementations, flow transportation costs for each of the two product flows, total transportation costs for the two flows and total roundtrip savings,

respectively, are calculated for the specific case shown in Figure 5.6 (excluding the theoretical roundtrip from  $i$  to  $j$  to  $m$  to  $n$ ):

$$C_{ij}^T f_{ij} = 68,73 \text{ NOK/t} \cdot 100\,000 \text{ t} = 6\,873\,000 \text{ NOK} \quad (5.24)$$

$$C_{kl}^T f_{kl} = 57,27 \text{ NOK/t} \cdot 60\,000 \text{ t} = 3\,436\,367 \text{ NOK} \quad (5.25)$$

$$C_{ij}^T f_{ij} + C_{kl}^T f_{kl} = 10\,309\,367 \text{ NOK} \quad (5.26)$$

$$R_{ijkl}^C g_{ijkl} = 17,73 \text{ NOK/t} \cdot 60\,000 \text{ t} = 1\,063\,364 \text{ NOK} \quad (5.27)$$

Here, we have used the earlier calculations of  $C_{ij}^T$ ,  $C_{ij}^T$  and  $R_{ijkl}^C$  from Equations (5.22) and (5.21), respectively. Thus, transportation costs without roundtrips are 10,31 million NOK. If 60 000 t are driven in the roundtrip, 1,06 million NOK are saved, resulting in actual transportation costs of 9,25 million NOK.

### 5.1.5 External shipments

The problem investigated is bounded to a geographically specified region. However, the amount of demanded products very seldom correspond perfectly with the amount of supply within the region. Therefore, to cope with mass balance, two external flow variables are defined,  $\varphi^{out}$  and  $\varphi^{in}$ , representing flow of products out from and into the specified region, respectively. All such flows are either out of a project site node, out of a recycling facility node or into a project site node. External transportation costs and emissions are linked to these two external flow variables, but as mentioned in Section 5.1.1, the external locations are not modelled as nodes. Instead, only one geographical location is used as an external disposal location (or sales location, see Section 5.1.6) to where products can be delivered and one geographical location is used as an external quarry from where products can be picked up. These distances are used to find two different external transportation costs for each node  $i$ , namely  $C_{i,ext}^T$  and  $C_{ext,i}^T$ .  $C_{i,ext}^T$  is the per tonne transportation cost for sending goods from project site or recycling facility  $i$  to an external disposal site, while  $C_{ext,i}^T$  is the corresponding cost associated with transport from an external quarry to project site  $i$ . The very same apply external emissions,  $E_{ext,i}^T$  and  $E_{i,ext}^T$ .

### 5.1.6 Economics between different nodes

As mentioned in Chapter 4 products are transported between different node types in several ways. Costs and incomes are assigned to each node when a product is transported either to or from the node, depending on which node type sends and which node type receives the products. As described in section 5.1.2, costs are linked to the flow variable,  $f_{ijpt}$ . All combinations and the way costs and incomes are imposed on each node are presented in Table 5.1, where the first column represent index  $i$  and the second column represent index  $j$ .

Table 5.1: Cost and income structure for each combination of product transaction between two nodes.

From node ( $i$ )		To node ( $j$ )		Cost type
Project site	Cost	Recycling facility	Income	Disposal cost
Project site	Cost	Disposal location	Income	Disposal cost
Project site	Cost	Filling location	Income	Disposal cost
Project site	Income	Project site	Cost	Purchase cost
Project site	Cost/Income*	External location	N/A**	Disposal cost/ purchase cost
External location	N/A**	Project site	Cost	Purchase cost
Recycling facility	Income	Project site	Cost	Purchase cost
Recycling facility	Cost	Disposal location	Income	Disposal cost
Recycling facility	Cost	Filling location	Income	Disposal cost
Recycling facility	Cost/Income*	External location	N/A**	Disposal cost/ purchase cost

\*) Depending on product, see Section 5.1.6 for details

\*\*\*) Economics of external locations not relevant within the scope of this thesis

Environmentally, it should generally be favourable to reuse products within the system before transporting them externally, because long travel distances result in high CO<sub>2</sub> emissions. A set of quality products,  $P^Q$ , however, are from a societal perspective better to sell outside the system boundaries than dispose inside the system. This is because e.g. disposing them would result in excavation of virgin materials in other demanding locations, which might well be geographically situated right outside the system. Since demands from sites outside the system

is unknown, we assume that only a fraction,  $1 - \gamma$ , of the quality products may be sold to the outside market, e.g. 50 %. The remaining quantities of quality products are, together with non-quality products, assumed disposed if transported to external locations. Thus, parameter  $\gamma$  decide the fraction of quality products disposed when shipped to external locations. Accordingly, cost/income for sites or facilities sending material externally depends on product type. It is the external transportation variables  $\varphi^{out}$  and  $\varphi^{in}$  that are linked to these product costs traded across the system boundaries. Even though there is a potential reward in selling products to external markets, the price structure makes internal trading favourable over external trade. This is because the purchase price inside system boundaries are lower than in the external market (e.g. as a result of price bargaining), and transportation costs are higher for external shipments because of longer travel distance. Regarding emissions, products brought from external quarries are assumed to have the climate footprint of virgin materials, thus higher than recycled materials from a recycling facility inside the system.

### 5.1.7 Storage

The amount of products stored at each node is represented with a variable for storage level at the beginning of each time period. The storage level should never exceed the maximum capacity at the respective node. Facility nodes are assigned with a maximum *temporary* storage capacity, given the fact that products stored at these locations either are to be processed or transported away from the facility node at a later time period. Filling and disposal locations are assigned with a maximum *permanent* storage capacity. Products shipped to one of these locations are to be stored until the end of the planning period. Project sites are assumed not to have any storage capacity. Thus, all supply must be transported away from the project sites at the respective time periods, as all demand must be met at the respective time periods. Products that are extracted from a project site and stored locally for the purpose of being reused at the same site are not included in the model, as these quantities are excluded from both supply and demand data.

### 5.1.8 Processes

The processes at facilities are modelled the following way: a specific amount of one or several products are sent as input through a process,  $r$ . The output of process  $r$  is then a specific amount

of one or several new products. An example is the process of crushing rock into crushed stone: e.g. 2000 tons of good quality rock extracted from a project site is sent through a stone crushing machine, producing 1900 tons of good quality crushed stone and 100 tons of small fraction waste stone, as shown in Figure 5.7.

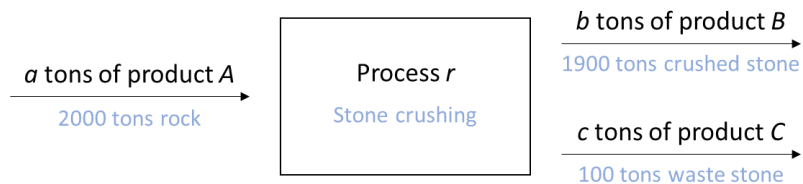


Figure 5.7: Process mass balance for crushing rock into crushed stone

This way of modelling the processes links what is transported to a facility and what is possible to transport away from the facility, described by the matrix  $B$ . Mass balance is not strictly required through a process, because some processes make use of mass types not included in the problem. This is the case for e.g. asphalt production, which require an amount of bitumen (typically 5 %) in addition to stone and asphalt granulate, see Figure 5.8.

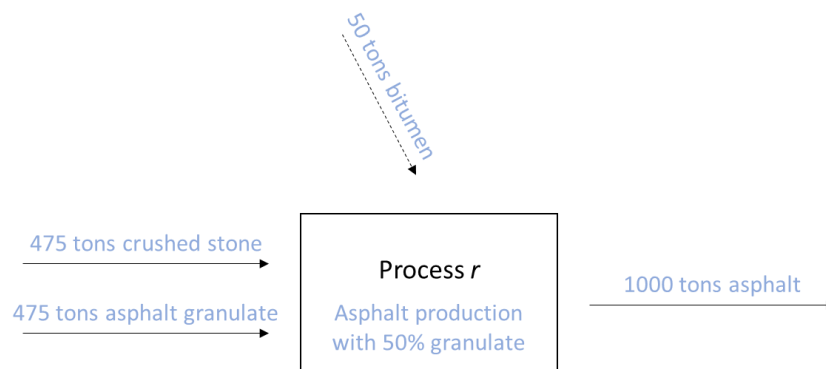


Figure 5.8: Process mass balance for asphalt production

As these processes occur at different facilities, we get the network shown in Figure 5.9. This is a case of the *pooling problem*, described by Haverly (1978) and Alfaki (2012). Streams of different product types enter the transportation network from the supplying project sites. Flow from these sources are fed into the recycling facility nodes, where the streams are mixed in the

processes, acting as pools. Processes form the final product mixes, which are sent to a terminal, represented by either a demanding project site node, a disposal node or a filling node.

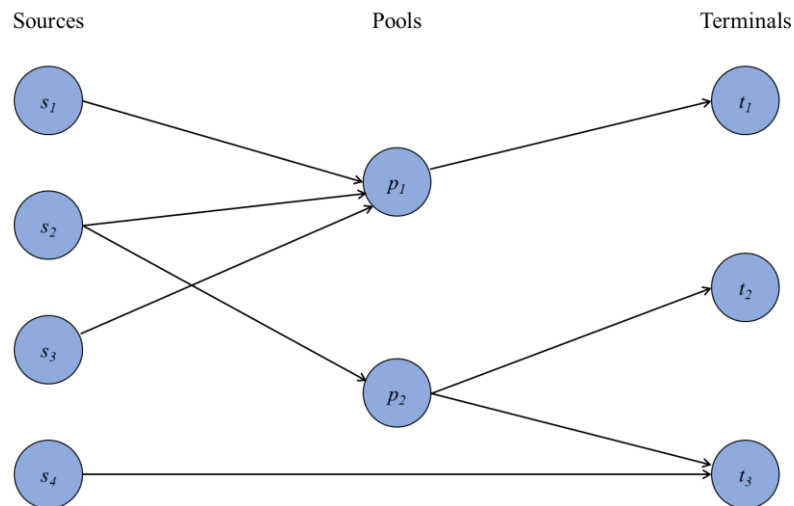


Figure 5.9: Network of the pooling problem. In our problem, sources represent supplying project sites, pools represent processes at recycling facilities and terminals represent demanding project sites, disposal sites or filling locations

The pooling characteristics of the problem make assigning process emissions to each individual product flow hard. This is discussed further in Sections 5.1.10 and 5.3.3.

### 5.1.9 Process costs

At a facility  $i$ , for each time period  $t$ , the process variable  $h_{imrt}$  represent the number of times process  $r$  is run with process machine  $m$ . This induces a variable processing cost, depending on the unit process cost,  $C_r^R$  for each process. This cost represents rental costs for mobile machines (e.g. stone crushers), and operational costs for machines which are invested on a long-term basis (e.g. asphalt or concrete plants). The binary variables  $y_{imt}$  and  $y_{imt}^{start}$  tells whether a machine  $m$  is used at facility  $i$  at time period  $t$  or not, and whether machine  $m$  is being set up at facility  $i$  at time period  $t$  or not, respectively. When  $y_{imt}^{start} = 1$ , an investment cost,  $C_m^M$  occurs, either representing the actual investment if it is a permanent machine or a start-up cost if it is a leased machine. For a machine that is leased, process costs are generally higher than for a machine that is financed through a big investment.

### 5.1.10 Allocation of process emissions

Recycling processes are driven by the demand of products. E.g. a process is run depending on the demand of the *output* product. Thus, it is relevant to be able to analyse the amount of process emissions required to produce a given product. The method of allocating process emissions at facilities to the products transported to project sites is not straightforward. Since one type of demanded product may be produced in several different ways, following different processing paths, it is not possible to operate with general product specific emissions. Say, e.g. that a project site demands 1000 tonnes of crushed stone in the fraction 8/16, it may be produced either from excavated rock through 2 crushing steps, or from crushed stone in the fraction 22/120 through 1 crushing step. As the first option emits more than the latter, emissions assigned to products must consider the amount of processing required for each specific case. Furthermore, coproduction occurs in many processes, meaning that a process run to produce a primary product also produces one or several secondary co-products. In the literature of Life Cycle Analysis (LCA) many different allocation methods are used (Majeau-Bettez, et al., 2017). In this thesis, however, we want to allocate all emissions from a process to the primary, demanded output product. This is done the following way. We assume that the relationship between the flow of a product,  $p$  from a facility  $i$  to a site  $j$  and the total flows of product  $p$  out from facility  $i$  equals the relationship between the emissions assigned to product  $p$  delivered to site  $j$  from facility  $i$  and the total emissions at facility  $i$  from production of product  $p$ , as shown in equation (5.28) and constraint (5.40). See Figure 5.10 for details.

$$\begin{aligned} & \frac{\text{flow of } p \text{ from } i \text{ to } j}{\text{total flow of } p \text{ out from } i} \\ & = \frac{\text{process emissions of } p \text{ delivered to } j \text{ from } i}{\text{total emissions from producing } p \text{ at } i} \end{aligned} \quad (5.28)$$

Process emissions of a product  $p$  delivered to project site  $j$  from recycling facility  $j$  are denoted  $e_{ijp}$ . As this method assigns process emissions to the *demanded* product, a slight modification to matrix  $B$ , described in Section 5.1.8, is required. In a case where a process produces an amount of a demanded output product and an amount of another waste product, all emissions



from this process should be distributed on the demanded product. Thus, the matrix  $B^D$ , describing the relative amount of demanded output product from a process is constructed according to Equation (5.29).

$$B_{pmr}^D = \frac{B_{pmr}}{\sum_{\rho \in P^D} B_{\rho mr}} \quad (5.29)$$

We illustrate this with an example. Say, e.g., that one specific process consumes 1 tonne of an input product, producing 0,5 tonnes of the demanded product X, 0,25 tonnes of the demanded product Y and 0,25 tonnes of waste product Z. Since process emissions should be distributed only on the demanded products, X and Y,  $\frac{0,5}{0,5+0,25} = \frac{2}{3}$  of total emissions distributes to product X, and  $\frac{0,25}{0,5+0,25} = \frac{1}{3}$  distributes to product Y.

## 5.2 Notation

The following notations are applied for sets, indices, variables and parameters in the mathematical model.

### 5.2.1 Sets

$N$	Nodes
$N^S$	Project sites, $N^S \subset N$
$N^F$	Recycling facilities, $N^F \subset N$
$N^D$	Disposal locations, $N^D \subset N$
$N^U$	Filling locations, $N^U \subset N$
$P$	Products
$P^D$	Products which are demanded at project sites, $P^D \subset P$
$P^R$	Products possible to include in roundtrips, $P^R \subset P$
$P^Q$	Quality products with an external demanding market, $P^Q \subset P$

$M$	Machines
$R$	Processes
$R_m$	Processes possible with machine $m$ , $R_m \subset R$
$S$	Projects
$N_s^S$	Project sites included in project $s$ , $N_s^S \subset N^S$
$T$	Time periods
$L$	Overestimations of the relationship between single flows and total flows

### 5.2.2 Indices

$i, j, k, l$	Node
$p$	Product
$m$	Machine
$r$	Process
$t$	Time period
$s$	Project
$q$	Overestimation

### 5.2.3 Variables

$s_{ipt}$	Storage level of product $p$ at node $i$ in the beginning of time period $t$
$f_{ijpt}$	Amount of product $p$ transported from node $i$ to node $j$ at time period $t$
$g_{ijklt}$	Artificial flow on roundtrip route between nodes $i, j, k$ and $l$ at time period $t$
$h_{imrt}$	Number of times process $r$ is run with machine $m$ at node $i$ at time period $t$
$y_{imt}$	$\begin{cases} 1, & \text{if machine } m \text{ is leased at node } i \text{ at time period } t \\ 0, & \text{otherwise} \end{cases}$
$y_{imt}^{start}$	$\begin{cases} 1, & \text{if machine } m \text{ is started leased at node } i \text{ at time period } t \\ 0, & \text{otherwise} \end{cases}$
$\varphi_{ipt}^{out}$	Amount of product $p$ out from node $i$ to external locations at time period $t$
$\varphi_{ipt}^{in}$	Amount of product $p$ into node $i$ from external locations at time period $t$
$e_{ijp}$	Process emissions distributed on the flow from $i$ to $j$ from producing product $p$
$l_{qijp}$	$\begin{cases} 1, & \text{if overestimation } q \text{ is applied to the flow of product } p \text{ from } i \text{ to } j \\ 0, & \text{otherwise} \end{cases}$

### 5.2.4 Parameters

$S_{ipt}$	Supply of product $p$ from site $i$ at time $t$
$D_{ipt}$	Demand of product $p$ to site $i$ at time $t$
$B_{pmr}$	Amount of product $p$ produced/consumed if process $r$ is run by machine $m$ one time.
$B_{pmr}^D$	Fraction of demanded product $p$ that is assigned emissions from running process $r$ by machine $m$ one time
$C_{ij}^T$	Transportation cost per ton from node $i$ to node $j$
$C_{i,ext}^T$	Transportation cost per ton between node $i$ and an external disposal site
$C_{ext,i}^T$	Transportation cost per ton between node $i$ and an external quarry
$C_p^D$	Cost of disposing one ton of product $p$ at a disposal location
$C_p^{FD}$	Cost of disposing one ton of product $p$ at a recycling facility
$C_p^U$	Cost of disposing one ton of product $p$ at a filling location
$C_p^P$	Purchase price for one ton of product $p$
$C_p^V$	Price for virgin products
$R_{ijkl}^C$	Monetary roundtrip saving for using roundtrip route between nodes $i, j, k$ and $l$
$R_{ijkl}^E$	Environmental roundtrip saving for using roundtrip between $i, j, k$ and $l$
$T_{mr}^R$	Process duration for one run of process $r$ with machine $m$ [hours]
$T^P$	Number of available hours in one time period
$C_r^R$	Process cost per ton processed products
$C_m^M$	Investment cost of machine $m$
$Q_i^D$	Disposal or filling capacity at node $i$
$Q_i^S$	Storage capacity (temporary) at node $i$
$E_{ij}^T$	CO <sub>2</sub> -emissions from transportation per ton transported from node $i$ to node $j$
$E_{i,ext}^T$	CO <sub>2</sub> -emissions from transportation per ton out from or into the system
$E_r^R$	CO <sub>2</sub> -emissions from one run of process $r$
$E_p^V$	CO <sub>2</sub> -emissions from producing product $p$ from virgin materials
$W_q$	Weight of overestimation $q$
$\gamma$	Fraction of quality products disposed if sent external

## 5.3 Constraints

The model constraints are presented in the following sections, categorized based on the structure of the problem. First, constraints related to transportation are described, including roundtrips. Secondly, constraints dealing with recycling processes are shown. Finally, the constraints needed to assign process emissions to projects are described.

### 5.3.1 Transportation and roundtrip constraints

The constraints describing transportation flows and the modelling of roundtrips are presented as following.

$$\sum_{j \in N} f_{ijpt} + \varphi_{ipt}^{out} = S_{ipt} \quad i \in N^S, p \in P, t \in T \quad (5.30)$$

$$\sum_{j \in N} f_{jipt} + \varphi_{ipt}^{in} = D_{ipt} \quad i \in N^S, p \in P, t \in T \quad (5.31)$$

$$\sum_{k \in N} \sum_{l \in N} g_{ijklt} \leq \sum_{p \in P^R} f_{ijpt} \quad i \in N, j \in N, t \in T \quad (5.32)$$

$$\sum_{i \in N} \sum_{j \in N} g_{ijklt} \leq \sum_{p \in P^R} f_{klpt} \quad k \in N, l \in N, t \in T \quad (5.33)$$

$$S_{ipt} + \sum_{j \in N} f_{jipt} + \sum_{m \in E} \sum_{r \in R} B_{pmr} h_{imrt} - \sum_{j \in N} f_{ijpt} - \varphi_{ipt}^{out} = S_{ip,t+1} \quad i \in N^F, p \in P, t \in T \quad (5.34)$$

$$S_{ipt} + \sum_{j \in N} f_{jipt} = S_{ip,t+1} \quad i \in N^U \cup N^D, p \in P, t \in T \quad (5.35)$$

$$\sum_{p \in P} S_{ipt} \leq Q_i^D \quad i \in N^U \cup N^D, t \in T \quad (5.36)$$

$$\sum_{p \in P} S_{ipt} \leq Q_i^S \quad i \in N^F, t \in T \quad (5.37)$$

Constraints (5.30) and (5.31) balance flows out from and in to project sites, respectively. Constraints (5.30) make sure all supply is transported out from a node at the same time period that the supply product is generated, while constraints (5.31) ensure that demands are being met. Constraints (5.32) and (5.33) restrict the amount transported in a roundtrip, as this cannot exceed the least of the amounts transported on each of the two node pairs in the roundtrip. Constraints (5.34) are balancing constraints for recycling facilities, while constraints (5.35) balance flows into filling and disposal locations deciding storage level for each time period. Finally, constraints (5.36) and (5.37) make sure that disposal capacities are not exceeded at filling and disposal locations and that temporary storage capacities are not exceeded at recycling facilities.

### 5.3.2 Process constraints

Furthermore, a couple of constraints are required to model the recycling processes. These are presented next.

$$\sum_{r \in R_m} T_{mr}^R h_{imrt} \leq T^P y_{imt} \quad i \in N^F, m \in M, t \in T \quad (5.38)$$

$$y_{im,t+1} \leq y_{imt} + y_{im,t+1}^{start} \quad i \in N^F, m \in M, t \in T \quad (5.39)$$

Constraints (5.38) make sure that process machines are not run more than the machine's capacity each time period, while also ensuring that only machines that are in use can be run. Constraints (5.39) say that a machine can only be used in a time period if it either was used the preceding time period or if it is acquired the same time period.

### 5.3.3 Constraints for distribution of process emissions

Following the assumptions presented in section 5.1.10, the distribution of process emissions to product flows may be expressed by the non-linear constraint (5.40) which, to clarify, is not included in the model.

$$\frac{\sum_{t \in T} f_{ijpt}}{\sum_{k \in N} \sum_{t \in T} f_{ikpt}} = \frac{e_{ijp}}{\sum_{k \in N} e_{ikp}} \quad i \in N^F, j \in N, p \in P \quad (5.40)$$

Constraint (5.40) is a result from the pooling problem characteristics discussed in Section 5.1.8. Linearizing it is hard, thus there has been developed several different formulations and solving methods for the pooling problem (Alfaki, 2012). For this thesis, a simplified approximation is applied. First, a number of overestimation weights,  $W_q \in [0,1]$  are created. From these, one weight is chosen for each flow,  $\sum_{t \in T} f_{ijpt}$  of product  $p$  from facility  $i$  to project site  $j$ , that is larger than the real fraction of  $\frac{\sum_{t \in T} f_{ijpt}}{\sum_{k \in N} \sum_{t \in T} f_{ikpt}}$ . Secondly, we distribute emissions to each flow,  $e_{ijp}$  such that the weight below the chosen one is a lower bound on the fraction of emissions assigned to the flow. Thus, the number of overestimation weights created influences the accuracy of the distribution, e.g. creating many possible weights increases accuracy, while also increasing computational complexity and duration. The modelling of this distribution is showed in Figure 5.10.

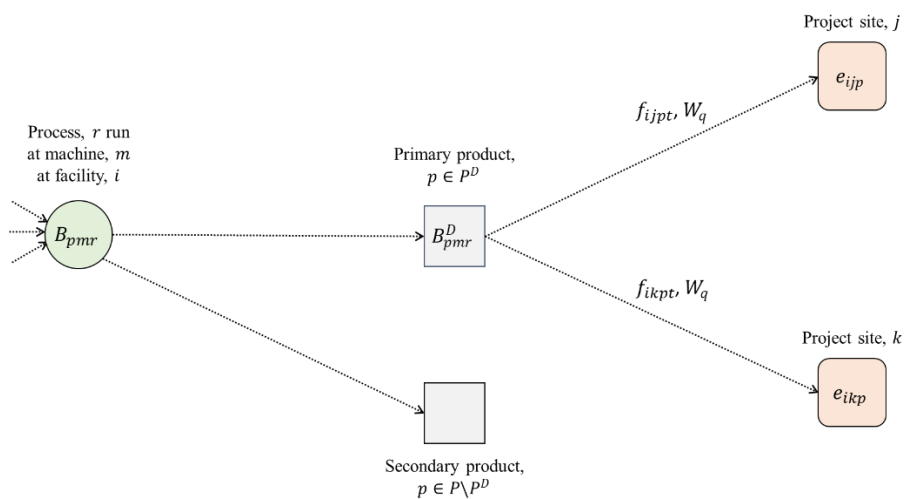


Figure 5.10: Distribution of process emissions to project sites

$$\sum_{j \in N^S} e_{ijp} = \sum_{m \in M} \sum_{r \in R} \sum_{t \in T} B_{pmr}^D E_r^R h_{imrt} \quad i \in N^F, p \in P^D \quad (5.41)$$

$$\sum_{k \in N^S} \sum_{t \in T} W_q f_{ikpt} - \sum_{t \in T} f_{ijpt} \geq -M_{qijp} (1 - l_{qijp}) \quad q \in L, i \in N^F, j \in N^S, p \in P^D \quad (5.42)$$

$$\sum_q l_{qijp} = 1 \quad i \in N^F, j \in N^S, p \in P^D \quad (5.43)$$

$$e_{ijp} \geq \sum_{k \in N^S} W_{q-1} e_{ikp} - M_{qijp} (1 - l_{qijp}) \quad q \in L, i \in N^F, j \in N^S, p \in P^D \quad (5.44)$$

$$e_{ijp} \leq M_{ijp} \sum_{t \in T} f_{ijpt} \quad i \in N^F, j \in N^S, p \in P^D \quad (5.45)$$

Constraints (5.41) says that for each facility, total emissions assigned to project sites equals total process emissions from that facility. Constraints (5.42) choose weights,  $W_q$  that are applied to product flows of  $p$  transported from  $i$  to  $j$ , overestimating the relative quantity of these flows as described above. Here,  $M_{qijp} = \sum_{t \in T} D_{jpt}$ , sum of demands of product  $p$  to site  $j$ , tightens the constraints. Since the emissions are minimized, the lowest overestimation weight will always be chosen. Constraints (5.43) make sure exactly one overestimation weight is chosen for each combination of facility, site and product. Constraints (5.44) say that the relative amount of emissions to site  $j$  resulting in processing product  $p$  at facility  $i$  must be at least the weight *under* the chosen weight from constraints (5.42). In Constraints (5.44),  $M_{qijp} = \sum_{k \in N^S} \sum_{t \in T} D_{kpt} \cdot \max_{m \in M, r \in R} (B_{pmr} E_r^R) \cdot W_{q-1}$ , the maximum process emissions linked to product  $p$  times the weight under  $q$  tightens the constraints. Constraints (5.45) set upper limits for the emissions distributed to a flow and make sure that no emissions are distributed unless there is a flow. Here,  $M_{ijp} = E_p^V$  give a tight formulation, assuming that no internal processes needed to make product  $p$  emit more than the emissions linked to making the product from virgin materials,  $E_p^V$ .

### 5.3.4 Variable declaration

Finally, variable declaration constraints are included.

$$s_{ipt} \geq 0 \quad i \in N^F \cup N^U \cup N^D, p \in P, t \in T \quad (5.46)$$

$$f_{ijpt} \geq 0 \quad i, j \in N, p \in P, t \in T \quad (5.47)$$

$$g_{ijklt} \geq 0 \quad i, j, k, l \in N, t \in T \quad (5.48)$$

$$h_{imrt} \geq 0 \quad i \in N^F, m \in M, r \in R, t \in T \quad (5.49)$$

$$y_{imt} \in \{0, 1\} \quad i \in N^F, m \in M, t \in T \quad (5.50)$$

$$y_{imt}^{start} \in \{0, 1\} \quad i \in N^F, m \in M, t \in T \quad (5.51)$$

$$\varphi_{ipt}^{out} \geq 0 \quad i \in N^S \cup N^F, p \in P, t \in T \quad (5.52)$$

$$\varphi_{ipt}^{in} \geq 0 \quad i \in N^S, p \in P, t \in T \quad (5.53)$$

$$e_{ijp} \geq 0 \quad i \in N^F, j \in N^S, p \in P \quad (5.54)$$

$$l_{qijp} \in \{0, 1\} \quad q \in L, i \in N^F, j \in N^S, p \in P^D \quad (5.55)$$

Constraints (5.46) make sure storage levels at recycling facilities, filling locations and disposal sites are never negative. Upper limits of the storage level variable are decided by constraints (5.36) and (5.37). Direct flow variables  $f_{ijpt}$  and roundtrip variables  $g_{ijklt}$  are set to non-negative values by constraints (5.47) and (5.48), respectively. Constraints (5.49) make sure processes are run a positive number of times. The process machine leasing variables  $y_{imt}$  and  $y_{imt}^{start}$  are set binary by constraints (5.50) and (5.51), respectively. Constraints (5.52) and (5.53) make sure external flow is positive either outward or inward, respectively. Finally, constraints (5.54) make sure only positive proportions of emissions are allocated to project sites, while the overestimation variable  $l_{qijp}$  is set binary by constraints (5.55).



## 5.4 Objective function

As described in section 2.3, several different stakeholders are involved in the logistics within the system boundaries, each with different cost structures related to transportation and processing. Furthermore, the primal aim for this master thesis is to contribute to more environmentally friendly planning of the logistics in the construction and demolition sector, within the scopes mentioned earlier. Nevertheless, we know that decision making rarely is done without economic motives. Therefore, the following section presents four different objective functions, divided in subsections concerning different perspectives. Two objective functions represent monetary costs for the whole system and individual projects, respectively, while two objective functions represent emissions from the two same perspectives. In the computational study presented in Chapter 6, the optimization is done both minimizing each individual objective function and minimizing a combination of the economic and environmental objective functions. When mixing the two in the objective, a weighted sum method is applied, with weights discussed in Section 6.2.1. As opposed to other papers combining economic and environmental impact in the objective function of supply chain management problems, this thesis does not convert the emissions to monetary figures using the parameter cost of carbon credits as a conversion factor (Eskandarpour, Dejax, Miemczyk, & Péton, 2015). This is because it shows to be difficult to set a general market price for carbon emission. However, this conversion could easily be included in the model at a later stage.

### 5.4.1 System perspective

Two objective functions are developed with a perspective of the overall system, minimizing total system emissions and total system costs. These are shown in Equations (5.70) and (5.71), respectively. The objective function describing total system emissions consist of six terms, while the objective function describing system costs consist of eight terms. Each of the terms are presented briefly below.

#### Internal transportation

Emissions and costs from internal transportation within system boundaries, linked to the flow variable  $f$  are represented by the terms  $TI_{SYS}^E$  and  $TI_{SYS}^C$ , respectively. Transportation flows

between all nodes, consisting of all products and at all time periods are included for both expressions.

$$TI_{SYS}^E = \sum_{i \in N} \sum_{j \in N} \sum_{p \in P} \sum_{t \in T} E_{ij}^T f_{ijpt} \quad (5.56)$$

$$TI_{SYS}^C = \sum_{i \in N} \sum_{j \in N} \sum_{p \in P} \sum_{t \in T} C_{ij}^T f_{ijpt} \quad (5.57)$$

### Roundtrip savings

As described in Sections 5.1.2 – 5.1.4, emissions and costs included in in equation (5.56) and (5.57), respectively, do not involve savings resulting from combining two flows in a roundtrip. Thus, terms for emission and cost savings from roundtrips are included, denoted  $TR_{SYS}^E$  and  $TR_{SYS}^C$ , respectively.

$$TR_{SYS}^E = \sum_{i \in N} \sum_{j \in N} \sum_{k \in N} \sum_{l \in N} \sum_{t \in T} R_{ijkl}^E g_{ijklt} \quad (5.58)$$

$$TR_{SYS}^C = \sum_{i \in N} \sum_{j \in N} \sum_{k \in N} \sum_{l \in N} \sum_{t \in T} R_{ijkl}^C g_{ijklt} \quad (5.59)$$

### External transportation

$TE_{SYS}^E$  and  $TE_{SYS}^C$  represent external transportation emissions and external transportation costs, respectively, linked to the amounts that are sent across the system boundaries, either out to an external disposal site, an external project or in from an external quarry.

$$TE_{SYS}^E = \sum_{i \in N^S \cup N^F} \sum_{p \in P} \sum_{t \in T} (E_{i,ext}^T \varphi_{ipt}^{out} + E_{ext,i}^T \varphi_{ipt}^{in}) \quad (5.60)$$

$$TE_{SYS}^C = \sum_{i \in N^S \cup N^F} \sum_{p \in P} \sum_{t \in T} (C_{i,ext}^T \varphi_{ipt}^{out} + C_{ext,i}^T \varphi_{ipt}^{in}) \quad (5.61)$$

### Recycling processes

Emissions linked to recycling processes are calculated per unit processed products, denoted  $R_{SYS}^E$ . Obviously, there are specific emissions linked to establishing or setting up a processing machine, particularly for massive constructions like a concrete or asphalt facility. However, these emissions are included in the variable process emissions represented by  $E_r^R$ , through Life Cycle Analysis (LCA) calculations. Even though LCA calculations are based on only general production rates of machines, we assume them to be accurate enough in this thesis. Recycling costs,  $R_{SYS}^C$ , however, consist of one term representing processing costs and a second term representing start-up costs when establishing a new machine.

$$R_{SYS}^E = \sum_{i \in N^F} \sum_{m \in M} \sum_{r \in R} \sum_{t \in T} E_r^R h_{imrt} \quad (5.62)$$

$$R_{SYS}^C = \sum_{i \in N^F} \sum_{m \in M} \sum_{r \in R} \sum_{t \in T} C_r^R h_{imrt} + \sum_{i \in F} \sum_{m \in M} \sum_{t \in T} C_m^M y_{imt}^{start} \quad (5.63)$$

### Disposal and filling

Emissions linked to disposal of products,  $D_{SYS}^E$ , consist of two terms, the first representing products sent to internal disposal or filling, the other representing external disposal. Both assume that if a quality product of the set  $P^Q$  is disposed or used as filling substance, there must be extracted the same amount of the product from virgin materials. Thus, each of these flows are multiplied with  $E_p^V$ . Disposal of non-quality products does not induce any decision relevant emissions. Disposal costs,  $D_{SYS}^C$  and costs for sending products to filling locations,

$U_{SYS}^C$ , however, include all products of the set  $P$ , but only a fraction  $\gamma$  of quality products are disposed.

$$D_{SYS}^E = \sum_{i \in N} \sum_{j \in N^D \cup N^U} \sum_{p \in P^Q} \sum_{t \in T} E_p^V f_{ijpt} + \sum_{i \in N^S \cup N^F} \sum_{p \in P^Q} \sum_{t \in T} \gamma E_p^V \varphi_{ipt}^{out} \quad (5.64)$$

$$D_{SYS}^C = \sum_{i \in N} \sum_{j \in N^D} \sum_{p \in P} \sum_{t \in T} C_p^D f_{ijpt} + \sum_{i \in N^S \cup N^F} \sum_{p \in P^Q} \sum_{t \in T} \gamma C_p^D \varphi_{ipt}^{out} \quad (5.65)$$

$$+ \sum_{i \in N^S \cup N^F} \sum_{p \in P \setminus P^Q} \sum_{t \in T} C_p^D \varphi_{ipt}^{out}$$

$$U_{SYS}^C = \sum_{i \in N} \sum_{j \in N^U} \sum_{p \in P} \sum_{t \in T} C_p^U f_{ijpt} \quad (5.66)$$

### Use of virgin products

Production emissions and product costs of virgin products brought into project sites from external quarries are represented by  $V_{SYS}^E$  and  $V_{SYS}^C$ , respectively.

$$V_{SYS}^E = \sum_{i \in N^S} \sum_{p \in P} \sum_{t \in T} E_p^V \varphi_{ipt}^{in} \quad (5.67)$$

$$V_{SYS}^C = \sum_{i \in N^S} \sum_{p \in P} \sum_{t \in T} C_p^V \varphi_{ipt}^{in} \quad (5.68)$$

### External product sale

Lastly,  $SE_{SYS}^C$  represent incomes from sale of quality products to external projects.

$$SE_{SYS}^C = \sum_{i \in N^S \cup N^F} \sum_{p \in P^Q} \sum_{t \in T} (1 - \gamma) C_p^P \varphi_{ipt}^{out} \quad (5.69)$$

### Total system emissions and costs

The resulting terms for system emissions and system costs are shown in Equations (5.70) and (5.71), respectively. Both of the terms are *minimized* in the objective function.

$$SysEmissions = TI_{SYS}^E - TR_{SYS}^E + TE_{SYS}^E + R_{SYS}^E + D_{SYS}^E + V_{SYS}^E \quad (5.70)$$

$$SysCosts = TI_{SYS}^C - TR_{SYS}^C + TE_{SYS}^C + R_{SYS}^C + D_{SYS}^C + U_{SYS}^C + V_{SYS}^C - SE_{SYS}^C \quad (5.71)$$

### 5.4.2 Project owners' perspective

There are two main reasons why objective functions from the project owners' perspectives has been derived. First, as mentioned in Section 2.3, project owners have major influence in how the logistics are organized and how much collaboration is applied. Thus, it is important to be able to quantify for project owners how different scenarios affect their respective projects. Secondly, optimizing from the perspective of individual projects make a relevant *base case*, because this represent a scenario without the collaboration of Bærum Ressursbank. Other (better) solutions can then be compared to the base case. All terms in the following section apply to each specific project of the set of projects,  $S$ , indexed  $s$ .

#### Internal transportation

Transportation emissions and costs within the system boundaries for each individual project are  $TI_s^E$  and  $TI_s^C$ , respectively. Emissions involve all shipments either from or to the project's sites. Costs, however, involve all shipments either from or to the project's site *except* transportation to another project's site. Transportation to another project's site represent products which are sold to the receiving project; thus, transportation costs are paid by the buying project.

$$TI_S^E = \sum_{i \in N_S^S} \sum_{j \in N} \sum_{p \in P} \sum_{t \in T} E_{ij}^T f_{ijpt} + \sum_{i \in N} \sum_{j \in N_S^S} \sum_{p \in P} \sum_{t \in T} E_{ij}^T f_{ijpt} \quad (5.72)$$

$$TI_S^C = \sum_{i \in N_S^S} \sum_{j \in N \setminus N_S^S} \sum_{p \in P} \sum_{t \in T} C_{ij}^T f_{ijpt} + \sum_{i \in N} \sum_{j \in N_S^S} \sum_{p \in P} \sum_{t \in T} C_{ij}^T f_{ijpt} \quad (5.73)$$

### Roundtrip savings

Roundtrip savings on a per project basis is calculated the following way. Each project gets the benefits from a roundtrip between nodes  $i$ ,  $j$ ,  $k$  and  $l$  if one or several of that project's project site nodes is included. Furthermore, the proportion of roundtrip savings allocated to each of the two direct routes included, is calculated on basis of the relative distances. If node  $i$  or  $j$  is a project site node of project  $s_1$ , the proportion of roundtrip savings allocated to project  $s$  is the proportion  $\frac{\mathcal{D}_{ij}}{\mathcal{D}_{ij} + \mathcal{D}_{kl}}$  of the total roundtrip savings between nodes  $i$ ,  $j$ ,  $k$  and  $l$ . Similarly, the proportion  $\frac{\mathcal{D}_{kl}}{\mathcal{D}_{ij} + \mathcal{D}_{kl}}$  is allocated to project  $s_2$  if either node  $k$  or  $l$  is one of that project's sites.

$$TR_S^E = \sum_{i \in N} \sum_{j \in N} \sum_{k \in N} \sum_{l \in N} \sum_{t \in T} \left( \left( R_{ijkl}^E g_{ijklt} \frac{\mathcal{D}_{ij}}{\mathcal{D}_{ij} + \mathcal{D}_{kl}} \middle| i \in N_S^S \cap j \in N_S^S \right) + \left( R_{ijkl}^E g_{ijklt} \frac{\mathcal{D}_{kl}}{\mathcal{D}_{ij} + \mathcal{D}_{kl}} \middle| k \in N_S^S \cap l \in N_S^S \right) \right) \quad (5.74)$$

$$TR_S^C = \sum_{i \in N} \sum_{j \in N} \sum_{k \in N} \sum_{l \in N} \sum_{t \in T} \left( \left( R_{ijkl}^C g_{ijklt} \frac{\mathcal{D}_{ij}}{\mathcal{D}_{ij} + \mathcal{D}_{kl}} \middle| i \in N_S^S \cap j \in N_S^S \right) + \left( R_{ijkl}^C g_{ijklt} \frac{\mathcal{D}_{kl}}{\mathcal{D}_{ij} + \mathcal{D}_{kl}} \middle| k \in N_S^S \cap l \in N_S^S \right) \right) \quad (5.75)$$

### External transportation

Terms for project specific external transportation emissions and costs,  $TE_S^E$  and  $TE_S^C$ , respectively, are modelled similarly to  $TE_{SYS}^E$  and  $TE_{SYS}^C$ .

$$TE_s^E = \sum_{i \in N_s^S} \sum_{p \in P} \sum_{t \in T} (E_{i,ext}^T \varphi_{ipt}^{out} + E_{ext,i}^T \varphi_{ipt}^{in}) \quad (5.76)$$

$$TE_s^C = \sum_{i \in N_s^S} \sum_{p \in P} \sum_{t \in T} (C_{i,ext}^T \varphi_{ipt}^{out} + C_{ext,i}^T \varphi_{ipt}^{in}) \quad (5.77)$$

### Recycling processes

The amount of emissions generated at recycling facilities as results of the demands from a project's sites, is explained in Section 5.1.10. The total process emissions allocated to each project is  $R_s^E$ .

$$R_s^E = \sum_{i \in N^F} \sum_{j \in N_s^S} \sum_{p \in P} e_{ijp} \quad (5.78)$$

### Disposal and filling

$D_s^E$ , emissions due to disposal of quality products include, as is the case for  $D_{SYS}^E$ , the emissions generated when virgin materials are used to make new products. Disposal costs are represented by  $DD_s^C$ ,  $DF_s^C$  and  $DU_s^C$ , to disposal locations, recycling facilities and filling locations, respectively. For disposals to external disposal locations, only a fraction  $\gamma$  of quality products sent out is disposed.

$$D_s^E = \sum_{i \in N_s^S} \sum_{j \in N^D \cup N^U} \sum_{p \in P^Q} \sum_{t \in T} E_p^V f_{ijpt} + \sum_{i \in N_s^S} \sum_{p \in P^Q} \sum_{t \in T} \gamma E_p^V \varphi_{ipt}^{out} \quad (5.79)$$

$$\begin{aligned}
DD_s^C = & \sum_{i \in N_s^S} \sum_{j \in N^D} \sum_{p \in P} \sum_{t \in T} C_p^D f_{ijpt} + \sum_{i \in N_s^S} \sum_{p \in P \setminus PQ} \sum_{t \in T} C_p^D \varphi_{ipt}^{out} \\
& + \sum_{i \in N_s^S} \sum_{p \in PQ} \sum_{t \in T} \gamma C_p^D \varphi_{ipt}^{out}
\end{aligned} \tag{5.80}$$

$$DF_s^C = \sum_{i \in N_s^S} \sum_{j \in N^F} \sum_{p \in P} \sum_{t \in T} C_p^{FD} f_{ijpt} \tag{5.81}$$

$$DU_s^C = \sum_{i \in N_s^S} \sum_{j \in N^U} \sum_{p \in P} \sum_{t \in T} C_p^U f_{ijpt} \tag{5.82}$$

### Product trade

With a project perspective, costs for purchasing products and income from selling products are included as  $P_s^C$  and  $S_s^C$ , respectively. Product cost occur for products sent to one of the project's sites from either a recycling facility, another project's site or from an external quarry. The project get income if products are transported from one of the project's sites to either another project's site, or to an external project. As described earlier, only the fraction  $(1 - \gamma)$  of quality products which are sent out (corresponding to variable  $\varphi_{ipt}^{out}$ ) are sold. Furthermore, when receiving products from an external quarry, emissions from virgin material extraction and processing are represented by  $V_s^E$ .

$$V_s^E = \sum_{i \in N_s^S} \sum_{p \in P} \sum_{t \in T} E_p^V \varphi_{ipt}^{in} \tag{5.83}$$

$$P_s^C = \sum_{i \in N^F \cup N^S \setminus N_s^S} \sum_{j \in N_s^S} \sum_{p \in P} \sum_{t \in T} C_p^P f_{ijpt} + \sum_{i \in N_s^S} \sum_{p \in P} \sum_{t \in T} C_p^V \varphi_{ipt}^{in} \tag{5.84}$$

$$S_s^C = \sum_{i \in N_s^S} \sum_{j \in N^S \setminus N_s^S} \sum_{p \in P} \sum_{t \in T} C_p^P f_{ijpt} + \sum_{i \in N_s^S} \sum_{p \in PQ} \sum_{t \in T} (1 - \gamma) C_p^P \varphi_{ipt}^{out} \tag{5.85}$$



### Total project emissions and costs

All terms presented above constitute the expressions for a project's total emissions and costs. These are shown in Equations (5.86) and (5.87), respectively. The sum of all projects' individual emissions and costs give total project emissions and total project costs given by Equations (5.88) and (5.89), respectively.

$$ProjectEmissions_s = TI_s^E - TR_s^E + TE_s^E + R_s^E + D_s^E + V_s^E \quad (5.86)$$

$$ProjectCosts_s = TI_s^C - TR_s^C + TE_s^C + DD_s^C + DF_s^C + DU_s^C + P_s^C - S_s^C \quad (5.87)$$

$$TotProjectEmissions = \sum_{s \in S} ProjectEmissions_s \quad (5.88)$$

$$TotProjectCosts = \sum_{s \in S} ProjectCosts_s \quad (5.89)$$

## 5.5 Pre-processing of variables

The size of the proposed model grows fast with the number of nodes, as many of the variables are linked to each node. This is especially the case for the roundtrip variable  $g$ , which does not have a linear correlation with the number of nodes. In this thesis, this challenge is coped with limiting the number of variables before solving the model. This section present how different limitations are applied when variables are created.

To start with, direct flow variables,  $f_{ijpt}$  are restricted to only the allowed flows showed in Figure 4.2. Thus, no flow variables are created from disposal locations, nor filling locations, as nothing is transported from these node types. Accordingly, no direct flow variables are created between two recycling facilities. Furthermore, certain products are defined not to be disposed and/or used to filling purposes. The corresponding flow variables are thus not created. Also, only certain disposal locations can receive contaminated products. Flow variables corresponding to these products therefore are not created to other disposal nodes. Since

recycling facilities should not be used extensively as intermediate storage, there are restrictions in which products that can be delivered to them. Therefore,  $f_{ijpt}$  is only created to facility  $j$  if product  $p$  is an input product of one or several recycling processes. Equally,  $f_{ijpt}$  is only created from a recycling facility  $i$  if product  $p$  is an output product from a process. Finally,  $f_{ijpt}$  is not created from project site  $i$  at time  $t$  when there are no supply of product  $p$ , nor to project site  $j$  at time  $t$  if there are no demand for product  $p$  at that site at that time period.

Roundtrip variables,  $g_{ijklt}$ , are pre-generated partly as suggested by Carlsson and Rönnqvist (2007). First,  $g_{ijklt}$  is only created if there are at least one direct flow variable  $f_{ijpt}$  between nodes  $i$  and  $j$  and between nodes  $k$  and  $l$ . Furthermore, a practical limit often imposed is that a backhaul route should have a certain required distance saving compared to hauling with only direct routes (Carlsson & Rönnqvist, 2007). In this thesis, the required distance reduction is set as a percentage of the distance travelled without using roundtrips. This is set to 80 %, but can easily be changed as an input parameter. This means that a roundtrip variable  $g_{ijklt}$  is only created if the empty driving distance is at most 80 % of the empty driving distance when hauling the direct tours between nodes  $i$  and  $j$ , and nodes  $k$  and  $l$ .

External outward transportation variable,  $\varphi_{ipt}^{out}$  is generated for project site  $i$  only if the site has supply of product  $p$  in time period  $t$ . Similarly,  $\varphi_{ipt}^{in}$  is created only if there is a demand of product  $p$  at site  $i$  at time period  $t$ . Furthermore,  $\varphi_{ipt}^{in}$  is only generated for  $i \in N^S$  and  $\varphi_{ipt}^{out}$  only for  $i \in N^S \cup N^F$ .

## 5.6 Model extension – time shifting of projects

In addition to the core model formulation described above, an extension to the model is developed. This extension enables project schedules to shift either one year back or one year forward in time, if this is beneficial for the objective function. Thus, three new variables are introduced, deciding which time period a project is starting at. The new notation and constraints are described below.

### 5.6.1 Variables

$$\begin{aligned}
 x_s^{+1} & \begin{cases} 1, & \text{if project } s \text{ is starting one year before original schedule} \\ 0, & \text{otherwise} \end{cases} \\
 x_s^0 & \begin{cases} 1, & \text{if project } s \text{ is starting at original schedule} \\ 0, & \text{otherwise} \end{cases} \\
 x_s^{-1} & \begin{cases} 1, & \text{if project } s \text{ is starting one year after original schedule} \\ 0, & \text{otherwise} \end{cases}
 \end{aligned}$$

### 5.6.2 Constraints

$$\sum_{j \in N} f_{ijpt} + \varphi_{ipt}^{out} = x_s^{+1} S_{ip,t+1} + x_s^0 S_{ipt} + x_s^{-1} S_{ip,t-1} \quad \begin{matrix} s \in S, i \in N_s^S, \\ p \in P, t \in T \end{matrix} \quad (5.90)$$

$$\sum_{j \in N} f_{jip t} + \varphi_{ipt}^{in} = x_s^{+1} D_{ip,t+1} + x_s^0 D_{ipt} + x_s^{-1} D_{ip,t-1} \quad \begin{matrix} s \in S, i \in N_s^S, \\ p \in P, t \in T \end{matrix} \quad (5.91)$$

$$x_s^{+1} + x_s^0 + x_s^{-1} = 1 \quad s \in S \quad (5.92)$$

$$x_s^{+1} \in \{0, 1\} \quad s \in S \quad (5.93)$$

$$x_s^0 \in \{0, 1\} \quad s \in S \quad (5.94)$$

$$x_s^{-1} \in \{0, 1\} \quad s \in S \quad (5.95)$$

Constraints (5.90) and (5.91) replace the original constraints (5.30) and (5.31), respectively, when including time shifting of projects. Thus, these are the new balance constraints for project sites. The right-hand sides of the two constraints enable supply and demand shift by one year. Constraints (5.92) make sure a project is either starting one year before originally scheduled time, at scheduled time, or one year after scheduled time. Finally, constraints (5.93) - (5.95) set all time shifting variables binary.

## Chapter 6 Computational study

In this chapter, analysis and results from a computational study is presented. Because of the practical nature of the problem assessed in this thesis, focus is on practical implementations of the model described in Chapter 5. Furthermore, the model is simple enough that runtime was less than 15 minutes for all instances, solved by exact solution methods with Mosel Xpress-IVE 7.9 optimization software from FICO, run on a Hewlett-Packard Pavilion 64-bit Windows 10 Home PC with Intel® Pentium® 1.90 GHz processor and 8,0 GB RAM. Technical analysis of the model is therefore excluded. Real data from the municipality of Bærum and surroundings have been used, provided by Bærum Ressursbank and other participants in the construction and demolition sector in Norway.

### 6.1 Case data

Five infrastructure projects are included in the system considered in the computational study. These are of different sizes regarding both supply and demand and number of project sites. Key specifications for each respective project are presented in Table 6.1.

*Table 6.1: Key specifications for each respective project*

<i>Parameter</i>	<i>Project 1</i>	<i>Project 2</i>	<i>Project 3</i>	<i>Project 4</i>	<i>Project 5</i>
<i>Number of project sites</i>	7	1	1	1	3
<i>Fraction of total surplus</i>	58,7 %	0,8 %	17,2 %	14,6 %	8,7 %
<i>Fraction of total demand</i>	92,6 %	0,1 %	5,3 %	2,0 %	0,0 %

The numbers of other location types included in the study are found in Table 6.2. As mentioned, one geographical location may be modelled with two different nodes if the location has allocated areas for both disposal and recycling.

Table 6.2: Case size in terms of number of nodes

<i>Location type</i>	<i>Project sites</i>	<i>Recycling facilities</i>	<i>Filling locations</i>	<i>Disposal locations</i>	<b><i>Total</i></b>
<i>Number of nodes</i>	13	5	4	4	<b>26</b>

The planning horizon considered is 10 years, with a yearly given supply from and demand to each project site. These are assumed even spread throughout the respective years. Supply exceeds demand to a great extent. Figure 6.1 shows net surplus and demand for each year, while Figure 6.2 shows accumulations of surplus throughout all years. As we can see, a majority of supply is concentrated around years 2022 – 2024, while demands are highest towards the end of the planning horizon.

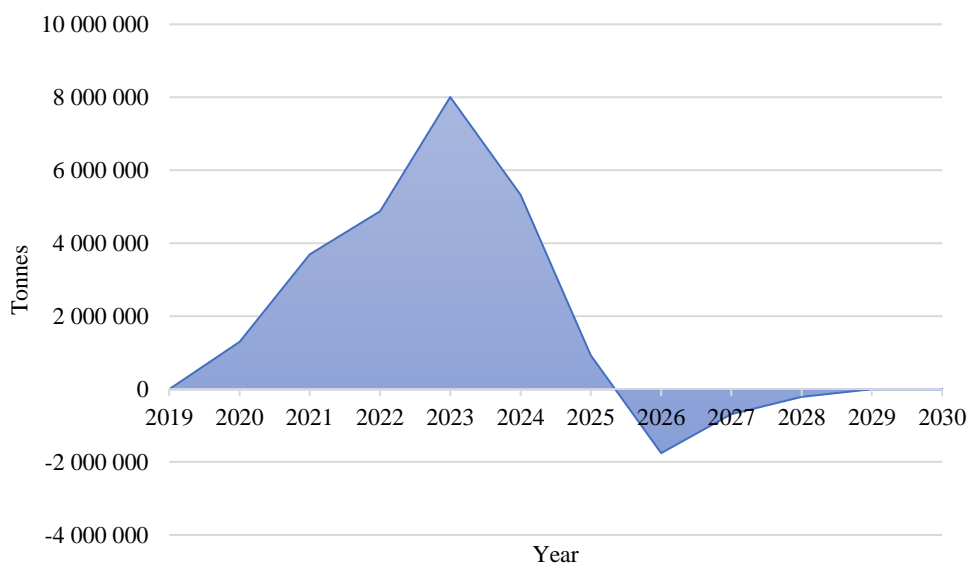


Figure 6.1: Net sum of surplus (positive numbers) and demand (negative numbers) from all projects included in Bærum Ressursbank

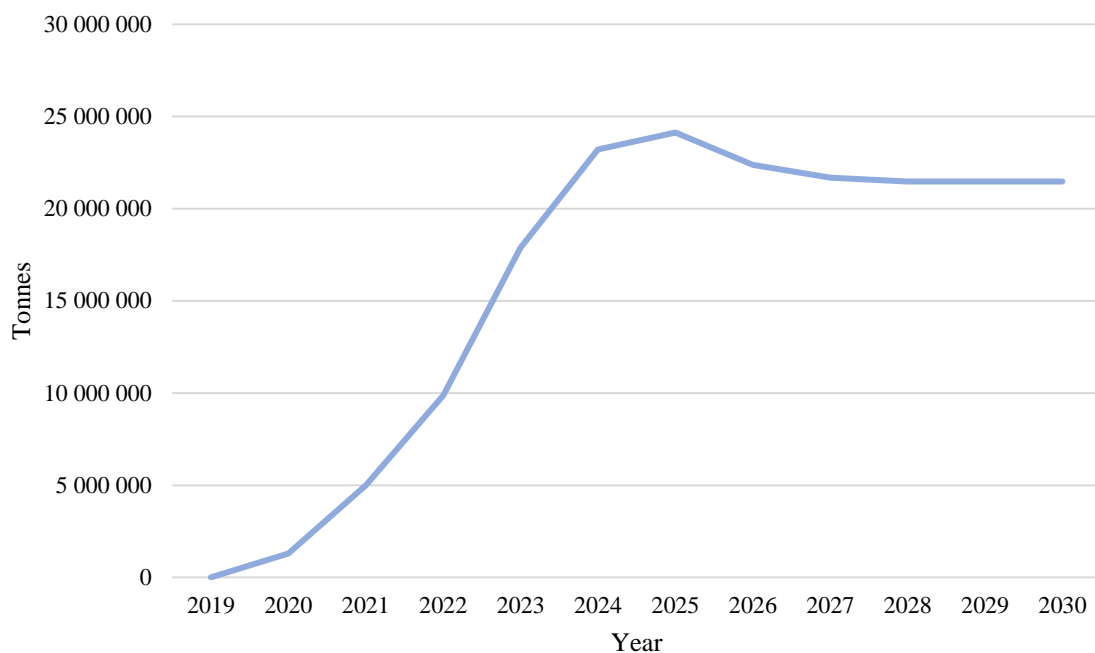


Figure 6.2: Accumulated sum of surplus and demand from all projects included in Bærum Ressursbank. Positive figures mean net surplus.

Supply and demand of masses are divided into 21 different products, presented in relative quantities in Tables 6.3 and 6.4. Here, quality products are denoted with a “\*”, showing which products are assumed to have a demanding market outside the system as well (as described in Section 5.1.5). In addition to these 21 products, seven secondary or intermediate products are involved in one or several of 19 different recycling processes.

Finally, transportation distances are calculated using a Google API with Excel, finding distances between each pair of nodes. An excel model for this is developed with the purpose of easily being able to include new locations in the model just by adding the locations’ addresses. The driving distances inside the system boundaries range from 0 to 52 kilometres, averaging 16,8 kilometres between two nodes. External driving distances to an external disposal site or from an external quarry range from 17 to 57 kilometres, averaging 33 kilometres.

Table 6.3: Relative quantities of different surplus products

<i>Product</i>	<i>Percentage of total surplus</i>
<b>Stone – good quality</b>	<b>32,7 %</b>
Excavated rock*	32,7 %
<b>Stone – poor quality</b>	<b>55,0 %</b>
Excavated rock	46,3 %
Machine sand	8,7 %
<b>Asphalt</b>	<b>0,4 %</b>
Flakes	0,2 %
Milled*	0,2 %
<b>Concrete</b>	<b>&lt; 0,1 %</b>
Without reinforcements	< 0,1 %
With reinforcements	< 0,1 %
<b>Soils</b>	<b>11,9 %</b>
Inorganic sediments	7,0 %
Food soil*	1,1 %
Clay	2,2 %
Tunnel floor silt	1,4 %
Tunnel sludge	< 0,1 %
Woodwork*	< 0,1 %
Stumps and roots	0,1 %

Table 6.4: Relative quantities of different demanded products

<i>Product</i>	<i>Percentage of total demand</i>
<b>Stone – good quality</b>	<b>31,6 %</b>
Aggregate 22/120*	29,7 %
Aggregate 32/63*	1,9 %
<b>Stone – poor quality</b>	<b>50,0 %</b>
Excavated rock	40,0 %
Aggregate 8/16	10,0 %
<b>Asphalt</b>	<b>1,1 %</b>
Warm*	1,1 %
<b>Concrete</b>	<b>16,0 %</b>
Finished*	11,5 %
Sprayed (Shotcrete)*	4,5 %
<b>Soils</b>	<b>1,3 %</b>
Construction soil*	1,3 %

## 6.2 Conceptual analysis

The first part of the computational study focuses on conceptual aspects with the model. In section 6.2.1, the multi-objective nature of the problem is investigated, analysing the Pareto front and trade-offs between environmental and economic optimization. Section 6.2.2 addresses different levels of cooperation from project individualization to full collaboration. Finally, Section 6.2.4 analyses whether influence on project schedules may give environmental and economic benefits.

### 6.2.1 Multiobjective optimization of costs and emissions

Even though this thesis aims to contribute to a more environmentally friendly construction and demolition sector, it is impossible to bypass the fact that economic aspects always are of major importance in any industry. In this section, we present a Pareto front, to understand the trade-offs between making decisions based on costs and emissions. The problem is solved with the multi-objective function (5.96), with *SysCosts* and *SysEmissions* described by Equations (5.71) and (5.70), respectively.

$$\min(\omega_{costs} \cdot SysCosts + \omega_{emissions} \cdot SysEmissions) \quad (5.96)$$

Then, the weighted sum method is applied a posteriori, meaning that we vary each of the weights  $\omega_{costs}$  and  $\omega_{emissions}$ , respectively, where both are strictly positive and  $\omega_{costs} + \omega_{emissions} = 1$ . Note that *SysCosts* and *SysEmissions* are expressed in different units, and the former generally has a much larger value than the latter. Note that, as mentioned in Section 5.4, it has been chosen not to convert emissions to monetary units because of large variations in such conversion factors used in the literature (Eskandarpour, Dejax, Miemczyk, & Péton, 2015). Thus, most of the values for  $\omega_{emissions}$  examined are closer to 1. The Pareto front is shown in Figure 6.3.



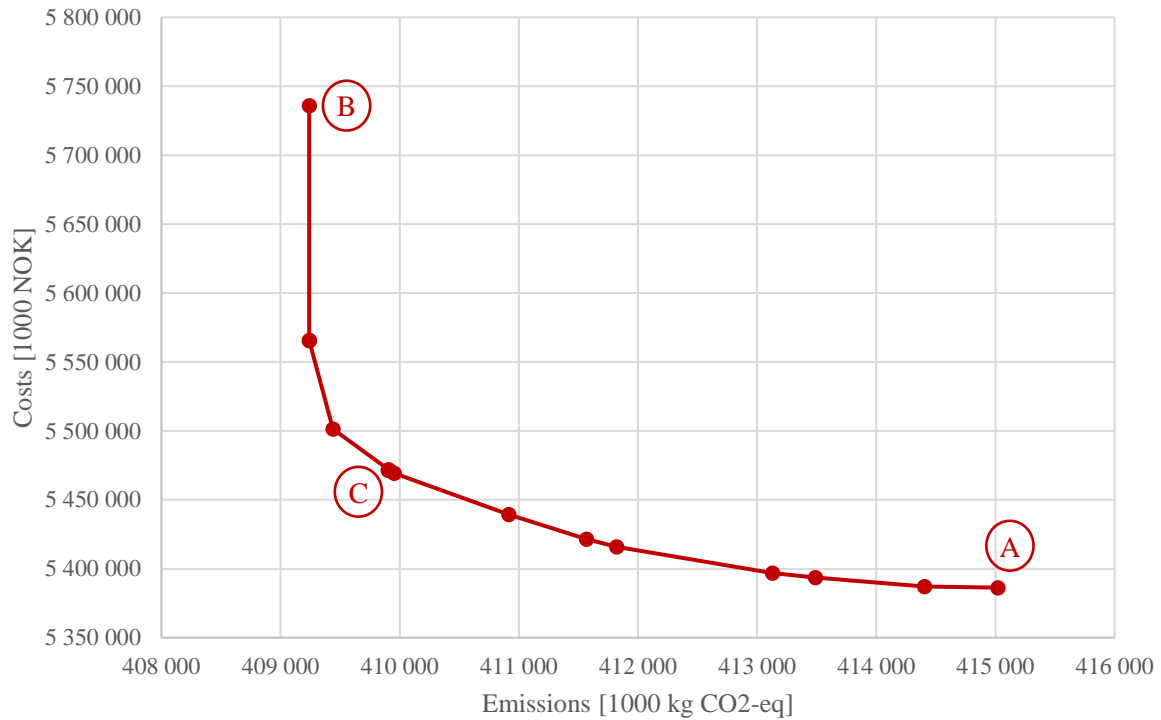


Figure 6.3: Pareto front for different weights on system costs and system emissions

The difference in total emissions vary less than 2 %, while total costs vary around 6 % between an entirely economic objective function ( $\omega_{costs} = 1$ ) and an entirely environmental objective function ( $\omega_{emissions} = 1$ ). The reason for this might be that transportation and processes drive both costs and emissions relatively similarly. However, within these ranges, the Pareto front seems relatively steep in both ends. Thus, moving from an entirely cost based optimization, represented by Point A in Figure 6.3, towards larger focus on emissions could arguably be favourable. On the other hand, Point B seems to be a poor option, as allowing just a minor increase in emissions may result in savings of several million NOK. Comparing the relative change in costs and emissions between the identified points on the Pareto front, Point C looks as a good compromise between costs and emissions. Compared to Point A, emissions are reduced by approximately 1 % while costs are 1 % higher. This correspond to  $\omega_{emissions} = 0,98$ . Increasing  $\omega_{emissions}$  further, gives relatively much higher expansions in costs than reductions in emissions.

## 6.2.2 Levels of cooperation

The model proposed in this thesis consider different levels of cooperation among the participants, composed by variations of both transportation collaboration and market collaboration. In this section, we consider three of these:

1. Individualized projects
2. Collaboration without roundtrips
3. Total system optimum

The lowest level of cooperation is planning transportation and logistics individually for each project. Each project chooses optimal transportation routes without taking into account other projects' demand nor supply, and vehicles drive empty back from each trip because the lack of backhauling or roundtrips. The second level of cooperation allow trade of products between different projects but exclude the possibility of roundtrip collaboration. Thus, a project's demand can be met by other projects' supplies either directly or via processing. The most comprehensive form of cooperation is called *system optimum*. Here, all participating projects consider other projects' supply and demand, and total system costs and total system emissions are minimized. Furthermore, projects collaborate on transportation, with the possibility to utilize backhauling and roundtrips, as discussed in Section 5.1.3. All three levels of cooperation are analysed with the multi-objective function minimizing total system costs and total system emissions, Equation (5.96). Weights are chosen according to the analysis from Section 6.2.1, with  $\omega_{emissions} = 0,98$  and  $\omega_{costs} = 0,02$ . Table 6.5 shows a comparison of key results for the three levels of cooperation.

Table 6.5: Comparison of key figures for three levels of cooperation

<i>Cost/emission</i>	<i>Unit</i>	<i>Individualized projects</i>	<i>Collaboration without roundtrips</i>	<i>System optimum</i>
<i>SysEmissions</i>	<i>[1000 CO2-eq]</i>	420 148	421 033	409 907
<i>SysCosts</i>	<i>[1000 NOK]</i>	6 261 519	5 858 308	5 471 829
<i>Tonne-kilometres</i>	<i>[1000 tkm]</i>	1 480 068	1 473 483	1 356 704
<i>Vehicle-kilometres</i>	<i>[1000 km]</i>	70 968	70 659	57 402
<i>Empty kilometres</i>	<i>[1000 km]</i>	35 950	35 800	21 826
<i>Recycling rate</i>	<i>[% of demand]</i>	80 %	99 %	99 %

Most of the environmental figures clearly improve with increased level of cooperation. Almost all of the demand to project sites can be met by reusing or recycling wastes from other project sites. Tonne-kilometres and vehicle-kilometres decrease in some degree from individualized planning to collaboration without roundtrips. This is mainly because less of the supply is sent to external locations away from Bærum Ressursbank. However, introducing roundtrips result in much greater transportation savings. As we can see, this is mostly due to reduced kilometres driving without cargo. As much as 40 % of empty kilometres are reduced with roundtrips. However, only 2 % of total system emissions are saved when introducing roundtrips. The reason for this is that driving an empty vehicle emits less than driving a full vehicle. Thus, reducing empty kilometres does not affect emissions the same way as reducing total tonne-kilometres. Nevertheless, the benefits are massive for the local environment as less kilometres are driven by lorries, even though these benefits are not reflected by analysing emissions alone. Finally, the reason why system emissions are higher when collaborating without roundtrips than individually planning projects is the weights which we chose for the multi-criterion optimization (e.g. the decrease in costs supports a slight increase in emissions). Total system costs decrease consistent with level of collaboration. To show the causes of this behaviour, system costs are decomposed in Figure 6.4.

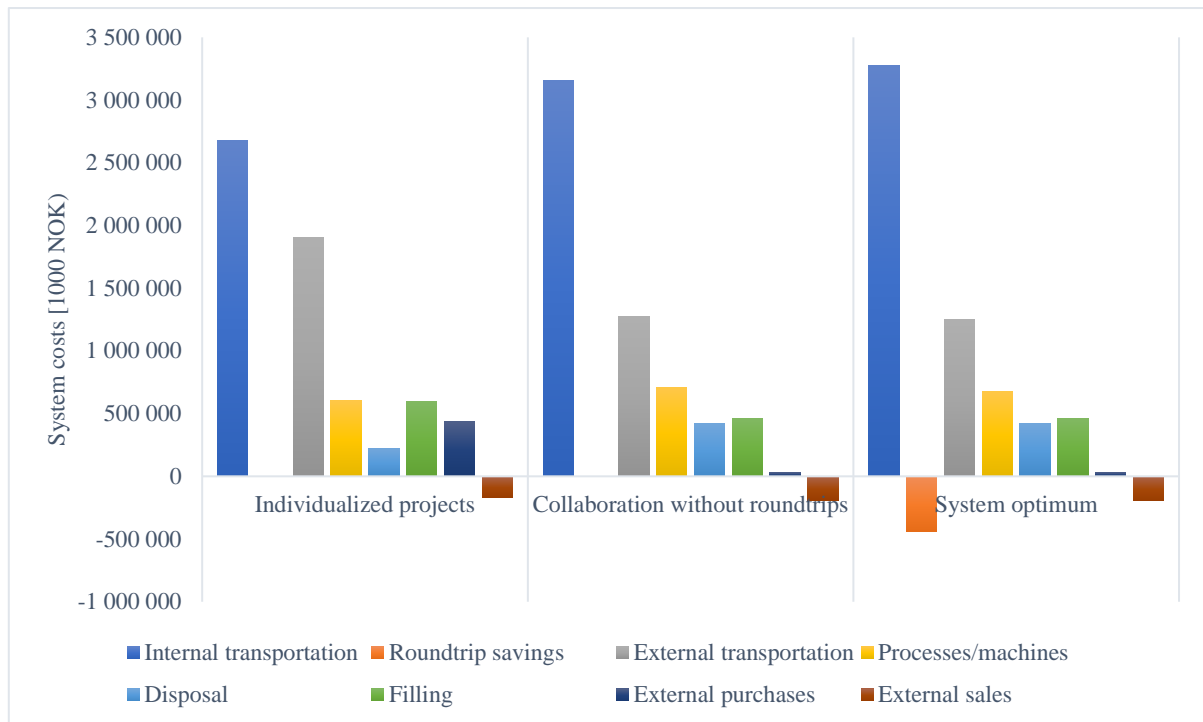


Figure 6.4: Comparison of cost drivers for three levels of cooperation

Interestingly, internal transportation costs increase with higher level of cooperation. This might seem strange but must be considered in connection with roundtrip savings and external transportation costs. When collaborating without roundtrips, external transportation costs are reduced compared to individualized projects, because less demand must be transported from external quarries. The sum of internal and external transportation costs is in fact 150 million NOK less for the case with collaboration. Similarly, the sum of internal transportation, roundtrip savings and external transportation for collaboration with roundtrips is 350 million NOK less than without roundtrips and almost 500 million NOK less than for individualized planning. Comparing other costs, external purchases are almost excluded from the two highest levels of cooperation. On the other hand, processing costs are higher. This is obviously because more waste can be reused after recycling as an alternative to external purchases. However, the increase in process costs is small compared to the decreased cost for external purchases.

### 6.2.3 Varying the external disposal parameter, $\gamma$

As mentioned in Section 5.1.6, it is assumed that a fraction of high-quality products is tradable in the external market, while the remaining is disposed of. Apparently, this

assumption very much influences both costs and emissions linked to products sent to external locations. If the proportion of products being sold is high, disposal costs are replaced by income. Furthermore, emissions linked to disposals due to alternative excavation of virgin materials (as discussed in Section 5.4.1), will decrease. In the other analyses in this chapter,  $\gamma = 0,5$  is assumed. However, the chosen value for this parameter might have impacts on the model solution. To investigate this further, Table 6.6 shows model behaviour when varying the fraction of disposed quality products,  $\gamma$ . Here, the model is solved using the multi-criterion objective function obtained in Section 6.2.1 with corresponding weights.

Table 6.6: Comparison of varying parameter  $\gamma$ . Negative values are income.

Cost/emission	Unit	Avg.	Case A	Case B	Case C	Case D
Quality disp.fraction, $\gamma$	[%]	44 %	100 %	50 %	25 %	0 %
System Emissions	[1000 kg CO2-eq]	408 906	417 344	409 907	406 115	402 257
External transportation	[1000 kg CO2-eq]	44 158	40 215	40 090	40 241	56 084
Disposal emissions	[1000 kg CO2-eq]	13 234	23 597	16 047	12 734	557
System Costs	[1000 NOK]	5 351 267	5 765 107	5 471 829	5 257 856	4 910 274
External transportation	[1000 NOK]	1 373 679	1 251 737	1 247 888	1 252 560	1 742 531
Processes	[1000 NOK]	681 732	705 482	673 482	674 482	673 482
Disposal costs	[1000 NOK]	367 311	490 012	420 680	370 940	187 611
Ecternal sales	[1000 NOK]	-326 862	0	-195 362	-345 689	-766 399
Internally disposed products						
Amount	[1000 tonnes]	4 523 165	5 154 740	5 150 470	5 146 210	2 641 240
Relative to capacity	[%]	38 %	43 %	43 %	43 %	22 %

The higher proportion of external shipments that are disposed of, the higher become both system emissions and system costs. This is mainly because of increased direct disposal costs as well as indirect emissions resulting from the additional need to extract virgin material when disposing quality products. Furthermore, being able to sell more externally obviously give higher incomes from sales. As we can see, however, the differences between  $\gamma = 50\%$  and  $\gamma = 100\%$  are relatively small, with only a 5 % difference in system costs. In comparison, setting  $\gamma = 0\%$ , e.g. being able to sell 100 % of the quality products externally, reduces system costs with 10 % compared to  $\gamma = 50\%$ . In Case D, when all quality masses that are transported externally are sold, income from sales are very high and disposal emissions are very low. Interestingly, varying  $\gamma$  between 100 % and 25 % does not affect internal disposals considerably, but setting  $\gamma = 0\%$  reduces the amount of internal disposals by almost 50 %.

From the multi-objective point of view, it suddenly become more beneficial to sell as much of these quality products externally instead of disposing them internally, since each external sale no longer is accompanied with an equal amount of disposal. However, the results show that as long as  $\gamma$  is not very low, the precise value of the parameter is less important.

#### 6.2.4 Changing project schedules

When project schedules for public and private infrastructure projects are decided, coordination with other projects is rare. Such projects are complex and there are obviously other aspects to consider when deciding when to start building or demolishing. Nevertheless, it is interesting to analyse the economic and environmental impacts of letting the projects' operating periods change somewhat from the original schedules. Thus, the model extension described in Section 5.6 is applied. Table 6.7 shows the effects of letting each respective project schedule shift either one year backward or one year forward.

Table 6.7: Effects of shifting project schedules either forward or backward one year

<i>Cost/emission</i>	<i>Unit</i>	<i>Original schedule</i>	<i>With time shift</i>	<i>Relative change</i>
<i>System Emissions</i>	<i>[1000 kg CO<sub>2</sub>-eq]</i>	409 907	407 337	-1 %
<i>System Costs</i>	<i>[1000 NOK]</i>	5 471 829	5 246 980	-4 %
<i>Disposals</i>	<i>[1000 tonnes]</i>	8 765 523	6 797 189	-22 %

As we can read, neither the reductions in emissions nor the reductions in costs are particularly considerable. In the case tested here, it is rather unlikely that these savings are significant enough compared to the inconvenience of changing the planned time schedules of the projects. These savings could, however, potentially increase by increasing the allowed time shift from one year to several years. Nevertheless, the savings mostly stem from reductions in the amount of disposed products. Overall disposal costs reduce with 24 % while reductions in filling costs are 10 %. These reductions are quite large, and the fact that less of the masses are being disposed of is of environmental importance. Finally, note that none of the projects start at the original scheduled time period when optimized with the possibility of one year time shift.

## 6.3 Specific analysis for Bærum Ressursbank

The model described in this thesis has been developed in close collaboration with Bærum Ressursbank. Even though the model is applicable to other cases, regions or industries, it has been tailored for the situation in Bærum. Therefore, the first part of the computational study will try to address industry specific needs. After several conversations with Bærum commune and other participants in Bærum Ressursbank, the following questions have been detected:

1. Quantifying the effects of cooperation in a collaborative initiative such as Bærum Ressursbank, compared to individual managing of logistics for each project. The effects are divided in two categories:
  - a. Commercial effect concentrating on environment and costs
  - b. Political effect focusing on environment and inconvenience for local residents
2. Show consequences from different political and operational decisions:
  - a. Is it beneficial to establish disposal sites inside the region?
  - b. How sensible is the solution to changes in projected schedules?
  - c. How are emissions influenced if a major project rejects to participate in the collaboration?

### 6.3.1 Commercial and political effects of cooperation

Project owners and politicians are the two types of stakeholders which are important to influence when trying to make any practical changes to logistics and transportation in the construction and demolition sector. Bærum Ressursbank must be able to show specific data demonstrating the advantages for each respective stakeholder.

Environmental issues are of major concern for governments and municipalities. This includes both local and global environment, ranging from resident inconvenience to global warming. Therefore, the following results are compared considering political effects:

- Total system emissions
- Total number of tonne-kilometres

- Total number of kilometres driven without cargo
- Total number of vehicle-kilometres
- Amount of material recycling

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. Nevertheless, recent focus on 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
- Total system costs

In both analyses, commercial and political, respectively, the system optimal case is compared to a base case. Both cases are optimized with equal input data, but with different objective functions. The base case represents the assumed common practice among projects today, each project optimizing costs individually, without inter-project trading of materials nor transportation collaboration. Thus, the base case is optimized with the objective function (5.97). Here, project costs are minimized for each individual project, *without* any information about other projects' demand nor supply, before summing.

$$\sum_{s \in S} \min ProjectCosts_s \quad (5.97)$$

The system optimal solution is obtained when minimizing total costs for the entire system, showed by the objective function (5.98), where *SysCosts* is described by Equation (5.71).

$$\min SysCosts \quad (5.98)$$

The reason why costs are minimized instead of emissions or a combination of these is a matter of preference, as both would give relatively equal results, according to Section 6.2.1. In this analysis, costs are chosen to keep the objectives as equal as possible for the base case and



system optimum, as the base case is assumed optimized only with economic incentives. Results from the political and commercial analyses are presented in Table 6.8 and 6.9., respectively.

Table 6.8: Political comparison between base case and system optimum

<i>Cost/emission</i>	<i>Unit</i>	<i>Base Case</i>	<i>System optimum</i>	<i>Change</i>
<i>SysEmissions</i>	<i>[1000 CO2-eq]</i>	520 533	415 020	-20 %
<i>Tonne-kilometres</i>	<i>[1000 tkm]</i>	2 035 240	1 373 750	-33 %
<i>Vehicle-kilometres</i>	<i>[1000 km]</i>	97 389	58 142	-40 %
<i>Empty kilometres</i>	<i>[1000 km]</i>	49 146	22 127	-55 %
<i>Recycling rate</i>	<i>[% of demand]</i>	80 %	99 %	
<i>Recycling rate</i>	<i>[% of supply]</i>	35 %	43 %	

As Table 6.8 shows, there are environmental benefits from a collaboration based on optimization of the system as a whole. Total emissions may be reduced, impacting both global and local environment. However, even more gains can be obtained regarding measures of resident inconvenience. Planning focusing on the entire system combined with transportation collaboration with backhauling and roundtrips between different projects, both total tonne-kilometres, total kilometres driven by vehicles and total kilometres driven with empty vehicles reduce drastically. As we can see, recycling rates for the Base Case scenario are decent, with a possibility of getting as much as 80 % of demand from other sites within Bærum Ressursbank, either directly or via recycling processes. This high rate results from the fact that one of the projects stands for a major proportion of both demand and supply. Thus, recycling of waste from this project is included in the Base Case. However, all projects collaborating in Bærum Ressursbank increase the recycling rate to 99 % of demand. Thus, only 1 % of demand must be shipped from locations outside Bærum Ressursbank or excavated from quarries.

Table 6.9: Commercial comparison of base case and system optimum

<i>Cost/emission</i>	<i>Unit</i>	<i>Base case</i>	<i>System optimum</i>	<i>Change</i>
<b>SysCosts</b>	<b>[1000 NOK]</b>	<b>8 176 910</b>	<b>5 386 307</b>	<b>-34 %</b>
<b>ProjectsCosts</b>	<b>[1000 NOK]</b>	<b>5 821 175</b>	<b>6 011 199</b>	<b>3 %</b>
Costs project 1	[1000 NOK]	4 182 060	4 424 968	6 %
Costs project 2	[1000 NOK]	30 330	58 612	93 %
Costs project 3	[1000 NOK]	784 425	859 989	10 %
Costs project 4	[1000 NOK]	677 115	360 544	-47 %
Costs project 5	[1000 NOK]	147 245	215 377	46 %
<b>ProjectsEmissions</b>	<b>[1000 kg CO2-eq]</b>	<b>401 388</b>	<b>412 828</b>	<b>3 %</b>
Emissions project 1	[1000 kg CO2-eq]	357 367	351 546	-2 %
Emissions project 2	[1000 kg CO2-eq]	2 297	2 350	2 %
Emissions project 3	[1000 kg CO2-eq]	23 416	27 995	20 %
Emissions project 4	[1000 kg CO2-eq]	16 318	24 443	50 %
Emissions project 5	[1000 kg CO2-eq]	1 989	4 192	111 %

Looking at Table 6.9, total system costs obviously reduce significantly when optimizing for minimal system costs. However, totals of costs and emissions related to all projects *increase*. Furthermore, we see that project specific costs or emissions, or both increase massively for the respective projects, with major individual differences. Even though this might seem strange it has logical explanations. First, the individual projects for which costs or emissions increase most are the smallest projects in terms of supply and demand. Thus, these increases are smaller relative to total costs and emissions. Secondly, the 3 % increase in total project costs and total project emissions when optimizing for the whole system are offset by reduced costs for other parties than project owners. This include disposals of waste material from recycling processes among others. However, one significant aspect with this kind of collaboration arises; total benefits must be allocated to each participant in a fair way. Several sharing mechanisms for such cost and saving distributions have been developed to cope with these issues. Among others, Frisk et al. (2010) discuss different methods applied to collaborative forest transportation in Sweden, a conceptually related problem to the one in this thesis. They provide an optimization-based allocation method aiming that each participant's relative profits are as equal as possible. The method is not applied in this thesis, but implementation is not too complicated.

### 6.3.2 Consequences of operational decisions

Organizing and planning a cooperation like Bærum Ressursbank is complicated, involving several uncertain parameters. Thus, this section tries to address some of these, analysing the effects of specific scenarios. All scenarios presented below are optimized using the multi-objective function from Equation (5.96), with weights as found in Section 6.2.1.

#### Disposal sites inside Bærum Ressursbank

One important uncertainty is linked to the question about where and how many areas will be allocated to disposal and filling locations. As mentioned in Chapter 1, these decisions are outside the scope of this problem and are modelled as input parameters. Today, there are a few large disposal locations outside of the area of Bærum Ressursbank, which may be used when disposal capacity outside Bærum Ressursbank is full. Thus, it is interesting to look at how beneficial the potential internal disposal locations are, and whether one or several of them are redundant. Table 6.10 and 6.11 summarize analyses done comparing varying numbers of disposal sites. Cases 1a and 2a include no disposal sites. For each subsequent case, one more disposal site is introduced. Since some of the locations are already decided to be used as disposal sites, while others are more uncertain, cases 1a – 1e start by introducing the locations most certain to be used, while cases 2a – 2e start with the smallest locations ending with the largest. Thus, Table 6.10 may give an indication of whether or not to consider the potential disposal sites which one has not decided upon yet. Table 6.11 show more generally how disposal behaviour changes with increased internal disposal possibilities.

Table 6.10: Comparison of disposal behaviour depending on number of internal disposal sites, introducing disposal sites according to certainty of usage.

Cost/emission	Unit	Avg.	Case 1a	Case 1b	Case 1c	Case 1d	Case 1e
Number of disposal sites	[#]	2	0	1	2	3	4
Internal disposal capacity	[1000 tonnes]	6 240	0	1 000	8 500	9 700	12 000
Internal disposals	[1000 tonnes]	3 238	0	1 000	4 887	5 150	5 150
Disp. capacity utilization	[% of capacity]	-	-	100 %	57 %	53 %	43 %
External disposals	[1000 tonnes]	4 980	7 366	6 424	3 878	3 615	3 615
Total disposals	[1000 tonnes]	8 217	7 366	7 424	8 765	8 765	8 766
System emissions	[1000 NOK]	414 035	421 722	418 205	410 459	409 882	409 907
System costs	[1000 NOK]	5 540 539	5 681 101	5 588 989	5 488 822	5 471 951	5 471 829

Apparently, an increased number of disposal locations generally result in increasingly more masses disposed inside Bærum Ressursbank. However, for cases 1a – 1e, the amount of internally disposed masses seems to reach a plateau after two of the disposal sites are included. The reason for this is that Case 1c include the by far largest disposal location, accounting for more than half the total disposal capacity. Thus, Table 6.10 indicate that the two potential locations which are least certain to be used does not contribute much to the solution. After the largest disposal site has been taken into usage, neither system emissions nor system costs decrease noteworthy by including more locations. In fact, the last location introduced in Case 1e is not utilized at all. Note also that, for the case including all disposal sites, three of them are never fully occupied.

Table 6.11: Comparison of disposal behaviour depending on number of internal disposal sites, introducing disposal sites according to capacity size.

Cost/emission	Unit	Avg.	Case 2a	Case 2b	Case 2c	Case 2d	Case 2e
Number of disposal sites	[#]	2	0	1	2	3	4
Internal disposal capacity	[1000 tonnes]	3 940	0	1 000	2 200	4 500	12 000
Internal disposals	[1000 tonnes]	2 274	0	1 000	1 543	3 674	5 150
Disp. capacity utilization	[% of capacity]	-	-	100 %	70 %	82 %	43 %
External disposals	[1000 tonnes]	5 528	7 366	6 424	5 883	4 353	3 615
Total disposals	[1000 tonnes]	7 802	7 366	7 424	7 427	8 027	8 766
System emissions	[1000 NOK]	415 954	421 722	418 205	416 937	412 998	409 907
System costs	[1000 NOK]	5 565 419	5 681 101	5 588 989	5 561 017	5 524 159	5 471 829

The results from Table 6.11, where disposal sites are introduced in capacity increasing order, show a more linear behaviour. The amount of internally disposed masses increases steadily, while external disposals decrease as disposal capacity increases. Both system emissions and system costs also decrease steadily. A rather interesting discovery from both Table 6.10 and 6.11 is that the variations in system costs and system emissions are relatively small, even though the distribution of internal and external disposals change. Emissions decrease with only 3 % from the case with no internal disposal sites to the case with all four disposal sites used. The fact that number of internal disposal sites does not have a major influence on the results show that it might be more important to find beneficial purposes and reuse materials instead of disposing them in the first place.

These results indicate that further study is required to consider whether all disposal sites actually are needed or not, or if parts of the areas designated to disposals could be used to other purposes. Other considerations should also be taken into account, as how the demand for disposals will be in the future, and whether some of the potential disposal sites are socially less favourable for the locals than others.

Even though internal disposal capacities are rarely utilized completely, it is worth mentioning that the filling locations' total capacity of 6,84 million tonnes is fully utilized in all cases above. This is a result that make sense in the light of the Recourse Pyramid, discussed in Section 2.2.1, as using excess masses to beneficial purposes is of higher priority than disposal.

### Effect of a delayed project

Rather frequently and of different reasons, large infrastructure projects are being delayed. This almost happened to one of the projects included in Bærum Ressursbank, but because of increased founding, the project continued as planned. Therefore, we look at how sensitive the results from the optimization model are to small changes in project schedules. This is done the following way. First, the model is run with planned schedules for all projects. Then, each individual project is assumed to delay with two years. In other words, both supply and demand for the respective project shift two years forward. Finally, system emissions and system costs are compared to the case with all projects run as planned. The results are shown in Table 6.12.

Table 6.12: Relative economic and environmental effects of a delayed project. Percentages represent deviations from the case when all projects run as scheduled.

Cost/emission	Unit	All at schedule	Project 1 delayed	Project 2 delayed	Project 3 delayed	Project 4 delayed	Project 5 delayed
System Emissions	[1000 kg CO <sub>2</sub> -eq]	0 %	-3 %	2 %	0 %	1 %	-1 %
System Costs	[1000 NOK]	0 %	0 %	2 %	-4 %	4 %	-1 %

Accordingly, the results do not seem to be considerably sensitive to small changes in project schedules, variations being less than 5 %. As one project is delayed one or two years, the model finds new ways of collaborating and routing transportation and reusing wastes.

### 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 take part of a collaboration with other projects because they themselves might be able to organize transport and reusage as efficiently alone as together with the collaboration. Therefore, it is interesting to compare total system emissions and costs for a case where the major project is included and a case where it is excluded. The results are presented in Table 6.13.

Table 6.13: Comparison of system emissions and costs for inclusion and exclusion of a major project

<i>Cost/emission</i>	<i>Unit</i>	<i>All projects collaborating</i>	<i>Major project excluded</i>	<i>Relative change</i>
<i>System Emissions</i>	<i>[1000 kg CO<sub>2</sub>-eq]</i>	409 907	424 427	4 %
<i>System Costs</i>	<i>[1000 NOK]</i>	5 471 829	6 373 391	16 %
<i>Empty kilometres</i>	<i>[1000 km]</i>	21 826	28 786	32 %

Total system emissions and costs are higher when organizing the major project outside the collaboration. This is mainly due to reduced possibilities to utilize waste products in other products and reduced roundtrip cooperation between projects. Again, the effects on empty driving are not reflected entirely in the effects on emissions. Nevertheless, when excluding itself from the collaboration, both individual project costs and project emissions for the major project increase with 9 % and 8 %, respectively. These cost savings correspond to 400 million NOK. Thus, it should be both economically and environmentally beneficial for the major participant to participate in the collaboration.

## Chapter 7      Concluding remarks

In this thesis, an optimization model minimizing emissions and costs related to transportation and logistics in the construction and demolition sector has been developed. The model can be used as a tool both deciding optimal transportation networks and analysing different operational scenarios. Either way it is aimed to support decision making both for government agencies and commercial participants in the construction and demolition industry. The model has been developed to address real needs of an industrial collaborative initiative called Bærum Ressursbank. Real cases from the area in and around the municipality of Bærum has therefore been studied using the model.

From the computational study, several main findings are identified. First, the trade-offs between environmental and economic optimization are considered. Including both perspectives in some extent seems to be beneficial. However, since costs and emissions correlate to some degree, the exact weighting between the two objectives in a multi-criteria problem has less significance.

Secondly, collaboration between construction and demolition projects shows to enable increasing recycling of construction and demolition waste and therefore reducing excavation of virgin materials. Close to all demanded construction masses can be met by surplus waste from other projects within the collaborating system, either directly or through recycling processes. Collaboration between projects on both material trade and transportation shows to have considerable impacts of reducing emissions and total system costs, ranging between 20 % and 40 %.

Furthermore, transportation collaboration between different projects seems to give locally important benefits. Planning transportation with use of backhauling and roundtrips, such that vehicles drive less without cargo, does decrease emissions to some extent. However, significant reductions in empty kilometres driven are not reflected in the common environmental measures of only considering CO<sub>2</sub> emissions. In the cases studied in this thesis, roundtrips reduced empty kilometres by as much as 40 % - 60 %. These results have considerable impacts on resident inconvenience and local environment even though not reflected by the objective functions. This

corresponds with the findings of Eskandarpour et al. (2015), stating that the scope of environmental measures should be broadened beyond direct greenhouse gas emissions. Also, several environmental benefits are hard to quantify, e.g. the fact that using masses to beneficial purposes at filling locations is way better than disposing them. Furthermore, as de Andrade (2017) and others emphasise, recycling of construction and demolition waste not always shows to be the economically best solution. Therefore, regulations might be needed in order to increase the rate of recycling. Suggestions of such which have proven to give results are increased disposal costs or legal enforcements on a minimum share of wastes going through recycling processes (de Andrade, 2017).

The results also show that optimizing for the total system not always give better solutions for each individual participant. Thus, to implement such collaboration as described in this thesis, it is necessary to allocate the total benefits on a system level to each individual participant in a fair way. Such incentivizing mechanisms are not covered in this thesis but should be emphasized in future work. However, the analysis also indicates that individual participants, at least the major players from the cases studied benefit from collaboration.

Some of the findings from this thesis might seem more or less counterintuitive compared to earlier works, as e.g. some relatively insignificant cost and emission reductions. There are several possible reasons for this. First of all, the model requires lots of input data, of which some is harder to determine than others, involving several appraisals and assumptions. As mentioned earlier, traditional mindsets treat certain data as industry secrets. Thus, some subjective assumptions have been made regarding input data, which itself involves uncertainty. Secondly, the base case which most of the analysis has been compared against might be too good. As described, the base case is created by optimizing each individual participant without collaboration. However, it is rather unlikely that each participant actually optimizes their behaviour in real life. Nevertheless, this approach to model the base case is chosen to prevent the results from being unlikely positive.

The main contribution of this thesis is the development of a mathematical model which can be used as a useful tool in the construction and demolition sector. The model will further be implemented in real world applications, producing increasingly more accurate results with even better input data.



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