Construction and demolition waste transport in Stockholm

A geospatial and comparative analysis between road- and intermodal transport

JUAN RAUL DUVALON CLARK
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Juan Raul Duvalon Clark

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KTH Royal Institute of Technology
School of Architecture and Built Environment
Department of Transport Science
Division of Transport Planning, Economics and Engineering
SE-100 44 Stockholm, Sweden

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Supervisor:
Dr. Behzad Kordnejad, Postdoctoral researcher, Division of Transport Planning, Economics and Engineering, KTH

Examiner:
Dr. Albania Nissan, Associate Professor, Division of System analysis and Economics, KTH

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Summary

The growth that Stockholm has lately experienced is expected to continue in coming decades. Such time prolonged population growth pose a stress over the city's infrastructure and the construction sector which by time craves an update to satisfy the demand. Thus, numerous investments in construction, demolition and renovation projects are ongoing in Stockholm year-round. And these projects generate massive quantities of waste material that need to be handled that in the present are transported almost exclusively by truck. That is the problem this thesis project looks upon: finding alternative solutions for transporting construction and demolition wastes (CDW) in more economically and environmentally effective manner.

For addressing this problem, the project aims to assess the best way of transporting these wastes by either road or intermodal transport in terms of cost- and energy- efficiency. This was done by assessing the current situation of the CDW market and its technical requirements. Furthermore, a scenario based analysis was performed for establishing if and under what circumstances are intermodal transport services a better choice than road for transporting construction and demolition wastes. For answering these questions, a set of qualitative and quantitative methods were indistinctively used. For example, geospatial- and multi criteria- analysis for creating a base for comparison and geostatistical analysis for shaping the data in a manner that could allow the scenario comparison previously proposed.

Hence, similarities between Stockholm and other international experiences was established, as a first glance into the possibility for more efficiently transporting CDW. This was not however, the only results obtained. The analysis also renders the optimal distance for transporting CDW, which in this case was in concordance with the break-even distance concept treated in the theoretical framework. Finally, the condition in which intermodal transport is more efficient for waste transporting in comparison to road transport was established. In addition, the conditions in which some intermodal service configurations are better than other intermodal services were also established in the scenario based analysis.

There is still however, much room for improvement. Particularly in this study, the scale and scope could be widened to assess a greater deal of parameters in the analysis. And in general, other alternatives as the so-called logistics centers could be explored and compared with the already existing alternatives. In general, the objectives of this project were satisfactorily achieved.

Keywords: Construction and demolition waste, landfill, intermodal transport, network analysis.
Sammanfattning


Likheter mellan Stockholm och andra internationella erfarenheter togs fram som en första anblick i möjligheten att effektivisera transporter av CDW. Detta var dock inte de enda resultaten som erhölls. Analysen tittar också på det optimala avståndet för transport av CDW, vilket i detta fall var i överensstämmelse med det jämviktsbegrepp som behandlades i den teoretiska ramen. Slutligen etablerades villkoret för att intermodal transport ska vara effektivare för avfallstransporter i jämförelse med vägtransporter. Dessutom fastställdes villkoren för att vissa intermodala servicekonfigurationer är bättre än andra intermodala tjänster i den scenariobaserade analysen.


Nyckelord: Bygg- och rivningsavfall, deponering, intermodal transport, nätverksanalys.
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I like to thank specially to Violeta de Lama, a dear friend that has been a great support during these two years. To Jan Öjmartz, for his support and invaluable friendship. And to Malin Isaksson for her invaluable contributions.

Finally, I dedicate this thesis to my mother Merlinda Clark Bloomfield, my daughter Amelia Ingrid Merlinda Öjmartz and my family, because they are the energy that has kept me going through rough times.

Sincerely,

Juan Raul D. Clark

2017-06-03
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1. Introduction

Substantial amounts of construction and demolition wastes (CDW) are generated in Stockholm yearly. That is, because of the nearly 400 construction projects carried out over the city every year (Ecoloop, 2017). Some of the masses can be reused, but most of them must be transported for recycling or deposition into landfills (Magnusson, o.a., 2016). The transportation occurs mostly by truck, and after these masses reach destination, the trucks must drive back and the cycle starts again. Therefore, a better alternative for transporting those masses is of great importance. This thesis project looks upon the need of transporting CDW in a more economically and environmentally responsible manner.

1.1. Background

Stockholm is one of the fastest growing cities in Europe (Savage, 2016). Between 1990 and 2002 Stockholm grew by 13% (Schmitt, o.a., 2012), and this growth is expected to continue. For instance, in 2020 the city's population is expected to reach 1,012,488 inhabitants for an increase of 11 percent with respect to previous years (Savage, 2016). This population growth creates pressure on the political sphere and the construction sector to continue improving the city's infrastructure, to accommodate the rising numbers of inhabitants (Savage, 2016). And these improvements concern not only the already inefficient housing market, but also the transport sector and other key infrastructure systems vital for the city's operation.

As response of the needs for infrastructure mentioned before, numerous investments in construction, demolition and renovation (CDR) projects are ongoing in Stockholm. These projects generate massive quantities of waste material that need to be handled. For instance, construction projects happening in Stockholm generates approximately 5-15 million tons of waste per year (Dalenstam, 2015). These masses are transported almost exclusively by truck, representing about a quarter of the total volume of goods transported on Swedish roads” (Ecoloop, 2017).
That scenery depicts the problem this project is attempting to tackle. That is, that CDW are currently transported by road with its consequent impact on the environment and society, “because of its high-energy consumption, noise, congestion, infrastructure deterioration” (Ecoloop, 2017) and costs. To solve this problem, alternative solutions for transporting CDW in more economically and environmentally effective manner are on demand.

1.2. Project aim

The need of effectively transporting CDW provides an advantage for transport companies. For instance, new cost-effective solutions of waste transport can increase these companies’ market share and revenues. Furthermore, these solutions might make transport services not only more efficient, but more energy effective. “One part of these more efficient transport systems is a shift to alternative modes, where rail transport services are expected to be able to partly replace the current trucking” (Ecoloop, 2017). That is the aim of this project, to assess the best way of transporting CDW by either road or intermodal transport in terms of cost- and energy efficiency.

1.2.1. Objectives

In response to the problem definition stated previously, this study has the objective of developing a proposal for optimal transportation of CDW. This will be done by comparing different scenarios in which different transport modes will be predominant. Light into these problems come in the form of questions that serve as guide through the analysis:

- What does the situation of the CDW system currently look like?
- Which minimum technical requirements are needed when comparing the transport systems?
- Is intermodal transport more efficient than road for transporting CDW in a Stockholm context?
- Under what circumstances are rail based transport services more efficient than road based transport services?
1.2.2. Scope and limitation

The region of interest (ROI) of this project is limited to the Stockholm County. That is, because the CDW being transported are generated solely in the county, at least for what concern this project. However, the landfills in which these wastes are going to be deposit differ in location (Figure 1). In other words, the ROI comprises CDW generated in Stockholm County but the networks used for their transport and the landfills in which they are deposited comprise a bigger area. That distinction is made to separate the ROI – Stockholm county, from the study area because of the preeminence it poses for this project.

The long distances managed in this project provide a good base for comparing transport modes, but also introduce limitations on the study. For instance, the diversity of road data used for the analysis difficult the creation of a network and its further analysis. Another technological limitation of this study is the selection of the landfills and the intermodal terminals. As the data was not to be found in official sources, resulting layers are created using alternative sources, with the inherent errors it might possess.

Other limitations present in this project are those of administrative type. For example, landfills should be located close to intermodal stations, and that these stations must be operated by Green Cargo. Furthermore, these terminals must be intermodal terminals and not only wagon load terminals. These constraints significantly reduce the number of choices available for the analysis (Figure 2). There are also limitations, most of them technological, that because of their nature will be regarded as constraints in the network construction and as such not be included here.

Finally, this project does not concern with investigating the loading and unloading of waste in pre- and post- haulage stages. However, it does consider handling time at intermodal terminals. Furthermore, the analysis is only concerned with the transport of waste resulting from construction and demolition projects around Stockholm.
Figure 1: Location of the study area and the region of interest (ROI)
1.3. Method

The methodology of this study is of an empirical nature, but using both descriptive and explanatory methods for analyzing the results and arriving to conclusions. Another way of generally categorize the methodology used in this study, is by the stages in which it was divided (Figure 3). That is, the study background, the theoretical framework and the case study unfolding. In general, the methodology followed in this study looked at the transport of CDW in Stockholm County. For it, intermodal rail based transport services were compared with road transport -the main services used for transporting CDW now days, to state the effectiveness in terms of costs and emissions of intermodal transport over unimodal road services.
In the first stage, the study background, the project was conceptually constructed. In it, the problematization of the project was stated, along with the aim, objectives and the methodology used. These topics responded to why, how and what was done to fulfill the project objectives. Furthermore, the study area and ROI, along with the project limitations and importance were stated using mainly literature review.

The second stage of the project, the theoretical framework, served as a base to link the study background with the analysis and results. That is, because of the analysis of diverse concepts that helped with understanding what had to be done and why. For instance, the conceptualization of CDW with which this stage begun, served for understanding the nature of the goods transported. It also served to confirm the analysis procedure by looking at previous international experiences in CDW transport.
Other relevant concepts were of importance when understanding the methodology rationale. For instance, the conceptualization of intermodal transport that helped with understanding the transport mode that was the core for the scenario comparison. Break-even distance on the other hand, was another important concept when analyzing intermodal and road services in relation to the operation costs per kilometer driven in each transport mode. Finally, route planning introduced the base of the network analysis. Also, routing planning helped to understand the importance of such studies in logistics and transportation.

In the final stage the case study was implemented for further scenario analysis and the subsequent transport mode proposal. This stage started with the network implementation and analysis in ArcGIS. That is, because of the geospatial nature of this project. The network analysis in ArcGIS derived from road and rail data taken from “Trafikverket”. Once the data was properly cleaned - bereft of undesired aggregates and re-projected, the network was created and the nodes – landfills, terminals and construction sites, were introduced for creating transects representing different travel alternatives. The direction of the travel was always from the construction sites – represented for this study by construction projects being carried out in KTH Royal Institute of Technology now days, to landfills in any of the transport modes and services chosen.

The landfills chosen and their geolocation (Figure 1) are the following:

- Tvätaverket in Södertalje
- Finspång in Noprköping
- Ekokmen in Örebro
- Storfors in Kristinehamn
- Forsbacka in Gävle
- Dåva in Umeå
The geospatial representation of the travel transect for each transport mode from construction sites to the landfills was not the sole result obtained from the network analysis. Their distance and travel time resulted also from there. And it is from the distance that the MCA was completed. By including the travel distance in the operations and emissions costs (OEC) data obtained from the ITCM proposed by Kordnejad (2014), the cost (SEK) and the emissions (ton) per travel, and the cost (SEK) per kilometer were obtained for each transportation mode. In this way, both the qualitative and the quantitative methods were matched for the analysis. Furthermore, the best routes for each transect were chosen for each transport service to be compared.

All this information permitted was not only to compare transport modes in terms of costs and emissions per travel, but also to compare them in terms of costs per kilometer traveled and finally compare transport modes for comparing their effectiveness when transporting CDW. That is in general, a brief description of the project reasoning, with clear omissions of relevant details that were discussed later in the analysis.

1.4. Disposition

The work in this project is portrayed around six chapters. However, for simple understanding a different classification could be used. That is, the problem definition, the theoretical framework, the analysis and the results (Figure 3).

Chapter one, the introduction, is the part in which the research problem is defined, along with the research objective, the scope and the method followed in this project.

The theoretical framework is depicted in chapter two. This chapter introduces the reader to the basic concepts of CDW and relevant aspects of intermodal transport. Chapter three on the other hand, is the recipient of the network implementation, the analysis and the relevant information from which the results derive.

The analysis of the results is addressed in chapter four, and the conclusions and recommendations for future projects are addressed in chapters five and six.
2. Theoretical framework

2.1. Construction and demolition waste

Sweden generated circa 7.7 million tons (MT) of CDW in 2012, a decrease of 1.7 MT in comparison with 2012 when 9.4 MT were generated. Both hazardous and non-hazardous wastes experienced a decrease in 2012 with respect to previous year (Table 1) and the Swedish Environmental Protection Agency (SEPA) plans, in its Waste Management Plan (WMP) for 2012-2017, to reduce CDW waste even further by 2020. Nonetheless, all human activity generates waste and construction is not different regardless the effort for increase efficiency and thus decrease waste generation. Such wastes must be transported for either recycling or deposition, and nowadays most of that transport is carried by truck, an environmentally inefficient way of transporting low value goods (EC, 2015).

<table>
<thead>
<tr>
<th>Waste category</th>
<th>2010 (MT)</th>
<th>2012 (MT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-hazardous CDW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CDW from buildings</td>
<td>1.24</td>
<td>1.20</td>
</tr>
<tr>
<td>Soils</td>
<td>4.00</td>
<td>3.50</td>
</tr>
<tr>
<td>Dredging spoils</td>
<td>3.50</td>
<td>2.07</td>
</tr>
<tr>
<td>Hazardous waste</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CDW from buildings</td>
<td>0.19</td>
<td>0.17</td>
</tr>
<tr>
<td>Soils</td>
<td>0.45</td>
<td>0.72</td>
</tr>
<tr>
<td>Dredging spoils</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>9.38</td>
<td>7.67</td>
</tr>
</tbody>
</table>

*Table 1: Breakdown on CDW (EC, 2015)*

2.1.1. Definition

Waste is defined as any substance or object which the holder discards or intends or is required to discard. This definition is covered by the “Directive 2008/98/ec of the European parliament and of the council of 19 November 2008”, article tree, paragraph one. But also in the Swedish Environmental Code “Miljöbalken” in chapter 15 (EC, 2015).

As for CDW, there is not clear differentiation of what is construction or demolition waste. Both types of waste are grouped as a class and “defined according LoW 17xxxx entries in the Ordinance of Waste SFS 2011:927, Annex 4” (EC, 2015).
2.1.2. Classification

As mentioned before, CDW will be divided in this project into hazardous and nonhazardous for easier understanding. There are however, other classifications worth mentioning. For example, concrete, stone, metals, wood, glass, plaster, ceramic material, plastics. They can come from new construction, rebuilding or demolition projects (CRDP).

2.1.3. CDW in Stockholm

Waste management is of great importance in Sweden. So much is that they recycle nearly 98 percent of their waste and even import waste from other countries (Fredé, 2017). The country counts for waste management with modern infrastructure, a high number of recycling plants and an extensive legislation developed during the last years (Cantó, et al., 2016). However, as not all wastes can be totally recycled, there is still a need for landfills and other facilities, despite the leaning the country has towards “minimizing landfills in favor of waste-to-energy treatment plants for final disposal of waste” (Cantó, et al., 2016).

The city of Stockholm is also committed with the sorting, management and recycling of wastes. That is, to meet the national requirements regarding resource consumption and environmental impacts imposed by the Environmental Code. In the case of construction and demolition waste, the industry has voluntarily committed itself to recovering 50 percent of the wastes generated, and to lower transport costs and landfill charges (Stockholm Vatten, 2016).

The European Comission (2015) point different actors responsible for the creation and management of construction and demolition waste in Stockholm. For instance, building and demolition companies are the ones creating the wastes. On the other hand, waste transport, sorting and treatment companies, together with incinerators and landfills, are responsible for the management and recycling of these wastes. Authorities on the other hand, are responsible for policy making and monitoring the activity both in the phase of creation, but also during transport and recycling.
A big part of construction and demolition wastes can be recycled, but a small percent of these wastes requires other kind of treatment, especially waste belonging to the hazardous category, for example, materials containing environmentally hazardous substances that must be transported by an approved carrier, to a landfill (Stockholm Vatten, 2016). Recyclable materials on the other hand can just be transported to recycling plants.

As for the case of excavated materials in the city of Stockholm, masses are dug up either to landfill or for reuse depending on the degree of pollution and the disposal possibilities. If the pollutant content exceeds certain target values, the masses are classified as hazardous waste. Some masses are even used for filling jobs in construction projects or deposited on shaft pits if there is no other disposal opportunity (Stockholm Vatten, 2016).

### 2.1.4. International experience

When evaluating why intermodal transport would have higher profitability over other transport modes there are not only economic variables to consider. In fact, environmental and social variables play an important role in these calculations. For instance, cost like carbon emissions, energy consumption and cost for society with decreasing risk for traffic accidents and traffic congestion are variables that make intermodal a more efficient choice.

When managing high flows and long transport distances, railway and waterway transport services are the most environmentally friendly and cost-effective options (Cantó, o.a., 2016). United States of America (USA) is the perfect broth for practically prove this statement, in the sense that throughout the country there are many examples in which rail based transport have made the difference. Firstly, the shipping of 510 thousand tons per year of waste to the state of Oregon, around 500 kilometers far away (StattleGovernment, n.d.).

Secondly, multimodal railway transport will be used to deliver waste from Imperial County to Los Angeles County (LASCD, n.d.). The amount that will be transported by train once a day is equivalent of 182 long-haul trucks and therefore the change to multimodal railway transport reduces the amount of organic gases by 90 percent (Cantó, et al., 2016).
Finally, USA seems to prefer the landfill deposition instead of incineration, which is proven to be more inefficient and costly both financially and environmentally. However, the good news is that USA seems to be shifting from road based waste transport systems to rail base transport systems, making the whole industry more cost effective and environmentally friendly (Richardson, 2015).

The map of waste transport in Europe is vastly different than in USA. For instance, the United Kingdom (UK) is a good example of the difference between USA and Europe. However, what makes UK an interesting case are the similarities it has with Sweden, rather than its differences with USA. For instance, both rail and waterways are used for waste transport and multimodal services carry over 315 thousand tons of waste per year (SITA, n.d.). Just by rail, more than 790 thousand tons of waste was transported in 2005 (Browne, et al., 2007).

France on the other hand, is closer to Swedish standards and policy than the UK. For instance, both countries comply with European Union Directives, promote CO2 emissions and traffic congestion reduction in populated areas and both encourage a shifting to multimodal transport services (Cantó, et al., 2016). Furthermore, in Paris the Monoprix logistic chain is based on the use of multimodal transport services in urban areas as a substitute of rucks transport. Thus, there has been a reduction of the traffic congestion and the dependency on road transport, despite the raise in costs (SNCF, n.d.).

In general, it seems there is a shift towards rail based transport services and multimodal transport in general instead of truck services or unimodal transport. In it, intermodal seems to gain preeminence over other transport modes when transporting freight. That shift however, is observed mostly in industrialized countries -in what concerns this study- like European countries and USA. Thus, there is no possibility of stating a global shift towards multimodal. For that, other economic and geopolitical condition should be analyzed. For instance, the case of transport in Africa, Latin-America, India and South-East Asia among other examples.
2.2. Intermodal transport

Kim (2005) refers to intermodal transportation as the transport from origin to destination by a sequence of at least two transportation modes (Figure 4). Road and rail transport are the modes that concern this project, and the transfer between them is executed at an intermodal terminal (Figure 5). Thus, the advantages from both modes are exploited, achieving lower operation costs and better prices and sustainability (Figure 6). As we can see, intermodal transport seems to be practical for long-distance transport; road transport provides accessibility and flexibility, while rail transport has lower unit cost and high capacity (Zhu, 2012).

Despite all the advantages already shown, at a regional scale, using intermodal transport has some drawbacks. Firstly, the difference in total cost between intermodal and unimodal transport when changing transport modes. Secondly, investment on infrastructure and human labor required in intermodal terminals increase costs. Thirdly, the cooperation between different transport operators need in intermodal transport may complicate the whole transport chain. Finally, the increased sensitivity of intermodal transport towards policy change when the number of modes increases, so will the sensitivity (Zhu, 2012).

Figure 4: Scope of unimodal- and multimodal-operations, transshipment and unit loads (Kordnejad, 2016).
2.3. Break-even distance

Cost, time and distance are the most important factors when choosing transportation mode. However, there are other factors qualitative worth considering. For instance, reliability, punctuality, flexibility and frequency, but these are less relevant compare to the quantitative ones for this study (Vasilevskaya, 2016).
Break-even distance (BED) (Figure 7) is an important concept for evaluating and estimating the feasibility for intermodal freight transport systems. Usually, intermodal has higher costs and transportation times than road, nullifying the comparison. However, break-even distance creates a common frame in which both modes can be compared (Vasilevskaya, 2016).

![Figure 7: Cost structure for intermodal transport and break-even distance (Kim, o.a., 2011)](image)

Different authors have different approaches to the term. Rutten (1995) compare different transport modes in search for the optimal break-even distance, that he defines as the “distance at which the costs of intermodal transport equal to the costs of truck-only transport”. Other authors, inspired in Rutten’s and Johan Woxenius work, also attempt to determine the optimal BED. For example, both (Cantó & Escolano, 2016; Vasilevskaya, 2016) state a BED of around 300 km. The first of these authors however, state this distance related to the optimal transport of waste, which is consonance with this project. And going even further, Cantó & Escolano (2016) also state that considering external factors can make intermodal feasible in short distances, e.g. between the 2-60 km.
Technological improvements might help shorten break-even distance. For instance, improvements in rail operation, efficiency, utilization of train space and length, transshipment technology, terminal location and operational price decreases (Vasilevskaya, 2016). Some state that different policy making approaches might help decrease break even distance. For example, by introducing distance-based taxation which would increase long-distance truck costs. However, even the fact that any method used for decreasing break-even distance is valid, technological improvement seems to be more efficient for achieving a real decrease in break-even distance. In it, decreasing terminal handling costs is of great importance.

2.4. Route planning

Route planning is one of the analysis in which this project is based. That is, because the cost and analyzes being implemented are based on routes created for each one of the transport modes being evaluated. In this phase, some theoretical background for routing and a plan of the routing that will be used in the analysis will be presented.

The best route planning could save the delivery time, cut labor cost and transport cost, avoid any delay and traffic jam, and control the transport risk. Today, there are already many solutions for route planning, like real-time route planning. For an important element in supply chain planning, most of the time, route planning will be integrated with Enterprise Resource Planning (ERP), Customer services and Inventory control (Zhu, 2012).

2.4.1 Travelling Salesman Problem (TSP)

This problem, popular in the combinatorial optimization field was first proposed in 1930 (Goyal, 2010). Recently, it has been applied on vehicle routing and engineering optimization in the form of story problem. In it, given a list of cities and their pairwise distances, the task aims to find the shortest potential route which exactly visits each city once and finally returns to the starting city (Larrañaga, et al., 1999).
When analyzing the TSP in two-dimensions, the resulting algorithms can be divided in exact and approximation algorithms. For instance, exact algorithms can accurately obtain the global optimal solution, but at the expense of computing power. In contrast, approximation algorithms can get approximately optimal solutions in a reasonable time in general (Chen, et al., 2016).

### 2.4.2. Vehicle Routing Problem (VRP)

Since its appearance in 1959, VRP has become an important problem in logistics and distribution (Dantzig, et al., 1959). Unlike the TSP, the VRP is “a more realistic description of route planning”. However, it has the same principle as TSP. In general, the problem can be understood as a multi-TSP problem where there are one or several TSP routes in a delivering plan and every truck has the same departure and destination (Zhu, 2012). That is the case of this project, in which the starting point -KTH for road and intermodal transport and Tomteboda for rail transport (Figure 1)- is the same but the destinations vary in location as described in the routing section.

In general, there could be multiple routes for thousands of collecting points with diverse delivery time and capacity constraints (Zhu, 2012). However, for simplification, only the best routes were chosen for further analysis.
3. Case study: CDW transport in Stockholm

3.1. Conceptual implementation of the network

The transport network is generally shaped, as previously discussed, by nodes connected by edges formed by the geospatial representation of road- and rail-transport services (Figure 5). Geometrically, the network has a pyramidal shape, with its top represented by the construction sites. These, to facilitate the analysis, are depicted as cartographic symbols out of scale representing the construction projects being carried out in KTH premises. That is the beginning of all shipments being send from Stockholm for deposition on the landfills.

The base of the network is portrayed by the landfills in which the CDW are to be deposited and both rail and road edges represent the ways of transportation and the connection between the ends of the pyramid. In the case of road services that is the way in which the network in conformed, because only road transport in participating in the transport.

The intermodal transport component of the network on the other hand, has a more elaborated shape. Both the top and the base of the pyramid are represented by the same element, and road transport is still used for transporting wastes from the initial stage to the landfills. However, for long distance travel road is supplanted by rail transport services, and intermodal terminals were used for connecting road and rail transport services.

All elements of the network analysis were chosen considering places that had connection to Green Cargo operated facilities. For instance, most intermodal terminals used were operated by Green cargo and the landfills used in this study are located on a reasonable distance (< 40 Km) from these terminals. That supposed a limitation of the network elements used (Figure 2) and the number of possible outcomes.

This conceptual implementation however, had to be put in practice but before that, some technological considerations concerning each transport mode had to me made.
3.2. Transport mode choice

There are at least two transport modes this project considers for CDW transport, road transport -unimodal- or intermodal transport. However, maritime transport services would also be a valid choice, if continuous data for its analysis could be provided.

Intermodal transport is the preferred choice for this project because of the large quantity of goods that rail services can transport at lower costs than its counterparts (Zhu, 2012). Furthermore, an environmental approximation to the difference in cost of the transport modes mentioned before might lighten their difference when estimating external costs for different transport modes.

One element that is common to both transport modes, in what concerns this project, is the standard packaging unit in which CDW are to be loaded for transportation. That is, technologies equivalent to modern ISO containers which are based on lift-on/lift-off (LoLo) or roll-on/roll-off (RoRo) systems and standards. Its benefits vary, among other factors, depending on the transport mode combinations used. For instance, the benefits of LoLo systems in comparison with its RoRo counterparts “are both of economic and ecological” (Mateo, 2014). However, the decision between systems depends on each project. Furthermore, LoLo systems seems to be less expensive and with lower CO\textsubscript{2} emissions when they are “included in a logistics chain that integrates rail transport and concerns high-volume cargo” (Mateo, 2014). Both systems are oriented to “lowering transportation costs” (Vasilevskaya, 2016), but LoLo systems has higher load capacity (Mateo, 2014), reason for which they are chosen for containerization in this project.

In this project, 20’ and 40’ dry cargo containers (Figure 8B) with standard characteristics (Table 2) are proposed for transporting CDW, but the analysis will be performed solely in 20’ containers for simplifying the analysis.

Other technologies of importance for this project are swap bodies (Figure 8A), that along with containers are the best choice for both rail and truck CDW transportation. However, semitrailers are also worth mentioning despite its increased weight in comparison with containers and swap bodies.
### Table 2: Container dimensions (ShippingContainers24, n.d) & (Maersk, n.d)

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>20'</th>
<th>40'</th>
<th>45'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>6,06</td>
<td>5,87</td>
<td>12,19</td>
</tr>
<tr>
<td>Width (m)</td>
<td>2,44</td>
<td>2,33</td>
<td>2,44</td>
</tr>
<tr>
<td>Height (m)</td>
<td>2,59</td>
<td>2,35</td>
<td>2,59</td>
</tr>
<tr>
<td>Door Width (m)</td>
<td>2,28</td>
<td>2,28</td>
<td>2,28</td>
</tr>
<tr>
<td>Door Height (m)</td>
<td>2,26</td>
<td>2,26</td>
<td>2,26</td>
</tr>
<tr>
<td>Floor Area (m²)</td>
<td>13,93</td>
<td>28,33</td>
<td>31,88</td>
</tr>
<tr>
<td>Volume (m³)</td>
<td>32,85</td>
<td>66,83</td>
<td>86,1</td>
</tr>
<tr>
<td>Gross weight (ton)</td>
<td>30,48</td>
<td>32,55</td>
<td>32,5</td>
</tr>
<tr>
<td>Tare weight (ton)</td>
<td>2,44</td>
<td>4,06</td>
<td>4,6</td>
</tr>
<tr>
<td>Payload (ton)</td>
<td>28,20</td>
<td>28,80</td>
<td>27,6</td>
</tr>
</tbody>
</table>

**Figure 8:** Types of unit loads. From left to right: Swap bodies (A), Open top containers (B) and Minor capacity containers (C) (Panav, 2017) (ShippingContainers24, n.d) & (Sortera, n.d)

### 3.2.1. Rail services

Rail transport services are chosen, as said, using Green Cargo terminals geolocation as base. That is, because this project focuses in using the advantages that the rail component of intermodal transport provides in comparison with unimodal road transport. Green Cargo is the biggest goods transport operator in Sweden with its roots in the origin of the national rail traffic. The company’s daily goods flow in the national territory is of 400 trains, the equivalent to 10,000 trucking or a caravan with trucks over 30 miles long. Furthermore, Green Cargo offers eco-labeled door-to-door transport both the national territory and throughout Europe through the numerous company partners (GreenCargo, 2014).
In general, the standard train dimensions in which this project based its calculations were of a 607 meters' train, with 22 wagons and operating in a maximum distance per travel of 703 Km. Thus, such train has a maximum capacity of 88 TEU at 100% loading factor. However, this project assumed that trains might run in average at 80% loading factor, which is equivalent to 70 TEU, 770 Euro Pallets, 210 Semi-trailers (ST) or 115 Swap-bodies (SB). Thus, obtaining a standard measure that allowed comparing road and intermodal transport.

As standard packaging units are essential for loading and transporting CDW by road, the type of locomotives and wagons are the technological drives for transporting them by rail. In this context, dissimilar types of intermodal railcars and wagons of the S type were proposed to be used. They are suitable for carrying 20', 40' and 45' ISO containers (AstraRail, 2017), but also for transporting ST and SB. Locomotive types are not mentioned here, because the cost estimations already included locomotive types.

Four basic models were considered as base for intermodal wagons (Table 3). For example, the Sgnss 60', the Sggmrss 90' or the Sffggmrrss; all models are used by Green Cargo. However, the cost calculations for rail transport were based on Sggrss 80' (Figure 9), composed by two interconnected wagons united by three bogies to form a six-axel articulated intermodal wagon (AstraRail, 2017). This choice obeys to the need of a standardized measure that makes rail and road transport comparable. With the train dimensions already mentioned, 22 wagons of the type Sggrss 80' can carry 88 ISO containers of 20'. That is the equivalent to 44 trucks, but more detail of the truck technical characteristics will be provided later.

\[^{1}\text{Twenty Foot Equivalent Units}\]
Other intermodal wagons with dimensions and characteristics fit the one mentioned above can also be used. For instance, Sdgms, Sdgms T2000, Sdgmrss TWIN, Sgnss, Sgnss-v and Lgs-x (GreenCargo, 2014). Furthermore, as the selected wagons, these wagons have a maximum load of 22.5 Ton but their peak performance is reached at 20 TON. These wagons also support ISO containers of 20’, 40’ and 45’. Sgnss-v and Lgs-x wagons on the other hand are suitable for transporting the minor capacity containers (Figure 8 C).
3.2.2. Road services

Road transport services follow the structure of rail in the sense as for a single road trip, the total amount on trucks and/or tractors had to carry the equivalent of the 607 meters' train carrying 22 wagons of the Sggrss 80’ type. The difference is however, the technologies used for aiding their transport across the road network. This project assumed, considering the standard packaging units mentioned above, that road transport would be based on a truck that carries either a container, a ST or a SB depending on the supporting technologies and the combination used (Figure 10).

![Figure 10: Trucks combination (Kordnejad, 2016)](image)

The trucks can come with or without crane (Figure 11) that support loading and unloading in construction sites and landfills. In this this case however, the preferred choice was trucks with crane to reduce costs at construction sites and landfills. The combination in which trucks could appear was dependent not only on the type of truck, but also on the connection technologies used. This project based the truck analysis on the EU standard (Figure 10), that would result in 44 trucks at for every 607 meters’ train.
Other technologies mentioned before are SB (Figure 8A & 10), “a special kind of containers used mostly in Europe” (Smita, 2016). This kind of containers are “not standardized, but useful all the same” (Smita, 2016). They are provided with a strong bottom and a convertible top making them suitable for shipping of many types of products. But what makes them interesting in this case is their use in intermodal transport. See containers with lower payload (Table 4). The reason for taking them in consideration is their higher manoeuvrability. The cons on the other hand, are the lower payload that might increase transport costs in both rail and truck modes.

For transporting containers by road, diverse types of trailers are proposed (Figure 12). Trailers “dimensions and capacity (Table 5) may vary depending on their manufacture” (DSV, n.d), but in general they fit both road and rail transport. Furthermore, they might come with or without aluminum side boards, curtains, and with raiseable top in some cases.
Table 4: Minor capacity containers (Sortera, n.d)

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>10 m³</th>
<th>18 m³</th>
<th>30 m³</th>
<th>30 m³ with lid</th>
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<tbody>
<tr>
<td>Width (m)</td>
<td>2.42</td>
<td>2.42</td>
<td>2.57</td>
<td>2.54</td>
</tr>
<tr>
<td>Internal Length (m)</td>
<td>4.50</td>
<td>6.00</td>
<td>6.00</td>
<td>6.00</td>
</tr>
<tr>
<td>External Length (m)</td>
<td>4.70</td>
<td>6.20</td>
<td>6.20</td>
<td>6.32</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.31</td>
<td>1.61</td>
<td>2.34</td>
<td>2.56</td>
</tr>
<tr>
<td>Payload (ton)</td>
<td>8.00</td>
<td>8.00</td>
<td>8.00</td>
<td>8.00</td>
</tr>
</tbody>
</table>

Table 5: Truck trailers (DSV, n.d)

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Open</th>
<th>Curtain</th>
<th>Trapaulin</th>
<th>Mega</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tare weight (ton)</td>
<td>6.50</td>
<td>7.20</td>
<td>7.20</td>
<td>7.20</td>
</tr>
<tr>
<td>Payload capacity (ton)</td>
<td>31.90</td>
<td>32.80</td>
<td>32.30</td>
<td>32.80</td>
</tr>
<tr>
<td>Cubic capacity (m³)</td>
<td>91.00</td>
<td>90.00</td>
<td>100.00</td>
<td></td>
</tr>
<tr>
<td>Width (m)</td>
<td>2.84</td>
<td>2.48</td>
<td>2.48</td>
<td>2.48</td>
</tr>
<tr>
<td>Height (m)</td>
<td>2.70</td>
<td>2.67</td>
<td>2.94</td>
<td></td>
</tr>
<tr>
<td>Door opening width (m)</td>
<td>2.45</td>
<td>2.46</td>
<td>2.45</td>
<td></td>
</tr>
<tr>
<td>Door opening height (m)</td>
<td>2.67</td>
<td>2.65</td>
<td>2.90</td>
<td></td>
</tr>
<tr>
<td>Side opening height (m)</td>
<td>2.65</td>
<td>2.65</td>
<td>2.87</td>
<td></td>
</tr>
</tbody>
</table>

3.2.3. Intermodal transshipment

Intermodal terminals are the connection between rail and road transport modes. They integrate transport modes together by facilitating freight movement from one mode to another. In our area of study (Figure 1), the terminals location is the base for the selection of landfills and for the network configuration. Furthermore, they also determine the technologies to be used for transshipment.
Many are the combinations of intermodal transshipment technologies available and the geographical distribution of these different technologies across Europe. In Johan Woxenius (1998) “Intermodal Transshipment Technologies – An Overview” a meticulous overview of the transshipment technologies available is presented. This study served as base for other studies of which this project is based. For instance, Kordnejad (2013; 2014 and 2016) proposed the Intermodal Transport Cost Model (ITCM), which is the base for the costs obtained in this project. Such costs, in the case of intermodal transport, are dependent on the type of terminal, as it is the transshipment technology.

Two types of intermodal terminals are relevant for this study, Conventional Terminals and Cost-efficient Small-scale terminals (CESS terminals). Conventional terminals are based on handlers and reach-stackers (Figure 13), while CESS terminals are base on forklift trucks (Kordnejad, 2014). A detailed discussion about the terminals was not in place, as only existing terminals were chosen for this study. In consequence, only transshipment technologies were taken into consideration.

Intermodal transshipment is crucial for the functioning of intermodal terminals. Changing transport mode is associated with time and cost increment, loss of efficiency and higher risk of cargo damage which all together lower the level of reliability for a potential user of the system (Vasilevskaya, 2016). However, as the CDW are of low value cargo and non-susceptible to damage, most of these risks are irrelevant.

As the core technologies of this study are oriented towards the smaller scales, crane technologies are avoided. Instead, container lift and moving vehicles (Vasilevskaya, 2016) are to be used. These technologies will provide the maximum capacity and utilization for this scale of work, but will also provide a more cost-effective terminal operation.
Container lift and moving vehicles (Figure 13)

- Empty container handler is a vehicle used for lifting, stacking and yard transportation of empty ISO containers.
- Laden container handler is a vehicle used for lifting, first row stacking and short distance yard transportation of laden ISO containers.
- Reach stacker is a lift truck used for short distances fast container transportation. Reach stackers are more flexible and have higher stacking and storage capacity compare to forklift trucks.
- Heavy forklift trucks (RoRo Forklifts) is a vehicle used for heavy-duty fork lifting and short distance transportation of container.
- Automated guided vehicle - unmanned, automated container transport vehicle used for container transportation between the harbor quay and the storage area.

![Figure 13: Transshipment machinery. Empty container handler (A.) (WRMH, 2017), Laden container handler (B.) (Direct Industry, n.d), Reach stacker (C.) (Linde, n.d.), Heavy forklift truck (D.) (Hyundai, 2016).](image)

3.3. Data collection and processing

When the network was conceptually implemented and the technological assumptions made, it was then time to prepare for the analysis. For it, data that served the purpose of this project had to be gathered and preprocessed.

The collection and analysis of the data was straight forward process. The GIS data obtained for modeling both rail and road services was obtained from Trafikverket (2016). In the preprocessing stage the road data was reduced according to speed limit, setting an average of 65 km/h in order to gain in computing time by reducing the amount of data being analyzed.
However, the information of driving directions, road classification and level - Tunnel, Bridge, Street- along with street names were also affected by the pre-processing. The rail data on the other hand, was set at an average speed limit of 80 km/h. However, this network did not count with much more information, cause of which not much preprocessing was done.

The nodes are, as previously said, comprised by the landfills, intermodal terminals and the construction sites (Figure 1). The landfills and the intermodal terminals were selected according to the project limitations. The construction sites on the other hand, are represented by construction projects currently being carried out on KTH Roral Institute of Technology premises, as representation of the projects carried out in Stockholm at the moment this study is being performed. The reason for this is that using just one origin gives the pyramidal shape, used in numerous network and classification studies that has GIS and remote sensing, as base.

In general, all GIS data was set to a common coordinate system, WGS 84. That is, because it is the same coordinate system in which the base maps obtained from ArcGis online comes. After preprocessing, a network dataser was conformed with all the data and the constraints already mentioned in which the routing was performed.

3.4. Routing

The routing in this project is made using ArcMap. That is, because as stated in Zhu (2012), ArcMap will present the real distance of each node instead of straight distance. Furthermore, it will consider the road condition, traffic situation and some geographic elements. Finally, ArcGis can handle large number of nodes with specific details showing on the map.

When the network dataser was conformed with all the data and the constraints already mentioned, an MCA was performed using the construction sites as starting point for the routing, and the landfills as destination. The routing was done for both road and intermodal transport services and from all the possible alternatives, just the best choices were selected.
For the selection, regression analysis in excel was used for determining the best combination of routes for both transport modes being analysed (Figure 1). The resulting combination of routes, according to the regression analysis, explained about 65% of the travel choices at 95% confidence. The travel distance, the variable of importance for this study, had a stronger significance \( p\text{-value} = 0.001 \) at 95% confidence than travel time; thus showing that the costs and emissions depend on the distance traveled rather than the time the travel takes.

Once the best routes were determined, the OEC information was added to the resulting paths for the analysis and the creation of the decision-making scenarios. This was done both in excel and ArcMap to facilitate further analysis and graphical representation.

### 3.5. Cost modeling and analysis

As previously said, the cost model of this analysis used data from ITCM (Table 6) stated in Kordnejad (2014, 2016). In it, the total transport cost (TTC) for a given transect is the sum of the transport services plus the terminal handling:

\[
\text{TTC} = \text{RC} + \text{HC} + \text{TC}
\]

Where:
- RC is the total cost generated by rail operations.
- HC is the total cost for road haulage.
- TC is total cost for terminal handling.

There are however, some assumptions of great importance when adapting the OEC data obtained from Kordnejad (2014, 2016) to the purpose of this study. Firstly, the units for CDW loading are the 20’ container, equal to the TEU in (Table 6). Secondly, a 607 meters long train, composed by 22 Sggrss wagons (four 20’ containers per wagon) at 80% loading factor in the base unit used for calculate the cost per transect in each transport mode and the average cost (Table 6) and the average cost per kilometer. Thirdly, the cost of road transport uses an EU standard truck with a linked trailer (Figure 11). Thus, it would require 44 trucks to even a 607 meters’ train.
Cost and emissions are obtained by combining the distance traveled, the number of Unit Loads (UL) - in this case containers, Euro Pallets or SB - and the costs/emissions per kilometer provided by the ITCM (Figure 6). The case of intermodal services, which depends on terminal transshipments, combines just either costs or emissions with UL. The resulting value is then summed to the rail transport value for representation in ArcGis or just assigned its one block when managed in excel. Once the data was properly managed and graphically represented, it was then time to proceed to scenarios analysis and results discussion.

Table 6: Cost, emissions and conversion units (Kordnejad, 2014; 2016)
14. Results

The first tangible results obtained were linked to the routing, the network analysis and the regression analysis. From them, six transects (Figure 1) were render that would, as previously said, be served as base for the scenario analysis. Other important information provided by the analysis are the length and travel time of the transects and each transport mode (Table 7).

<table>
<thead>
<tr>
<th>Transects</th>
<th>Length (km)</th>
<th>Time (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Road</td>
<td>Intermodal</td>
</tr>
<tr>
<td>Tvetaverken_KTH</td>
<td>33.45</td>
<td>49.22</td>
</tr>
<tr>
<td>Finspång_KTH</td>
<td>178.59</td>
<td>196.72</td>
</tr>
<tr>
<td>Ekomen_KTH</td>
<td>194.59</td>
<td>225.59</td>
</tr>
<tr>
<td>Storfors_KTH</td>
<td>264.02</td>
<td>322.50</td>
</tr>
<tr>
<td>Forsbacka_KTH</td>
<td>185.27</td>
<td>207.74</td>
</tr>
<tr>
<td>Dåva_KTH</td>
<td>641.46</td>
<td>721.36</td>
</tr>
</tbody>
</table>

Table 7: Transects resulting from the network analysis and the regression analysis.

These results, combined with the OEC (Table 6) provided the final elements for further scenarios analysis. From that union, the distance at which the cost of road transport services equals the cost of intermodal rail based transport (Figure 13) was obtained. That distance is coincidental with the break-even distance (Figure 7) stated previously. Both graphs are not exactly coincidental, and the one obtained in this study (Figure 13) has a slight exponential tendency, but both reach the break-even distance at 300 km. A closer look on Figure 13 shows that the average distance for pre-haulage for intermodal transport is 150 km, then rail services follows up to 600 km, finalizing with post-haulage as in Figure 5. Both pre- and post-haulage possess the same exponential growth than road services possess (Figure 13). This difference with the theoretical BED (Figure 7) is just a reflection of the constraints road services has in the network analysis.
Furthering the analysis, the results previously mentioned are divided into scenarios. So far, the analysis has versed over road- and intermodal transport services but as what has already been said, intermodal transport can be divided according to the intermodal terminal being used. Thus, three scenarios result from this division. The first scenario depicts road transport, the second scenario depicting intermodal transport using conventional terminal and the third scenario depicting intermodal transport using small scale intermodal terminal services.

Comparing costs and emissions per transect for each scenario (Figure 14 & 15), it can be seen which transects have the higher costs, and which ones are the most environmentally harmful. For example, the transport to Dåva, of around 650 km is the peak for both costs (Figure 14) and emissions (Figure 15). That is, because it greatly exceeds the break- even distance, proving that the further from this point the more the costs and the emissions rise. The transect to Tvetaverken on the other hand, has such a small distance - > 50 km, that is nearly no difference between transport services.
The costs at this point are slightly lower for road transport. But for transects near the break-even distance, the cost for road transport begin to surpass the intermodal transport. This implies disregarding the feasibility of transporting CDW at short distances proposed by Cantó & Escolano, (2016), at least in what concerns this project.

**Figure 14**: Cost per kilometer per transect for each transport mode

**Figure 15**: Emissions per kilometer per transect for each scenario
A closer analysis to each transport mode scenario showed that as previously said, costs and emissions possess a lineal positive relation with the travel distance. Road transport for example, shows an increase in cost and emissions when distances increase (Figure 16). There is however, as to road concerns, a relationship between the network constraints and the transect chosen that results in difference in costs and emissions. For example, the transect to Forsbacka possess low costs and emissions because it has a high distance to cover, but at higher speed, being a first order road. For road services, both costs and emissions are high.

The intermodal scenarios on the other hand, possess marked differences between each other and in relation with road transport (Figure14 & 15). For the second and third scenarios (Figure 17 & 18), the costs and emissions decrease in comparison with road transport. But that is not the only difference with road transport. As it can be seen, the distance traveled increase when changing to intermodal transport as a cause of the transport mode change, but the travel time decreases (Table 7).

When comparing both intermodal scenarios, some differences arise. First, despite the equal distances, both costs and emission decrease when changing types of terminals and transshipment technologies. That is, intermodal transport using conventional terminals (Figure 17) possess higher costs and emissions than it is when small scale terminals are the choice (Figure 18).

In general, intermodal transport is less costly (Figure 19) and with lower emissions (Figure 20) than road transport, but the transshipment technology used seems to have an effect in costs and emissions. As we can see, the third scenario depicting intermodal transport using small scale terminals (Figure 18) is the most suitable for transporting CDW in Stockholm.
Figure 16: Scenario #1. Road transport. Representation of both costs and emissions.
Figure 17: Scenario #2. Intermodal transport with conventional terminal.
Figure 18: Scenario 3. Intermodal transport with small scale terminal.
Figure 19: Comparing costs between scenarios
Figure 19: Comparing emissions between scenarios
5. Conclusion

In conclusion, the objectives of the project were successfully achieved. For what concern this project, the small scale intermodal terminals offer more cost-effective choice for transporting CDW than intermodal transport using conventional terminals. And that is the proposal of this study, a shift to intermodal transport for reducing costs but most of all emissions to the environment. With the existent technology, such shift can be done swiftly and at relatively low cost considering the technology already existing.

What does the situation of the CDW system currently look like?

Stockholm is a leading European capital with a strong, knowledge-based economy. Similarly, its cultural, economic and political preeminence is higher in a Nordic context. Currently, there are nearly 2 million inhabitants in the 26 municipalities in which the Stockholm County is divided, and the total population is expected to raise in coming decades. Such population increase will require a continuous development in infrastructure and housing, but also a smarter and more effective urban planning. Currently, there are over 100 construction projects planned in and around the city - all with a strong focus on sustainability and the Stockholmers of today and tomorrow. (Stockholmsstad, n.d.).

Is intermodal transport more efficient than road for transporting CDW and under what conditions?

As it has been stated throughout this project, intermodal services constitute a better choice than road when transporting these low value goods. But in short distances this difference is not so relevant. It is when reaching 200 km that intermodal services become more relevant than road services. When reaching 300 km, the equivalent to the break-even distance, the costs per kilometer of road- and intermodal transport services equals.
6. Discussion

Despite the satisfactory results, great deals need to be said about the project. First, regarding the data and the network analysis: The optimal database for such analysis would be a database that has all traffic information included from the delivering server. Also, a database that comes in the coordinate system being used which was not the case of this study. All preprocessing work might induce errors on the data being handled both of concept and geometry errors in the case of a vector database. This does also difficult the network creation just because geometry errors generally induce errors in the network. Luckily some other open source software’s like QGIS are available to sort the problem out and continue with relatively low inconvenience. The recommendation is to try choosing the best data instead of mixing different data, or take advantage of new technologies that allow online, real time geospatial analysis.

As for the cost analysis, it would have been helpful to have an understanding on how the original cost model work. In this case the data needed for this study was extracted from it, making the understanding harder of the elements of the cost model being developed.

Finally, further studies of diverse ways of transporting CDW are advised. In this study, it has been made quite a broad assumption about the parameters to use, what to focus on and what the scope of the study is. Still it has been provided insightful results but a more detailed study would help improving the knowledge of the CDW transport in a Stockholm context and it would provide a deeper understanding of the technological requirements. Furthermore, it would also serve to explore some key aspects that was not explored in this project. That is, the legal framework surrounding CDW; other alternatives as the so-called logistics centers could be explored and compared with the already existing alternatives. However, this study satisfactory provided the results expected, thus fulfilling its purpose.
References


