UNIVERSITÉ LAVAL

# ASSESSING STRATEGIES FOR REDUCING CARBON EMISSIONS ASSOCIATED WITH WOOD PRODUCTS TRANSPORTATION

**Mémoire**

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# RÉSUMÉ

Suite à la ratification par le Canada de traités de réduction des émissions de gaz à effets de serre (GES), différents paliers de gouvernement ont mis en œuvre des politiques visant la réduction des émissions industrielles et liées au transport. Depuis 2013, le Québec, conjointement avec la Californie et l’Ontario, ont mis en place un marché du carbone pour encourager les entreprises à réduire leurs émissions. L’industrie forestière, s’appuyant sur le transport de marchandises, pourrait bénéficier de ce régime en termes de prise de décision sur la planification du transport.

Cette étude vise à analyser le potentiel des stratégies de réduction des émissions de carbone et à proposer des suggestions appropriées sur la prise de décision en matière de la planification du transport. Quatre stratégies sont principalement envisagées : la réduction de la vitesse, la conduite écologique, le transport intermodal et les modes de chargement. Combinant les stratégies, des modèles d'optimisation dont l'objectif est de minimiser des coûts sont développés sous les contraintes des émissions. Ces modèles impliquent la planification de la distribution de la gestion de la chaîne d'approvisionnement et des problèmes de tournées de véhicules. Microsoft Excel, OpenSolver, Gurobi et LocalSolver sont principalement utilisés pour la modélisation et l’optimisation. Un front de Pareto est par la suite utilisé pour illustrer la relation entre le coût de transport et les émissions de carbone.

Pour démontrer les méthodologies, une étude de cas est présentée en utilisant des données réelles. Il est constaté que l'éco-conduite présente un potentiel de réduction des émissions intéressant dans une gamme réaliste d'augmentation des prix. Le choix des stratégies varie selon les préférences du décideur et la difficulté de mise en œuvre des stratégies.

# ABSTRACT

With the ratification of greenhouse gas (GHG) reduction agreements by Canada, various levels of government implemented policies to reduce transport-related and other industrial emissions. Since 2013, Québec, together with California and Ontario, has established a carbon market to encourage firms to reduce their emissions. The forest industry could benefit from this scheme in terms of improving efficiency and lessening the environmental impact of wood product transport.

This study aims to assess the potential of carbon emission reduction strategies and to provide recommendations on improving the logistics of transporting wood-based materials. There are four main strategies considered in this paper; namely low-speed driving, eco-driving, intermodal transportation, and optimizing loading pattern. By combining these strategies, optimization models are developed with the objective of cost minimization under the constraints of emissions. These models involve the distribution planning of supply chain management and routing problems. Microsoft Excel, OpenSolver, Gurobi, and LocalSolver are mainly used for modeling and optimization. Pareto Front is also used to illustrate the relationship between transportation cost and carbon emission.

To demonstrate the methodologies, a case study is exhibited using real world data. It is found that eco-driving has considerable potential in reducing emissions under a feasible range of price increases. The selection of strategies is based on the decision makers' preferences and the difficulty of strategy implementation.

# TABLE OF CONTENTS

**RÉSUMÉ** .......... **III**

**ABSTRACT** .......... **IV**

**TABLE OF CONTENTS** .......... **V**

**LIST OF TABLES** .......... **VII**

**LIST OF FIGURES** .......... **VIII**

**ACKNOWLEDGEMENTS** .......... **IX**

**CHAPTER 1. INTRODUCTION** .......... **1**

1.1 CONTEXT AND BACKGROUND .......... 1
  *1.1.1 Greenhouse gas (GHG) and carbon emissions* .......... *1*
  *1.1.2 GHG Protocol and carbon trading* .......... *3*
  *1.1.3 Impacts of freight transportation* .......... *7*
  *1.1.4 Forest industry* .......... *7*

1.2 RESEARCH PURPOSE .......... 8

1.3 STRUCTURE OF THESIS CONTENT .......... 9

**CHAPTER 2. LITERATURE REVIEW** .......... **11**

2.1 TRANSPORTATION AND DISTRIBUTION PLANNING .......... 11

2.2 STRATEGIES FOR CARBON EMISSION REDUCTION ON LOGISTICS CHAIN .......... 12
  *2.2.1 Intermodal transportation* .......... *15*
  *2.2.2 Low-speed driving* .......... *17*
  *2.2.3 Eco-driving* .......... *18*
  *2.2.4 Optimizing loading pattern* .......... *20*

2.3 APPROPRIATE MODELS TO EVALUATE REDUCTION METHODS .......... 22

**CHAPTER 3. METHODOLOGY** .......... **25**

3.1 RESEARCH PROBLEM .......... 26

3.2 DATA COLLECTION .......... 27
  *3.2.1 Intermodal transportation and logistics* .......... *28*
  *3.2.2 Low-speed driving* .......... *28*
  *3.2.3 Eco-driving* .......... *29*
  *3.2.4 Multi-product loading patterns* .......... *29*

3.3 ROUTE GENERATION USING CARBON ROADMAP .......... 30

3.4 TACTICAL TRANSPORTATION PLANNING MODELS ........ 33

*3.4.1 General description ........ 34*

*3.4.2 Model #1 using single-product loading pattern ........ 35*

*3.4.3 Models using multi-product loading patterns ........ 36*

3.5 MATHEMATICAL PROGRAMMING SOLVERS ........ 39

3.6 PARETO FRONT ........ 41

*3.6.1 ε-constraint method ........ 41*

*3.6.2 Weighted-sum method ........ 42*

**CHAPTER 4. ANALYSIS AND DISCUSSION ........ 43**

4.1 CASE STUDY ........ 43

*4.1.1 Description ........ 43*

*4.1.2 Data collection ........ 43*

*4.1.3 Optimization ........ 49*

4.2 RESULTS AND DISCUSSION ........ 51

**CHAPTER 5. CONCLUSION ........ 60**

**REFERENCE ........ 62**

**APPENDIX A. DEMANDS FROM CUSTOMERS IN CASE STUDY ........ 68**

**APPENDIX B. PRODUCTION OF MILLS IN CASE STUDY ........ 74**

**APPENDIX C. LOCATIONS OF MILLS AND CUSTOMERS ........ 75**

**APPENDIX D. RESULTS OF MODEL #1 USING SINGLE-PRODUCT LOADING PATTERNS ........ 77**

**APPENDIX E. RESULTS OF HEURISTIC MODEL #3 USING MULTI-PRODUCT LOADING PATTERNS WITH FULL SHIPMENT ........ 78**

**APPENDIX F. RESULTS OF SIMPLIFIED MODEL #4 USING MULTI-PRODUCT LOADING PATTERNS WITH FULL SHIPMENT ........ 79**

# LIST OF TABLES

**Table 2.1 Recent studies on fuel economy and carbon emission reduction resulting from speed decrease and eco-driving** ...................................................................... 19
**Table 4.1 The dimensions of lumbers in foot and maximum number of packs loaded in a 53-foot truck trailer** ........................................................................................ 44
**Table 4.2 Transportation cost and emission of routes on speed of 105 km/h on road** ........................................................................................................................ 45
**Table 4.3 Transportation cost and emission of routes on speed of 95 km/h on road** 46
**Table 4.4 Transportation cost and emission of routes with eco-driving**.................... 47
**Table 4.5 Transportation cost and emission of routes on intermodal transportation**48
**Table 4.6 Percentage of trips with each transportation mean for set #1**.................... 53
**Table 4.7 Percentage of trips with each transportation mean for set #2**.................... 54
**Table 4.8 Percentage of trips with each transportation mean for set #3**.................... 54

# LIST OF FIGURES

**Figure 1.1 Canada's GHG Emissions by Economic Sector in 2013** (Environment Canada, 2015) ..... 2
**Figure 1.2 Quebec's GHG Emissions by Economic Sector in 2013** (MDDELCC, 2016) ..... 3
**Figure 1.3 The Québec cap and trade scheme for emission allowance** (Government of Quebec, 2016) ..... 5
**Figure 3.1 Methodology with the broad types of data coming into the steps** ..... 26
**Figure 3.2 Rear-end view of a 53-ft truck trailer** ..... 30
**Figure 3.3 Display of a Carbon RoadMap layer** (Vallerant, 2013) ..... 32
**Figure 3.4 Example of Combination of lumbers in groups** ..... 39
**Figure 4.1 Pareto Front of transportation cost and emission of model #1** ..... 53
**Figure 4.2 Pareto Front of heuristic model #3 using multi-product loading patterns with full shipment of data set #1** ..... 56
**Figure 4.3 Pareto Front of simplified model #4 with multi-product loading patterns with full shipment** ..... 57
**Figure 4.4 Comparison of Pareto Front of model #1 and simplified model #4 using multi-product loading patterns** ..... 58
**Figure 4.5 Comparison of simplified and heuristic models using multi-product loading patterns** ..... 59

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# CHAPTER 1. INTRODUCTION

## 1.1 Context and background

### 1.1.1 Greenhouse gas (GHG) and carbon emissions

The greenhouse effect is caused by greenhouse gas. Gases like carbon dioxide can absorb thermal energy and prevent solar radiation from reflecting off the atmosphere, resulting in increased temperatures on the earth's surface and lower atmosphere. Without this effect, the average temperature of earth's surface would decrease below the freezing point of water. On the contrary, if the greenhouse effect were to be more pronounced, global temperature would continue to increase year by year. Ultimately, it would worsen the ecological environment and change global climate by causing climate anomalies, sea-level rise, and an increase of arid land (Intergovernmental Panel on Climate Change, 2013).

The greenhouse gases (GHGs) are mainly composed of water vapour ($H_2O$), carbon dioxide ($CO_2$), methane ($CH_4$), and ozone ($O_3$), which contribute to roughly 36-70%, 9-26%, 4-9% and 3-7% of the greenhouse effect respectively on the earth's surface (Ram, 2014). In addition, there are some other secondary GHGs such as nitrous oxide ($NO_x$), sulfur hexafluoride ($SF_6$), hydrofluorocarbons (HFCs), perfluorocarbons (PFC), and chlorofluorocarbons (CFCs) that also play a role in influencing the greenhouse effect, Although the global-warming potential (an indicator to represent the capacity of gases to contribute to the greenhouse effect) of these aforementioned gases is higher than that of carbon dioxide, their concentrations in atmosphere are not considerable. While $H_2O$ is one key component of GHGs, its unique properties allow it to convert to different states in atmospheric circulation, and thus the content of water vapour in the atmosphere keeps balanced stability. However, $CO_2$, along with concentrations of other GHGs, are heavily affected by human activities (MacRae, Cuddeford, Young, & Matsubuchi-Shaw, 2013). It is therefore imperative to reduce the quantity of carbon emissions for mitigating greenhouse effect by adapting human activities (Solomon, Qin, & Manning, 2007). For this reason, the concentration of $CO_2$ is set as the standard unit for measurement of the overall greenhouse effect, which is called carbon dioxide equivalent ($CO_2$ eq.).

From 1990 to 2011, the global GHG emissions increased by 42%. In the year of 2012, Canada's gross emissions, having risen by 25.5% compared to those in 1990, accounted for 1.6% of the global GHG emissions (U.S. EPA, 2006). According to statistics in 2013, when analyzing emissions by economic sector, it was found that transportation was the second largest contributor to Canada's GHG emissions, which accounted for 23% of total emissions. The other key segments were oil and gas (25%), electricity (12%), buildings (12%), emissions-intensive and trade-exposed industries (11%), agriculture (10%), as well as waste and others (7%) (See Figure 1.1) (Environment Canada, 2015).

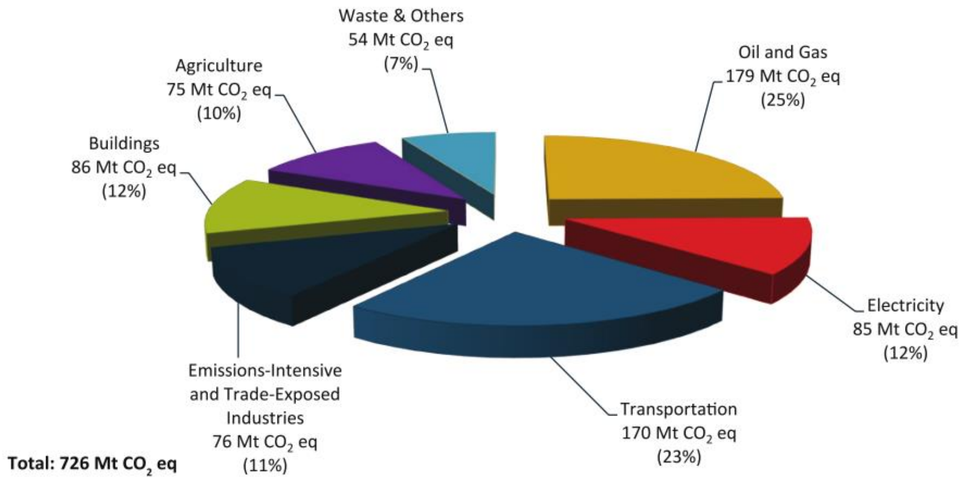


**Figure 1.1 Canada's GHG Emissions by Economic Sector in 2013** (Environment Canada, 2015)

Correspondingly, transportation made up 43% of total GHG emissions in the province of Quebec in 2013. Moreover, industry (30.8%), residential, commercial and institutional emissions (9.5%), agriculture (9.2%), waste (7.2%) and electricity (0.3%) were also key contributors to GHG emissions (see Figure 1.2) (MDDELCC, 2016).

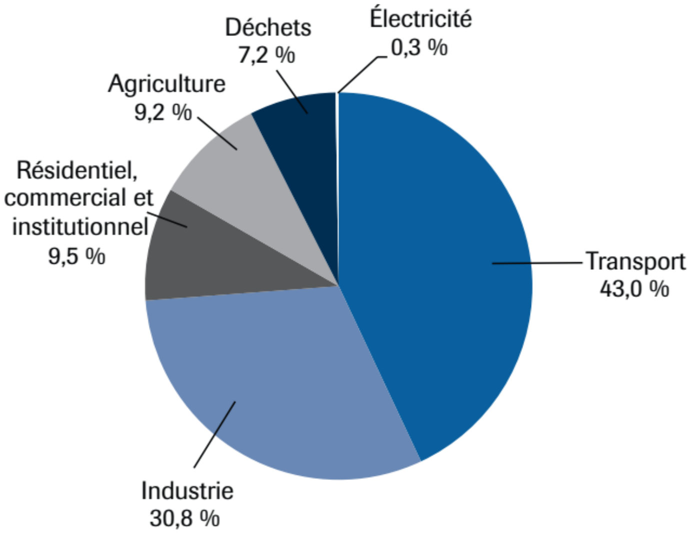


**Figure 1.2 Quebec's GHG Emissions by Economic Sector in 2013** (MDDELCC, 2016)

### 1.1.2 GHG Protocol and carbon trading

In 1997, the Kyoto Protocol was signed as the supplementary provision of United Nations Framework Convention on Climate Change (UNFCCC) in Kyoto, Japan. This protocol aimed to stabilize the concentration of GHGs in the atmosphere at an appropriate level in order to prevent dramatic climate change. Having signed the Kyoto Protocol, Canada pledged to cut down on its GHG emissions to 94% of 1990 levels (461 Megatons) between 2008 and 2012. Although Canada declared to withdraw from this protocol in 2011, it indicated a significant attempt for Canada to reduce GHG emissions. Furthermore, in Quebec, the government promised that it would achieve the goal of curtailing GHG emissions by 20% by and 30% by 2030 compared to the level of GHG emissions in 1990 (MDDELCC, 2015).

A new type of market for trading allowances of carbon emissions has recently been put in place by governments known to many as the carbon market. The cap and trade allowance scheme is an environmental policy instrument aimed to conserve energy and reduce emissions. It aims to encourage firms or individuals to reduce business carbon emissions and to invest and innovate in clean technologies for achieving environmental protection goals (Groenenberg & Blok, 2002). When a cap and trade system is implemented, the government sets a binding limit (called a “cap”) each year and distributes an emission allowance for each market participant in the system, meaning that a certain amount of free carbon credits is allocated to participants. Moreover, emission allowances could be collected from offset credits of unregulated emissions and early reductions credits. In order to reduce overall emissions, the allocated allowance of each participant is reduced each year by a certain percentage (Grubb, 2012).

In 2012, Quebec’s cap and trade system was published, which was formally linked with California’s system on 1st January 2014, becoming the largest carbon market in North America. In the cap and trade system, market participants that emit 25,000 tons or more of $CO_2$ eq. per year are regulated. For the first compliance period (2013-2014), only the industrial and electricity sectors are subject to the system. Fossil fuel distributors are also included in the system during the second and third compliance period (2015-2017 and 2018-2020). As of today, 132 entities or qualified bidders have joined in this cap and trade system. Overall, GHG emissions by sector include stationary combustion, transport, industrial processed solvent and other product use, and agriculture and waste (International Carbon Action Partnership, 2017a). At the end of each compliance period, all covered emitters should have enough allowance to cover their reported or audited GHG emissions. As shown in Figure 1.3, if the quantity of carbon emitted by the participant exceeds its allowance, the emitter ought to pay for the exceeded emissions by auctioning from governments or by purchasing from other companies. On the contrary, it can sell its surplus carbon emissions credits to other participants in the carbon market (Gouvernement du Quebec, 2014). Therefore, covered emitters should make trade-offs between the cost of purchasing their extra carbon emissions and the cost of improvement of production and transportation processes for reducing their carbon emissions (Flachsland, Marschinski, & Edenhofer, 2009).

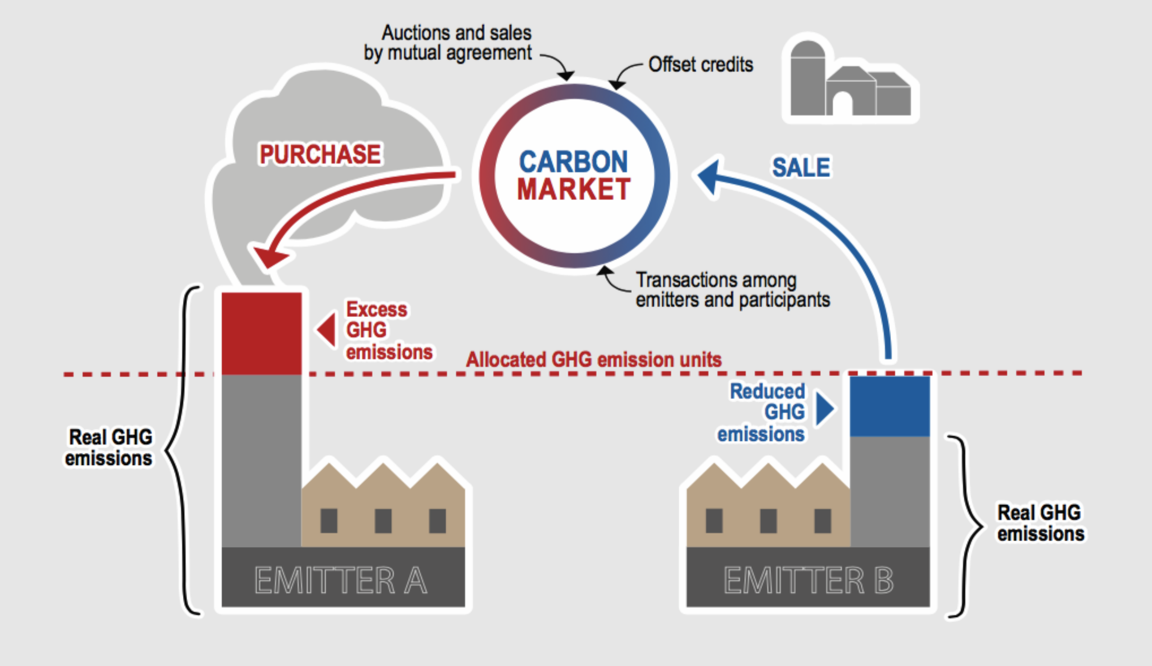


**Figure 1.3 The Québec cap and trade scheme for emission allowance** (Government of Quebec, 2016)

To establish this system, carbon emissions should be calculated based on a unified standard such as GHG protocol. GHG Protocol was established in 1998 and published in 2001 by World Resources Institutes and World Business Council for Sustainable Development, aiming to provide standards of counting and reporting GHG emissions for business so that firms or countries could use this protocol to set a target of GHG reduction (Schmitz et al., 2004).

When calculating GHG emissions, the firm must also take into consideration its operational boundaries. It should choose scopes for identifying emissions with its operations in order to avoid double counting. These scopes are classified by direct GHG emissions (Scope 1), electricity indirect emissions (Scope 2) and other indirect GHG emissions (Scope 3). Direct GHG emissions refer to GHG emitted by operations owned or controlled directly by the firm, such as fuel combustion on transportation (i.e. company-controlled vehicle fleet) and production procedures on equipment. Scope 2 refers to indirect emissions from purchased or consumed electricity. These two scopes must be counted and reported by companies. Scope 3 refers to other indirect GHG emissions such as extraction and transportation of raw materials. This scope enables GHG emissions generated upstream and downstream to be accounted for. Furthermore, it provides firms with standards to assess and choose supply chain partners, as firms could reasonably distribute limited sources by a better understanding of indirect emissions to effectively achieve emission reduction targets and maximize returns on investment.

For participants of cap and trade system in Quebec and California, Scope 1 and Scope 2 are used to calculate carbon emissions in order to summarize the quantity of carbon trade. A firm should first identify sources of GHG emissions within Scope 1, such as stationary combustion, mobile combustion, process emissions and fugitive emissions. For the forest industries, process emissions primarily indicate emissions from the production of pulp and paper. If they own or operate vehicle fleets, emissions from mobile combustion should be reported and paid. Then the firm should identify sources of indirect emissions from the consumption of purchased electricity, heat, and steam, which are covered by Scope 2. Finally, these emissions are estimated by selected calculation approaches indicated in GHG Protocol and summed up and reported to cooperate level (Schmitz et al., 2004). In terms of fuel consumption in cap and trade system, fuel suppliers who sell more than 200 litres of fuel per year are not given allowances free of charge and need to purchase them at auction or from the carbon market, while fuel consumers such as carriers can calculate their GHG emissions covered by Scope 2 and offset or trade them in the market (Government of Quebec, 2016).

### 1.1.3 Impacts of freight transportation

As mentioned earlier in the paper, the transportation sector, as the second largest contributor behind the oil and gas sector, comprised 23% of total GHG emissions in Canada in 2013 (Environment Canada, 2015). This category encompasses both passenger and freight transportation. Freight transportation can be further subdivided into five sectors: on-road heavy trucking, off-road, marine, rail, and intermodal. In 2008, the first four segments contributed 70%, 11%, 11% and 8% respectively to GHG emissions within the freight transportation sector in Canada (Sustainable Development Technology Canada, 2009). The report also indicates that GHG emissions increased by 12.6% in industrial freight transportation from 2002 to 2006, with heavy trucks being a principal cause of the increase (ibid.). Furthermore, statistical records for 2006 showed that industrial transportation accounted for 12.1% of total end-use energy in Canada (ibid.). For Canada to meet its commitments toward emissions reductions, a thorough investigation on reducing GHG emissions in the context of freight transportation remains of utmost significance.

### 1.1.4 Forest industry

In 2013, 12% of Canada's manufacturing GDP was attributed to the forest products industry (Eds, 2015). There is great potential in reducing the future carbon footprint of the forest industry due to the rapidly expanding market of wood products, especially for construction materials. Compared to cement or concrete, wooden materials are more environmental friendly, as the production and operation of wood products emit less carbon (Börjesson &

Gustavsson, 2000; Gustavsson, Pingoud, & Sathre, 2006). Moreover, the wooden buildings can be recyclable and less energy intensive (Gao, Ariyama, Ojima, & Meier, 2001).

In addition, the regional shipping of forest products is reliant on heavy-duty truck and rail transport. Research has shown that the forest products industry is one of the largest freight rail users along with coal, mining and chemical industries, and the forest industry alone accounts for about 20% of total annual revenue generated by the Canadian National Railway Company (CN) and 5% revenue for the Canadian Pacific Railway (CP) (Forest Products Association of CANADA, 2010). The forest products industry is proven to be one of the most significant industrial users of the surface transportation system in Canada (ibid.).

Given primary resource industries' dependence on freight transportation, coupled with the new policy of carbon trade in Québec, it is crucial for companies within the Québec forest products industry to consider the adverse ecological impacts associated with freight transportation, which should be calculated and classified under the aforementioned Scope 2 or Scope 3 (provided that the company does not use its owned vehicle fleets but rather subcontracts to other carriers) based on the GHG Protocol. The forest industry sector's largest emitters, pulp and paper mills, are covered in the cap and trade system as they own their sawmills, and thus there is an opportunity to conduct enterprise-wide reduction (Gouvernement du Quebec, 2014).

## 1.2 Research purpose

Environmental problems are emerging with the development of global industries and market economy, as well as concerns regarding current regulations of carbon emissions in mitigating the greenhouse effect. The carbon-trading scheme implemented in Quebec from

2013 onwards has proven to be one of the most effective ways in the province's mitigation efforts. The forest products industry contributes a substantial quantity of carbon emission, both directly and indirectly through its use of freight transportation services. As a result, we must examine the potential for GHG emissions reductions through improving freight transportation services, which in turn would benefit firms according to the carbon trading allowance scheme.

This study concentrates on the analysis of potential strategies for carbon emissions reduction by conducting transportation cost optimization under the implementation of the cap and trade system for GHG emissions in the value chain of the Quebec forest products industry. It aims at proposing feasible methods of reducing carbon emissions associated with supply chain and transportation activities and allowing firms to benefit from Quebec's cap and trade scheme to the fullest extent. There are various reduction methods in regards to freight transportation activities having been proposed and elaborated in the existing literature. Four appropriate and potential methods to decrease carbon emissions in the logistics chain of the forest products industry, specifically pertaining to transportation, are discussed in this study. A case study is explored in this study by implementing optimization models for supply routes around Lac Saint-Jean in Quebec. Potential emission reductions are then calculated and compared. The methods are evaluated based on the cost of implementation and the potential carbon reduction.

## 1.3 Structure of thesis content

This document consists of five parts. Chapter 1 is designed to provide some context to the application of the cap and trade scheme in forest industry companies regarding transportation planning. Chapter 2 provides a summary of recent studies in green freight transportation and related methods of emissions reduction in supply chains, and will also delve into various tools and models to assess GHG emissions. Chapter 3 will follow by investigating approaches for developing optimization models to provide a transportation plan taking into account the new carbon trade rules. Chapter 4 presents a case study to explain and discuss potential emission reduction strategies. Finally, the thesis concludes with Chapter 5, summarizing major findings as well as limitations that would benefit from future research.

# CHAPTER 2. LITERATURE REVIEW

With unprecedented growth in international trade and commerce in recent years, demand in freight transport has been noticeably increasing. However, the environmental ramifications of choosing freight cannot be neglected. A number of studies have taken green freight transportation into consideration, which aims to minimize emissions to the greatest extent while making transportation cost-effective. It is worth noting that as the predominant component of GHG, $CO_2$ is in direct proportion to fuel consumption, thus fuel-saving issues are pertinent when creating solutions to reduce emissions (ICF Consulting, 2006). The following literature review is focused solely on three aspects: the transportation planning framework within the logistics chain; methods or strategies for fuel efficiency improvement in addition to carbon emission reduction; and models and approaches to estimating the emission reduction.

## 2.1 Transportation and Distribution Planning

Transportation plays a crucial role in the logistics chain, facilitating the movement of materials from the supplier to the client (Tseng, Yue, & Taylor, 2005). The distribution and transportation process identifies how products are distributed and transported from supplier to customer (Lee & Kim, 2002). Transportation planning can be organized hierarchically through strategic, tactical and operational levels. Strategic planning represents the tip of the hierarchy and refers to a firm’s long-term planning of transportation policy. This level primarily determines the introduction of policies or the establishment of infrastructure such as determining optimal facility location. Tactical decision-making concerns the allocation of existing resources and design of service networks, including transportation route choice, work allocation among terminals, and operation of service. Operational planning is often considered to be the most dynamic level. This level refers to details such as quantities of deliverable goods to be shipped, the use of service, the logistics of dispatching vehicle fleets among other items. This hierarchical system ensures effective inter-communication between different decision-making levels, where operational planning policies are conducted by terms dictated by the higher levels. Moreover, the lower level can use specific models addressing specific problems and provide system performance feedback and recommendations to the higher level to assist in future decision-making processes, thereby increasing the flexibility of the decision-making system as a whole (Crainic & Laporte, 1997). Furthermore, the transportation planning model combines a variety of factors under certain constraints in order to achieve specific objectives, particularly that of cost minimization. In this study, distribution and transportation problems are tied to issues related to the tactical level.

The Vehicle Routing Problem (VRP) is one of the more prevalent transportation planning problems, which refers to issues in finding optimal routes with the shortest traveled distance in order to ship products to customers under side constraints. Bektaş and Laporte (2011) proposed an extension of the VRP called Pollution Routing Problem (PRP). The purpose of the PRP does not only focus on economic costs, but also on environmental effects and social impacts (Bektaş & Laporte, 2011). There is a trend that green freight transportation has been considered in the process of decision making. Economic costs and environmental effects are considered as bi-objective in this study when the transportation planning model is built.

## 2.2 Strategies for carbon emission reduction on logistics chain

Green freight transportation has become a trending issue across the globe in recent years. In Europe, a project named SuperGreen has been completed successfully in 2013. The United States has also begun implementing innovative ideas and moving towards a progressively eco-friendly direction, with the United States Environmental Protection Agency (EPA) having collaborated with the freight sector to run a program called SmartWay Transport. In addition, the Global Green Freight Action Plan, which is under the Climate and Clean Air Coalition (CCAC) to reduce short-lived climate pollutants, has been developed by the United Nations Environment Program and various countries including Canada. A presentation at the 2013 conference of the Transportation Association of Canada (TAC) introduced and compared five green trucking programs across different regions of Canada, namely The Green Fleets (Enviro-truck) Program, Trucks of Tomorrow, The GrEEEn Trucking Program, Ontario Green Commercial Vehicle Program (OGCVP), and FleetWiser (Greening the Fleet Rebate Program). These projects and programs not only focus on the improvement of freight transportation efficiency but also take into account the reduction of adverse effects on the environment and on society as a whole from the perspective of governments and commercial institutions.

The European Chemical Industry Council and the Association Européenne du Transport de Produits Chimiques (Cefic-ETCA) introduced several potential areas of improvement aimed at reducing carbon emissions (Cefic-ECTA, 2011) related to freight transportation. The study identified six points: modal shift, supply chain management, increase of vehicle utilization by decreasing the proportion of empty running, increase of vehicle utilization by increasing the payloads, the fuel efficiency of vehicles, and carbon intensity of fuel. There are subdivided methods under these listed aspects, such as avoiding unnecessary routes, shifting road transportation to greener rail transportation, and improving vehicle design and operation could all be of concern.

A previous study proposes more than 50 potential best practices for decreasing GHG emissions in freight transportation, among which some can also be examined in this paper (H. Frey & Kuo, 2007). These practices are organized in terms of transportation modes involving truck, rail, air, water, and pipeline transport. In addition, they indicate that methods in mitigating GHG emissions can be further sub-classified through reducing energy use and altering fuels. Out of total 59 identified practices, the costs of 13 cost-effective methods were assessed by collecting information from published reports and studies (ibid.). Five of these thirteen methods are related to road transportation, which is directly relevant to the supply chain of the forest products industry. These practices include off-board truck stop electrification, auxiliary power units, direct-fired heaters, hybrid trucks, and B2 biodiesel for trucks. This paper also points out that it is possible to achieve emission reductions on the order of 85% if the long-haul truck is replaced with a combination of rail and truck transport (ibid.).

Many studies focused on factors influencing carbon emissions from freight transportation have proposed key recommendations to decrease emissions. The Canadian government published a number of resources outlining fuel-efficient driving techniques to achieve a greener and more sustainable future in 2011 (Urban Environmental Programs, 2011). The Physics of MPG presented a series of methods of fuel economy on diesel engines, which also noted that shape character of the truck trailer can influence fuel consumption (The Physics of MPG, 2007).

One significant publication has summarized a number of factors that influence fuel consumption and presents a variety of fuel consumption models (E. Demir, Bektaş, & Laporte, 2014). These factors are mainly divided into five essential categories, including vehicle, environment, traffic, driver, and operations. Some of the factors related to mechanical improvement, environmental conditions and infrastructure include the features of engines, the shape of vehicles, altitude, and pavement types. The influences of driving speed and driver behaviour on GHG emissions in the freight transportation are also examined in this thesis.

In conclusion, there are various approaches that can be examined in this study. Four highlighted strategies are chosen: intermodal transportation, low-speed driving, eco-driving, and optimizing loading patterns. They will be discussed separately in the following sections.

### 2.2.1 Intermodal transportation

Intermodal freight transportation, which is defined as providing transportation services using more than one mode of transportation, has developed into a significant component to support trade globalization in transportation systems. It has been used to improve the efficiency and lower costs of distribution but it can also be used to reduce the emissions associated with transportation (Emrah Demir, Bektas, & Laporte, 2011).

In general, the levels of emissions from rail and water transportation are reported in the literature to be lower than those from road transport (Husdal, Jensen, Sorkina, & Port, 2012). The capacity of rail and water transportation is also more sizeable than that of road transport. The Iowa Department of Transportation (IowaDot), responsible for the construction, maintenance, and organization of the highway system in the U.S. state of Iowa, compares the cargo capacity of different transportation modes: the capacity of one barge is equal to that of 16 rail cars or that of 70 large truck trailers (Iowa Department of Transportation, 2016). However, road transport has an advantage in terms of time efficiency, especially in situations where long-distance shipping is required. Because of the specific requirements of rail or water infrastructure which are not accessible or connected with mills and customers in most instances, the rigidness in terms of flexibility provided by rail and sea transportation is inferior to that of road transport (K. M. R. Hoen, Tan, Fransoo, & Houtum, 2013).

By combining the benefits of each mode, intermodal transportation enables the system to be more efficient, cost-effective and sustainable (Mulligan & Lombardo, 2006). With the increasing exchanges of commodities, railways and short sea shipping (SSS) have been prioritized in the European Union's transportation policy as supplements to road transport, which presents numerous negative externalities in environmental terms and through traffic-related issues such as congestion, accidents, and noise. (López-Navarro, 2014). In Canada, the use of intermodal traffic rose by 32.6% from 2005 to 2014 (Railway Association of Canada, 2015).

Moreover, there is also research conducted to quantify environmental aspects and incorporate them into the decision-making processes in studies on intermodal transportation. A study assessing impacts of intermodal transportation on the environment concluded that it was substantially more environmentally friendly to use intermodal freight transportation rather than unimodal road transport when only considering energy use and emissions (Kreutzberger, Macharis, Vereecken, & Woxenius, 2003). In another study, environmental impact was considered in network optimization models of intermodal freight (Winebrake et al., 2008). Other research proposed to introduce environmental costs into transportation planning models with the objective of minimizing time and emissions (Bauer, Bektaş, & Crainic, 2010).

As mentioned in the introduction, the shipping of forest products primarily depends on heavy duty truck and rail in the region of North America. In this thesis, intermodal transportation refers to a combination of road and rail transportation.

### 2.2.2 Low-speed driving

Apart from intermodal transportation, there are some other potential methods of reducing fuel consumption. The most significant method is vehicle speed reduction as it is highly correlated to inertia, rolling resistance and air resistance, which influence the instantaneous engine load (Emrah Demir, Bektaş, & Laporte, 2014). A number of academic research have emphasized the potential of improving fuel economy by reducing driving speeds. A previous study in Belgium on the external costs of interurban freight traffic was based on a relationship between emissions and average speed of trucks for calculating the emissions of light duty and heavy trucks (Beuthe, 2002). In addition, a study in Netherlands focusing on modeling full cost of an intermodal and road freight transport network took advantage of the same average speed of each vehicle making a round trip of approximately the same length (Janic, 2007). Furthermore, another study regarding the emissions resulted from vehicle routing and scheduling also highlighted the significance of the speed over distance traveled (E. Demir et al., 2014).

The relationship between emission rates and travel speed has been demonstrated in the literature to be non-linear (Figliozzi, 2011). More specifically, fuel consumption and the emission rate of $CO_2$ per mile traveled decreased with the increase of vehicle speed operating up to optimal speed, before starting to increase again (Hong, 2014). In real driving conditions, there was a rapid non-linear growth in emissions and consumption as travel speeds dropped below 48 km/h (Barth & Boriboonsomsin, 2008). $CO_2$ emission per mile doubled when the speed decreased from 48 km/h to 20 km/h or when the speed decreased from 20 km/ to 8 km/h (Figliozzi, 2011). Over 48 km/h, the change of $CO_2$ emission was not evident until speeds reached 80km/h, with $CO_2$ emission per mile gradually increasing with increased speed (Barth & Boriboonsomsin, 2008).

### 2.2.3 Eco-driving

In the context of real-world transportation networks, congestion significantly influences $CO_2$ emissions and fuel efficiency. This is due to the fact that congestion is associated with idling and low-speed driving, which result in a rise in emissions. As fuel consumption is a function of not only speed but also acceleration rates, frequent changes in speed will increase emission rates (H. C. Frey, Rouphail, & Zhai, 2008).

A number of studies have investigated strategies on improving the efficiency of fuel consumptions. Some researchers have carried out experiments and concluded that if companies would be able to achieve approximately a 15% reduction in emissions if they developed better routing operations to avoid stop-and-go traffic situations (Baumgartner, Léonardi, & Krusch, 2008; Suzuki, 2011).

In addition to limiting acceleration practice and route choice, improving driving practice is one of the most cost-effective and eco-driving methods for reducing fuel consumption. It can have a positive impact on fuel economy regardless of technological issues associated with the vehicle (Ang-Olson & Schroeer, 2002). An effective driving program should take into account monitoring driver performance after the practice based on the data from electronic engine monitors to analyze detailed performance over time. Meanwhile, it is worth considering providing drivers with incentives to reduce fuel consumption, such as salary or vacation bonuses. If appropriately designed and implemented, driver training is found to be a very effective and efficient tool in improving driving behaviour. A number of studies have shown that driver training programs could improve fuel economy and result in fuel savings ranging from 5% to 20% (Liimatainen, 2008; Porter et al., 2013; Rakotonirainy, Haworth, Saint-Pierre, & Delhomme, 2011).

Table 2.1 summarizes the findings from previous studies on fuel economy and carbon emission reduction resulting from vehicle speed decreases and eco-driving. It provides the corresponding information and achievement in terms of fuel economy, $CO_2$ emission reduction, and cost-saving.

**Table 2.1 Recent studies on fuel economy and carbon emission reduction resulting from speed decrease and eco-driving**

| **Reference** | **Speed** | **Driver behaviour** | **Fuel economy** | **$CO_2$ saving** | **Cost** |
|---|---|---|---|---|---|
| (Caterpillar Inc., 2006) | - | best/worst | 25% (42.2-56.5 liters/100km road segment) | - | - |
| (Nylund, 2006) | - | best/worst | 30% | - | - |
| (Emrah Demir et al., 2011) | from 55km/h | - | 0.001 litre/km | - | - |
|  | 100 to 90km/h | - | 0.02 litre/km | - | - |
| (Walnum & Simonsen, 2015) | 30 to 40 km/h | - | 0.5 litre/10 km | - | - |
|  | 50 to 60 km/h | - | 0.2 litre/10 km | - | - |
| (Wåhlberg & Göthe, 2007)(Zarkadoula , Zoidis, & Tritopoulou, 2007) | - | Training | 10-15% | - | - |
|  | - | 3-months after training | 4-5% | - | - |
|  | - | Long-term | about 2% | - | - |
| (Kirschstein & Meisel, 2015) | Optimal speed: 40km/h | - | - | 61g $CO_2$ eq./tkm with the average speed of 83km/h | - |
| (SmartDrive, 2011) | - | 2-month practices | 13.7% (1460 gallons) | - | $5,853 |
|  | - | Top 25% drivers | 22% (3131 gallons) | - | $12,553 |
| (Ang-Olson & Schroeer, 2002) | 70 to 65 to 60 mph | - | 6.1 to 6.5 to 7.1 mi/gal | - | - |
|  | 70 mph to 65 mph | - | 6.0% (972 gal/year) | - | - |
|  | 65 mph to 60 mph | - | 7,6% (1,228 gal/year) | - | - |
| (Ogburn & Ramroth, 2007) | 115 km/h to 105 km/h | - | 7% (3100 litres/y) | 8.5 t GHG/year | - |
| (NESCCAF, ICCT, Southwest Research Institute, & TIAX, 2009) | 60 mph to 55 mph | - | 3.6% | - | - |
|  | 65 mph to 60 mph | - | Approximately 3% | - | - |
|  | 70 mph to 55 mph | - | 7.3% | - | - |

A previous study indicated that 40 km/h was regarded as a steady and optimal speed for keeping the heavy truck running in the lowest fuel consumption. Moreover, it also suggested that the vehicle emitted 61 g $CO_2$ eq. /t km with an average speed of 83 km/h.

Another study illustrates that a medium freight vehicle could increase 0.001 litres of fuel per km/h from 55 km/h under the condition of null load, acceleration and road gradient. From 90 to 100 km/h, this increase peaked up to 0.02 litre per km/h (Emrah Demir et al., 2011). In addition, various other research determined that a reduction of speed from 115 km/h to 105 km/h could bring 7% saving of fuel consumption - equal to 3100 litres of fuel or 8.5 tons of GHG emissions saving per year (Ogburn & Ramroth, 2007). It also mentions that 460 million litres of fuel consumption could be saved and 1.2 million metric tons of GHG emissions reduced per year once half of Canada's Class-8 fleet reduced their running speed to adhere to the above recommendation. Furthermore, it illustrates that fuel savings of 7.6% could be achieved if the vehicle speed is reduced from 65 mph to 60 mph (approximately from 105 km/h to 95 km/h). It is also reported that the difference in fuel consumption between the best and the worst driver regarding eco-driving ranged from 25% to 30% (Caterpillar Inc., 2006). SmartDrive Fuel Efficiency Study demonstrates that a two-month training program could reduce fuel consumption by 13.7%, and the top 25% of 695 tested heavy-duty vehicle drivers could save as much as 22% in fuel. These statistics translate to $12,553 saved if drivers were to conduct the test with 115,538 km in average annual driving distance recorded for 2011 (SmartDrive, 2011).

### 2.2.4 Optimizing loading pattern

There is an increasing recognition that organizations must address the issue of sustainability in their operations. Considering the comprehensive nature of the supply chain process, ranging from initial processing of raw materials to delivery to the customers, a focus on effective green supply chain management (GSCM) is a step towards maximizing energy efficiency and resource allocation (Ghatari, Hamid, Hosseini, & Shekari, 2012). GSCM is a concept derived from the traditional supply chain, which includes a firm's internal and external actions throughout the supply chain (Fortes, 2009).

One of the key elements in the success of GSCM is the process of making optimal transportation plans (Saridogan, 2012). A previous study focused on assessing the role of logistics and transportation in GSCM reveals that technological integration with primary suppliers and with major customers was positively linked to environmental monitoring and environmental collaboration (Saridogan, 2012). Another recent study investigating the effect of reducing energy consumption in green supply chain indicates that suitable assignment of the existing transportation fleet with specified capacity could cause a reduction in energy consumption by optimizing transportation in a green supply chain (Aziziankohan, 2017).

Truckload (TL) transportation is also common in practice and supply chain agents should consider TL transportation costs and emissions in controlling their inventory and transpiration operations (Emrah Demir, Bektaş, & Laporte, 2012). There are many studies which account for basic truck characteristics such as truck capacity and truck emissions in the context of environmentally sensitive logistics operations which also focus on vehicle routing problems (Bektaş & Laporte, 2011; Jabali, Van Woensel, & De Kok, 2012; Suzuki, 2011). For instance, a study in the U.S. has included an explicit transportation model with inventory control decisions to capture per truck costs and per truck capacities. It proposed a heuristic search method to consider emission characteristics of various trucks that could be used for inbound transpiration (Konur, 2014). Another study implemented a tabu search algorithm for considering a combination of capacitated vehicle routing and three-dimensional loading (Gendreau, Iori, Laporte, & Martello, 2006).

## 2.3 Appropriate models to evaluate reduction methods

In the view of life cycle assessment, the processes of freight transportation can be classified into four different cycles: manufacture, maintenance, operation and disposal at the end of life (Mötzl, 2009). In this paper, GHG emissions from freight transportation primarily refer to those from the operation of freight train or truck. Almost all GHG emissions from freight transportation are caused by fuel combustion (McKinnon & Piecyk, 2010). Furthermore, carbon emission is directly proportional to fuel consumption and thus can be accurately estimated using fuel consumption figures (Kirby, Hutton, McQuaid, Raeside, & Zhang, 2000). There are two common ways to convert fuel consumption to GHG emissions - energy-based approach and activity-based approach (Cefic-ECTA, 2011).

A previous study investigated a number of fuel consumption models on road transportation, which can be used to estimate carbon emissions (Demir et al., 2014). These models can be divided into two main parts: macroscopic models and microscopic models. Microscopic models focus on the instantaneous fuel consumption and emission rates, whereas macroscopic models use average aggregate parameters to estimate network-wide emission rates. In this study, the macroscopic model is considered.

Several types of macroscopic models have been investigated in the literature. For instance, models such as Network for transport and environment (NTM) and Ecological transport information tool (ECOTRANSIT) provide friendly web engines with route distance and truckload to roughly estimate carbon emissions (K. Hoen & Tan, 2010). Other models such as COPERT (computer program to calculate emissions from road transportation) and IVE (international vehicle emissions model) provide a mechanism to get exact estimations of carbon emissions, though more detailed information such as truck engine types and fuel types are required (ISSRC, 2008; Kouridis, Gkatzoflias, Kioutsioukis, & Ntziachristos, 2009).

Rail is treated as one of the most significant ways to ship forest products since sawmills are usually built in remote regions in proximity to forests, and where transportation infrastructure development is scarce. The capacity of a rail freight car is four or five times more than that of the freight truck. Moreover, it requires less manual labour than the truck. The crucial aspect of rail freight transportation is that it emits fewer emissions than the truck if shipping the same quantity of goods. CN company, which provides supply chain services with its rail facilities, puts forward a tool based on GHG Protocol to calculate and compare the quantities of carbon emissions from truck, rail and marine vessel. This model estimates emissions based on traveled distance at a macroscopic level. The fundamental emissions factors are distance, total freight weight, and freight weight per railcar/truck. Estimated results of total emissions could then be displayed online.

As previously mentioned, GHG Protocol offers a standard to classify and gather carbon emissions. It also provides tools to calculate GHG emissions (National Council for Air and Stream Improvement Inc. (NCASI), 2005) according to various sectors or sources, including GHG emissions models from transport or mobile sources. The level of required data is modest; for road freight transportation, information related vehicle type, traveled distance and total weight of freight would be required. These methods of estimation are similar to the method of calculating the emissions of intermodal transportation in this study, which are introduced in the next chapter.

The above research has contributed in important ways to the understanding of strategies for reducing carbon emissions in freight transportation. However, they have not considered transportation planning in response to the concerns of reducing carbon emissions associated with freight transportation on logistic chains. This study investigates four strategies of emission reduction including intermodal transportation, low-speed driving, eco-driving, and optimizing loading pattern together for a transportation plan taking into account the new carbon trade rules at a tactical level.

# CHAPTER 3. METHODOLOGY

This chapter covers the methodology of the decision-making on transportation planning in consideration of the rules of the carbon trade scheme. As mentioned in the previous chapter, the hierarchical decision-making focused in this study is at the tactical level. The objective of tactical planning is to achieve the goals of the strategic plan using the allocated resources derived from the strategical level. At this level, distribution and transportation problems typically come about due to route choice, transportation mode choice, use of terminals, delivery schedule generation, use of supply facilities, and space allocation among other factors. An integrated model involving all of these requirements listed is established. Additionally, the emission level is an essential factor concerned in this study, and thus the carbon budget is added in the transportation planning.

In Section 3.1, the research problem is elaborated. Section 3.2 is dedicated to the collection of required data. The next section emphasizes on Carbon RoadMap, by which appropriate delivery routes were generated. The tactical transportation planning models are then discussed in Section 3.4. Section 3.5 presents the mathematical programming solvers which were applied to solve the optimization models in this study. In the last section, Pareto Front is introduced to assess the trade-off solutions between cost and emission, with approaches to drawing Pareto Front also demonstrated. Figure 3.1 illustrates the methodology with the broad types of data coming into the steps.

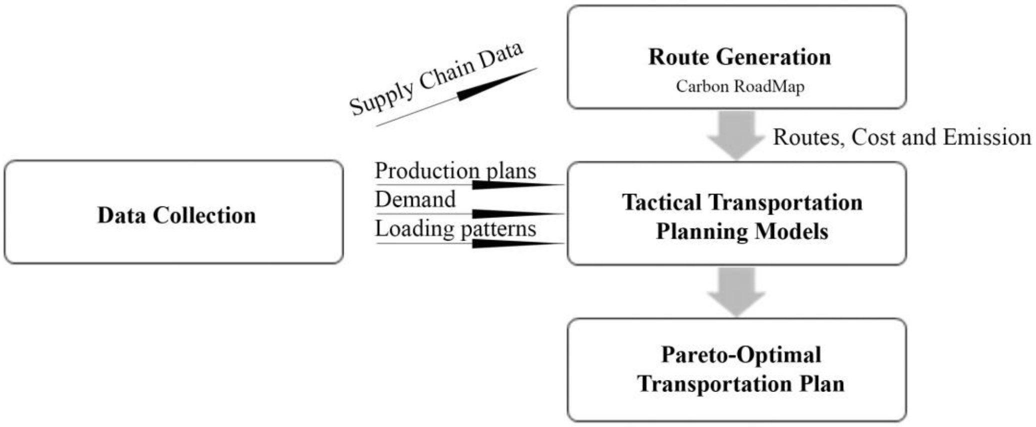


**Figure 3.1 Methodology with the broad types of data coming into the steps**

## 3.1 Research problem

This study focuses on a firm producing wood products in mills, which then supplies the products to its customers. The purpose is to minimize the total cost in consideration of the carbon emission reduction. It is assumed that the demand from customers is consistent with the historical demand, and mills are able to produce wood products to meet the demand. The firm needs a transportation plan to ship wood products from mills using the appropriate transportation means to satisfy the demand (in the form of a set of customer orders, consisting of a certain quantity of different products) during one planning horizon, which typically covers several weeks.

The transportation means involved in this study are considered as methods to reduce carbon emissions, which consists of normal road freight transport, low-speed driving, eco-driving, intermodal transportation (rail and road), and multi-product loading pattern strategies for all above methods. The route choices for road and intermodal are also determined.

Moreover, space allocation for storage is also regulated so that the stock cannot exceed the demand in the following period in order to control the inventory cost.

## 3.2 Data collection

Firstly, customer demand is generated according to a based off of the real-world wood products market. Since demand is a function of accepted orders by the firm, it is assumed that the mills have an appropriate ability of production to satisfy the demand. In this case, the orders from customers exceeding the mills' capacity to meet the demand would have been rejected.

Aside from the generation of demand and production plans, the data collection can be regarded as two-part corresponding to the strategies: cost and emission. As mentioned in the literature review, only cost and emissions from the operation process aspect of rail or truck are taken into consideration in this study. In addition, since fixed components such as the purchasing of trucks and office supplies are applied in all strategies involved in this study, they are not considered here as they can be offset. Moreover, GHG protocol provides the calculation tools and methods to develop comprehensive and reliable inventories of GHG emissions, not only by sectors like pulp and paper, but also for the transportation and mobile emissions in specific industries, given the quantity of fuel used, fuel combustion efficiency and the fleet size. This research followed the GHG protocol recommendations and methods to calculate emissions.

Excluding the rail portion of intermodal freight transport, the normal road freight shipping, the road component of intermodal transportation, and other transportation means take the distance, unit costs, and emissions into consideration in the model. In addition, cost consists of three additional parts: fuel cost, driving cost and maintenance cost – all of which are proportional to traveled distance (W. Ford Torrey & Murray, 2015). The fuel cost and driving cost are also dependent on average driving speed. The driving cost involves elements such as driver wages, the use of trailers, and consumption of tires. In addition, driving cost is determined by drivers' overall skill. The abovementioned values are for the most part collected from previous academic studies, technical reports, government announcements, and research organizations. They are specified according to the strategies in the following subsections. In the next section, Carbon RoadMap is introduced as it generates traveled distances and freight routes for each transportation mean.

### 3.2.1 Intermodal transportation and logistics

The intermodal routes and the terminals for transferring wood products between rail and road are generated from Carbon RoadMap. In general, the railroad offers a variety of equipment to meet different transportation requirements for all kinds of forest products. However, in order to simplify the problem, it is assumed that products are packed in a 53-foot container or beam car, which can be directly disassembled and attached to the tractor or the locomotive. Therefore, it is not necessary to repack the products during the transfer. In this study, the price and emission between rail terminals are obtained from price documents provided by railroads and price calculator on the CN website based on detailed information including origin, destination, carrier, and commodity (Canadian National Railway Company, 2010, 2017). In addition, the carrier in Canada is CN railroad, while the carrier in the United States is selected based on the region or the available service.

### 3.2.2 Low-speed driving

The previous literature review section summarizes recent research and reports on environmental and economic benefits from slower vehicle speeds and eco-driving. Some of the data is adopted in this study. It is worth mentioning that the data in European studies is reported in L per 100 km for fuel consumption and km per hour for vehicle speed, while in the American studies, fuel consumption is calculated in gallons per mile and vehicle speeds in miles per hour (mph), and consequently a unit conversion is applied in the following calculation. It also needs to be mentioned that the driving speed limit is set while taking into account safety considerations. The freight vehicle is regulated to run under 105 km/h in Quebec and Ontario in Canada, and thus a speed reduction of 7.6% from 105 km/h to 95 km/h can be considered in this study.

### 3.2.3 Eco-driving

Driver behaviour is one of the greatest potential factors influencing fuel efficiency and carbon emissions (E. Demir et al., 2014). It affects nearly all the factors related to the operation, including the maintaining of vehicle speed, idling times, and gear selection. According to a study evaluating truck eco-driving, fuel consumption and emissions data from SmartDrive (2011) are applied in this study since it includes a reliable sample size based on the use of individualized coaching in conjunction with an in-vehicle real-time feedback system rather than simulation (Boriboonsomsin, 2015). In this study, it is assumed that eco-driving can save 13.7% of fuel consumption or reduce approximately 13.7% of carbon emissions.

### 3.2.4 Multi-product loading patterns

A 53-foot trailer, which is a popular choice of vehicle for freight transportation in North America, is applied in this study. Although the most common unit of measure for wood products in North America is board-foot (fbm), it is important to note that lumbers are typically assembled in packs for delivery, and customer orders always consist of a quantity equivalent to an (integer) number of packs of each product. Hence, the number of packs that can be put on a railcar depends on the length of products. It is assumed that a car trailer can only contain four packs of wood products (two on the top and two on the bottom) in the view from one end, regardless of the product length, as shown in Figure 3.2.

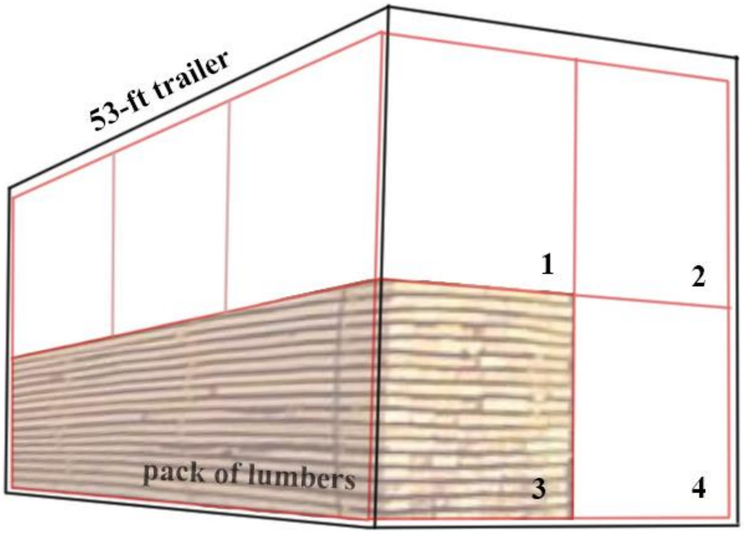


**Figure 3.2 Rear-end view of a 53-ft truck trailer**

## 3.3 Route generation using Carbon RoadMap

The traveled distance of shipped wood products is directly related to transportation cost. When environmental effects or carbon emissions are considered in distribution planning, both transportation costs and delays will be influenced. Generally, costs and delays increase with the reduction of carbon emissions, as transportation means with lower emissions generally have a lower speed. It is therefore necessary for decision makers to take three criteria (cost, delay, and emission) into account so that the shipping deadlines outlined in the demands of customers are met, while transport costs and environmental impacts are reduced to the greatest extent possible.

Carbon RoadMap, a web-based decision support system, aims to find a trade-off route to transport wood products from a single source to a set of one or more destinations based on the multi-criteria decision (transportation cost, carbon emission and delivery time)

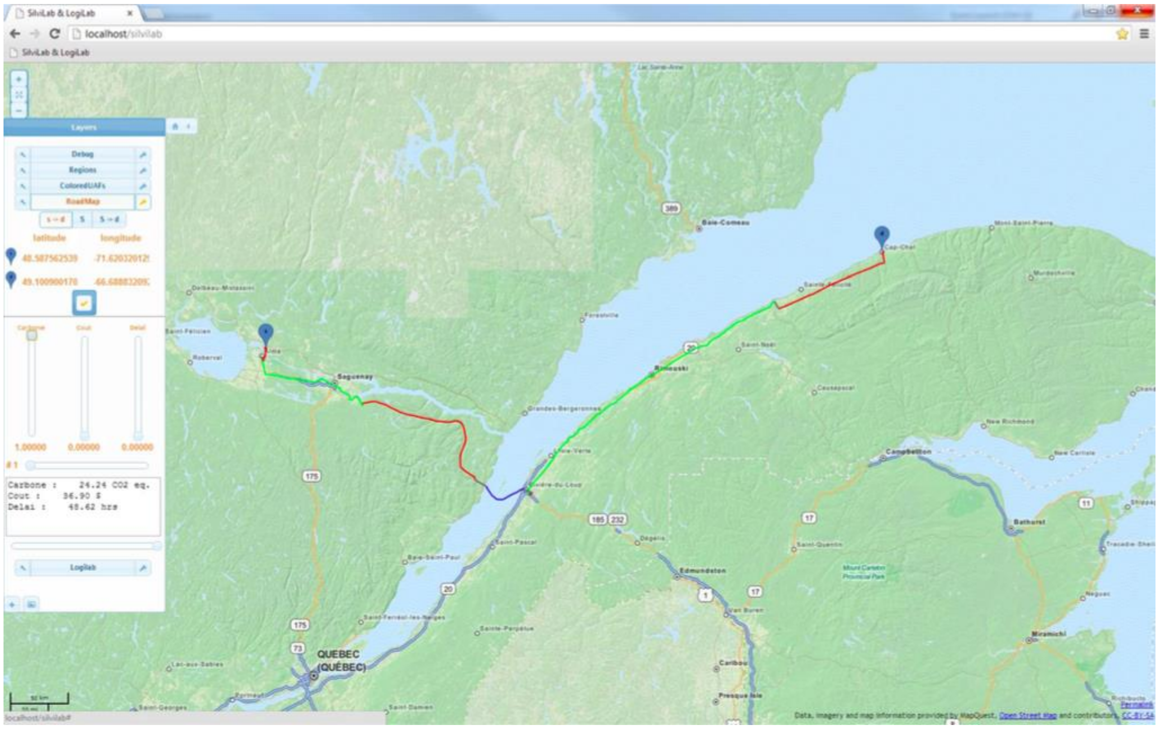
(Vallerant, 2013). This tool is mainly developed for the shipment of wood products in the North American transportation network. It uses an optimization algorithm based on the Dikjstra algorithm, which finds a set of non-dominated routes. The results are presented through an interface. Three transportation modes are considered in this system: road, rail, and ship. Routes using any combination of these transportation modes can be obtained.

Aside from the visualized routes on an actual map, the values of cost, time and emissions are presented by Carbon RoadMap for each generated route. Its manual introduces the calculation of these three criteria for a route segment, which can be expressed by one general equation (Vallerant, 2013):

$$\mathrm{c} = f_x + f_v * d \tag{3-1}$$

where $c$ signifies the value of criteria, $d$ represents the traveled distance, and fixed factor and variable factor are denoted as $f_x$ and $f_v$ respectively.

The fixed factor represents the cost, delay or emission generated during transition from one transportation mode to another if it is applied. Moreover, the variable factor is the unit value of criteria, which can be adjusted as needed. Likewise, the generation of routes requires coordinates of origin and destination or they can be directly selected on the interface. Figure 3.3 is an example displaying a Carbon RoadMap layer. The routes are visually shown in colours representing the transportation mode, and the corresponding value of the criteria is also given.



latitude longitude
48.587562539 -71.62032012
49.100900170 -66.6888320

Carbone 1.00000, Cout 0.00000, Delai 0.00000

```
Carbone :     24.24 CO2 eq.
Cout :    36.90 $
Delai :    48.62 hrs
```

**Figure 3.3 Display of a Carbon RoadMap layer** (Vallerant, 2013)

Although it is impossible to guarantee that the network is complete in the Carbon RoadMap system, especially for the routes between transitions of intermodal (as waystations and intermodal facilities as additional transportation arcs are constantly added to the North American transportation network) the missing segments of routes were updated and created in this study based on data from Google Earth and using information regarding terminal positions provided by CN.

In the equation (3-1), the key variable is the distance traveled from origin to destination. For different transportation methods, corresponding fixed and variable factors are applied. In order to simplify the calculation of cost and emissions, Carbon RoadMap is used in this study to generate routes and acquire corresponding distances. It simply needs to set all variable factors as one and set fixed factors as zero in the database to examine the generated results. Two appropriate routes between an origin to a destination respectively for road and intermodal transportation are then chosen. Finally, the values of cost and emissions are calculated for different strategies using equation (3-1) based on the corresponding distances of these routes.

Road freight transportation is the principal way of delivering wood products, while rail and ship may be used as optimizing means to reduce environmental impacts (Winebrake, Green, Comer, Corbett, & Froman, 2012). These three transportation modes are considered when Carbon RoadMap conducts the set of non-dominated routes. Generally, the ship, albeit the least efficient in terms of time, is the most economic and the eco-friendliest mode compared with other modes on the basis of ton per km. It is thus unrealistic to make use of a ship to deliver wood products if forest companies need to ship customers' demand within a timeframe of two weeks. When hundreds of routes are generated in Carbon RoadMap, the shortest route is chosen for both road transportation and intermodal transportation. The rail acts as the main part of the route for the intermodal transportation.

## 3.4 Tactical Transportation Planning Models

In this section, tactical transportation planning models are introduced. Firstly, a model considers a scenario where only one product type is being transported on a trip. This model integrates the following transportation means: normal road freight transport, low-speed driving, eco-driving and intermodal transportation. The model is then modified to apply various sizes of wood products on one route trip, in order to assess the optimizing loading pattern strategy. The abovementioned transportation means are also designed in the new models, which consider a trailer containing various types of products. Two approaches are presented to solve this problem, namely a heuristic model and a simplified model.

### 3.4.1 General description

The optimization model of the transportation plan is described as following. A set of mills is defined as I, and J as a set of customers. Each mill i∈I produces a set of products that is defined as P. The product p∈P is planned to be shipped by mean m∈M where M = {0, 1, 2, 3}. 0∈M signifies delivering at a speed of 105km/h by road, and 1∈M denotes delivery via intermodal transportation (intermodal transportation generally combines road and rail in this research), 2 and 3 represent speed reduction (driving at speed of 95km/h) and eco-driving on the road route. The planning horizon is denoted by T.

Each customer i has a non-negative demand $d_{pit}$ of product p in period t∈T, and the production quantity of product p in mill i in period t is denoted by $b_{pjt}$. The units for these two parameters are in packs since the wood products are generally sold in packs. Furthermore, $c_{ijmt}$ is the transport cost of mean m from mill i to customer j in $ per full truckload (FTL). As the total cost and emissions of optimization results are calculated based on the routes of each transportation mean, FTL is applied as the shipment unit in this study instead of one pack. In this case, the numbers of variables can be reduced so that the calculation is simplified, while allocation of products to trailers is not considered. As the unit is FTL, it needs to denote the number of packs of product p in a full shipment of route m as $v_{pm}$. Finally, $e_{ijm}$ represents emissions (in kilograms) associated to full shipment of mean m and $C_t$ stands for the upper bound of emission constraints.

Decision variables are then defined as follows: $X_{pijmt}$ signifies the quantity of product p in packs shipped from mill i to customer j by transportation mean m in period t; $L_{pijmt}$ is a non-negative integer variable denoting the number of routes of mean m used between mill i to customer j to ship product p in period t; $I_{pit}$ and $I_{pjt}$ respectively represent the end-of-period inventory of product p at mill i or customer j at the end of period t. It is assumed that the unit cost of inventory of each product is \$1 per piece, so $I_{pit}$ and $I_{pjt}$ could directly represent the inventory cost. $I_0$ is denoted as the initial inventory.

### 3.4.2 Model #1 using single-product loading pattern

The cost minimization objective of model #1 is given by

$$Minimize\ \sum_p \sum_i \sum_j \sum_m \sum_t c_{\mathrm{ijmt}} L_{pijmt} + \sum_p \sum_i \sum_t I_{pit} + \sum_p \sum_j \sum_t I_{pjt} \qquad (3\text{-}2)$$

This objective calculates the total cost, which consists of transportation cost and total inventory cost.

The constraints of the optimization model are shown as follows:

$$I_{pj(t-1)} - d_{pjt} + \sum_i \sum_m X_{\mathrm{pijmt}} - I_{pjt} = 0 \quad \forall p, j, t \qquad (3\text{-}3)$$

$$I_{pjt} \leq d_{pj(t+1)} \quad \forall p, j, t \qquad (3\text{-}4)$$

$$I_{pi(t-1)} + b_{pit} - \sum_j \sum_m X_{\mathrm{pijmt}} - I_{pit} = 0 \quad \forall p, i, t \qquad (3\text{-}5)$$

$$X_{pijmt} \leq v_{pm} L_{pijmt} \quad \forall p, i, j, m, t \qquad (3\text{-}6)$$

$$\sum_p \sum_i \sum_j \sum_m \sum_t e_{ijm} L_{pijmt} \leq C_t \qquad (3\text{-}7)$$

Constraints (3-3) and (3-5) state that the input flow must be equal to the output flow respectively at customers and at mills. It is then assumed that the customers would not stock more wood products than the demand in the following week would allow since it would be less economical in the view of inventory planning. Constraints (3-4) define this maximum inventory at customers. Constraints (3-6) ensure that a sufficient amount of FTLs is planned in order to ship all the products for each origin- destination pair. Constraints (3-7) enforce the emissions restriction.

### 3.4.3 Models using multi-product loading patterns

The strategy of optimizing loading patterns attempts to arrange various wood products in one car trailer on one single route trip as the products usually vary in physical dimensions. The other transportation means, namely normal road freight transport, low-speed driving, eco-driving and intermodal transportation, are still considered in the models. Firstly, the heuristic model considering multi-product loading patterns with partial loading is presented. To simplify the problem, the second heuristic model is then introduced by only allowing full trailer shipment. However, due to the fact that the heuristic approach cannot guarantee optimal results due to the seemingly endless configurations and combinations of various products packed into one trailer, a simplified model is finally included, which extracts typical patterns from all possible combinations.

#### *3.4.3.1 Heuristic model #2: Multi-product loading patterns with partial loading*

To begin, it needs to modify the optimization model so that all possible combinations of products in a carload are considered. Besides from all indices that were previously defined, a new index called g representing the loading patterns is added. $v_{pm}$ is changed to $v_{pg}$ representing the number of packs of products p in pattern g.

Decision variables are defined as follows: $X_{pijt}$ signifies the quantity of product p in packs shipped from mill i to customer j in period t; $L_{ijmgt}$ is a non-negative integer variable denoting the number of routes of mean m shipping pattern g used between mill i to customer j in period t; $I_{pit}$ and $I_{pjt}$ respectively represent the end-of-period inventory of product p at mill i or customer j at the end of period t.

The cost minimization objective is given by

$$Minimize\ \sum_i \sum_j \sum_m \sum_g \sum_t c_{\mathrm{ijm}} L_{ijmgt} + \sum_p \sum_i \sum_t I_{pit} + \sum_p \sum_j \sum_t I_{pjt} \qquad (3\text{-}8)$$

The constraints of the optimization model are shown as follows:

$$I_{pj(t-1)} - d_{pjt} + \sum_i X_{\mathrm{pijt}} - I_{pjt} = 0 \quad \forall p, j, t \qquad (3\text{-}9)$$

$$I_{pjt} \leq d_{pj(t+1)} \quad \forall p, j, t \qquad (3\text{-}10)$$

$$I_{pi(t-1)} + b_{pit} - \sum_j X_{\mathrm{pijt}} - I_{pit} = 0 \quad \forall p, i, t \qquad (3\text{-}11)$$

$$X_{pijt} \leq \sum_m \sum_g L_{\mathrm{ijmgt}}\, v_{pg} \quad \forall p, i, j, t \qquad (3\text{-}12)$$

$$\sum_i \sum_j \sum_m \sum_g \sum_t e_{ijm} L_{ijmgt} \leq C_t \qquad (3\text{-}13)$$

Similar to model #1, constraints (3-9) and (3-11) state that the input flow must be equal to the output flow respectively at customers and at mills. Constraints (3-10) define this maximum inventory at customers. Constraints (3-12) ensure that a sufficient amount of shipment is planned in order to ship all the products for each origin- destination pair. Constraints (3-13) enforce the emissions restriction.

It is noteworthy that the number of possible loading patterns is extremely substantial Incorporating the complete set of feasible patterns into the optimization model would cause it to be intractable, and so a restricted model is used which includes a limited number of *good* loading patterns:

$$Gh\ element\ of\ G \qquad (3\text{-}14)$$

Even if this restricted model is solved to optimality using a mixed-integer linear programming solver, the whole procedure is considered as a heuristic.

### *3.4.3.2 Heuristic model #3: Multi-product loading patterns with full shipments*

Another strategy for restricting the multi-product model is to stipulate that each trailer or railcar is fully loaded. Simply put, it means that the model is forced to ship the maximum number of product units allowed by the used loading patterns, i.e. $X_{pijt} = \sum_m \sum_g L_{\mathrm{ijmgt}} v_{pg} \quad \forall p, i, j, t.$

If it is enforced to fully load the car trailer, $X_{\mathrm{pijt}}$ is not required. The model kept the objective function as (3-8), and the constraints are modified as follows:

$$I_{pj(t-1)} - d_{pjt} + \sum_i \sum_m \sum_g L_{\mathrm{ijmgt}} v_{pg} - I_{pjt} = 0 \quad \forall p, j, t \tag{3-15}$$

$$I_{pjt} \leq d_{pj(t+1)} \quad \forall p, j, t \tag{3-16}$$

$$I_{pi(t-1)} + b_{pit} - \sum_j \sum_m \sum_g L_{\mathrm{ijmgt}} v_{pg} - I_{pit} = 0 \quad \forall p, i, t \tag{3-17}$$

$$\sum_i \sum_j \sum_m \sum_g \sum_t e_{ijm} L_{ijmgt} \leq C_t \tag{3-18}$$

Compared to the previous model, this approach limits loading options, but a fully loaded vehicle prevents the loss of space, and it might prove to be a more economical and eco-friendly way of shipping. Moreover, it reduces the number of variables so that the process of optimization could be expedited.

#### *3.4.3.3 Simplified model #4*

The heuristic approach requires building all feasible multi-product loading patterns into the optimization model. While the set of patterns is extremely large, rendering it difficult to guarantee an optimal solution solved by a Solver within a limited timeframe, a simplified approach is therefore introduced to divide the wood products into groups in order to reduce the number of feasible patterns. The rule applied in this study is given as follows: If the product lengths are similar, they can be packed in one car trailer. If the length of a product is significantly longer than that of a second product, the longer product is treated as several of the second product. Figure 3.4 demonstrates an example of grouping wood products. A pack of 16-ft lumbers is the equal of two packs of 8-ft lumbers, meanwhile a 12-ft lumber pack and a 14-ft lumber pack are similar so that they can be grouped.

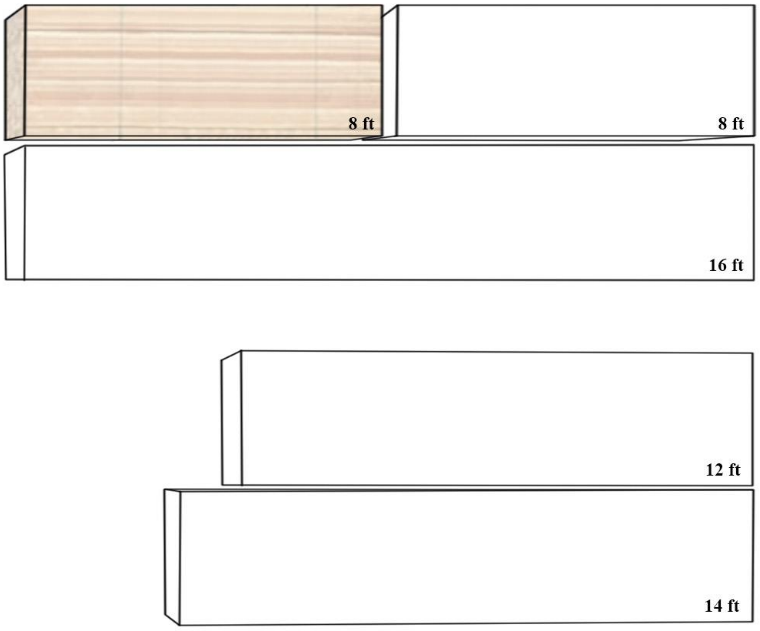


**Figure 3.4 Example of Combination of lumbers in groups**

Accordingly, the variables and flow constraints should be modified as follows: $L_{pijmt}$ is changed to $L_{aijmt}$ and $L_{bijmt}$, non-negative integer variables denoting the number of routes of mean m used between mill i to customer j to ship product groups a and b in period t, where group a indicates that products have similar lengths, and group b collects the products that have a proportional relationship.

$$\sum_{p\in a} X_{pijmt} \le v_{am}L_{aijmt} \quad \forall a,i,j,m,t \tag{3-19}$$

$$\sum_{p\in b} rX_{pijmt} \le v_{bm}L_{bijmt} \quad \forall b,i,j,m,t \tag{3-20}$$

Where r represents a factor to account that certain products take more space than others. For instance, r = 2 if 8-ft lumbers are packed with 16-ft lumbers.

## 3.5 Mathematical programming solvers

Microsoft Excel Solver is a frequently practical add-in to solve small-sized optimization models. It aims to determine the value of decision variables to obtain the maximum or the minimum or a specific value subject to a set of constraints. The model can be formulated by referring to cell values and formulas in the spreadsheet. However, there are limits on the number of variables and constraints. It generally allows 100 constraints and 200 variables in one problem. OpenSolver is an extended Add-in designed for Excel that could solve linear, non-linear and integer optimization problems (Mason, 2012). It makes use of many solvers, including the COIN-OR Branch and Cut (CBC) mixed-integer programming solver, in order to solve problems with a large of variables and constraints. The models presented in section 3.4 have at least ten thousand decision variables and hundreds of constraints. The CBC solver in many instances cannot give an optimal solution with a substantial number of constraints within a short time period, especially when emission constraints are taken into consideration.

Gurobi Optimizer is thus used as an alternative to find an optimal solution to the models (Gurobi Optimization Inc., 2017). Similar to CBC, Gurobi can be called directly from OpenSolver. This optimizer works to find the best solution within billions or trillions of possible solutions within a given timeframe. Moreover, it is much faster than CBC both in general terms and in the case of the models solved in this study.

LocalSolver is also an extended mathematical programming solver developed by a French group (Benoist, Estellon, Gardi, Megel, & Nouioua, 2011). It is however based on local search techniques rather than branch-and-bound or branch-and-cut algorithms. It is used to solve heuristic models using multi-product loading patterns. Unlike Gurobi, it cannot be called from within OpenSolver but instead uses its own LocalSolver programming language.

## 3.6 Pareto front

A state of resource allocation is called Pareto optimal if changing it worsens any one of its constituent resources. Pareto Front is the set of values presenting Pareto optimal sequences (Mathematics & Censor, 1977). The problem in this study can be treated as a bi-objective optimization problem. It aims to reduce carbon emissions as much as possible while cost minimization is essential in reaching an optimal trade-off goal between cost and emission. Pareto Front is thus employed to provide an analysis of conflicting objectives in multi-objective optimization, particularly cost minimization and emission minimization in this study. Decision makers can therefore choose interesting values on the front representing the trade-off. There are two wildly used methods for solving multi-objective optimization problems and deriving Pareto Front, namely ε-constraint method, and weighted-sum method.

### 3.6.1 ε-constraint method

The ε-constraint method is developed by Stephen Marglin (Marglin, 1967). It transforms a multi-objective optimization problem to one single-objective optimization problem subject to a bounding constraint related to the other objectives, and then to approximate Pareto Front (Steuer, 1986). In this thesis, the total transportation cost is the objective that should be minimized and the carbon emission is restricted by a constraint shown as follows:

$$\sum_p \sum_i \sum_j \sum_m \sum_t e_{ijm} L_{pijmt} \le C_t \tag{3-21}$$

where $C_t$ represents the upper level of emissions. The upper bound on $C_t$ is obtained from the models minimizing costs without a carbon emission limit. The minimum value of $C_t$ is determined by modifying models in section 3.4, in which the objective is changed to minimizing emissions instead of total cost. The objective function is given by:

$$Minimize \ \sum_p \sum_i \sum_j \sum_m \sum_t e_{ijm} L_{pijmt} \tag{3-22}$$

By setting a series of $C_t$ and optimizing the original model with constraints (3-21), a set of values of costs and emissions are obtained which can be plotted in Pareto Front.

### 3.6.2 Weighted-sum method

Another often used and classical method to obtain Pareto Front is the weighted-sum method. It is obvious that the ε-constraint method is restricted by new constraints, which will take more time for Solver to search an appropriate optimal solution within a small gap from the best possible result. The weighted-sum method is used to prevent this problem. All objectives are incorporated into one objective function, and weights are added for each objective. Compared to the original model, the emission function is also involved in the objective function. The numbers of variables and constraints are unchanged except for constraints of emission such as (3-7), (3-13) and (3-18). By changing the weight, a set of points is obtained to draw Pareto Front. The modified objective function is given by:

$$Minimize\ w * \left(\sum_p \sum_i \sum_j \sum_m \sum_t c_{\mathrm{ijmt}} L_{pijmt} + \sum_p \sum_i \sum_t I_{pit} + \sum_p \sum_j \sum_t I_{pjt}\right) + (1 - w) \sum_p \sum_i \sum_j \sum_m \sum_t e_{ijm} L_{pijmt} \tag{3-23}$$

where w represents the weight.

In this thesis, both methods are used. The weighted-sum method is easier and quicker to obtain a result with a small gap from the possible optimal solution in condition of a large number of variables and constraints. The same rule of sampling the series of $C_t$ in ε-constraint method and weight in weighted-sum method is applied: the range of $C_t$ or weight is divided into ten equal parts, like w = {1, 0.9, 0.8, 0.7… 0} is taken. If the value of cost and emission of one sample is significantly larger or smaller than the nearest sample point, the median between these two samples is added. Repeat this process until a smooth curve of cost and emission can be plotted.

# CHAPTER 4. ANALYSIS AND DISCUSSION

## 4.1 Case study

In order to explore the potential of reducing emissions of the listed strategies and to present tangible results, a case study is demonstrated. At first, a description of the problem is provided. In the next steps, data sources and the optimization process using models shown in section 3.4 are presented. Finally, an analysis of experimental results is provided as well as discussions pertaining to the strategies of emission reduction according to the case study results.

### 4.1.1 Description

Considering the known demand of fifteen types of lumbers of varying sizes in packs from twelve clients in the eastern North America, a forest company which operates two mills in the Lac-Saint-Jean area of Quebec, Canada should devise an efficient transportation planning process to deliver their products for an 8-week planning horizon.

### 4.1.2 Data collection

In order to analyze diverse situations, three sets of demand and production plans were generated. The production quantities are sufficient to satisfy all demands from customers. The demand of the same size lumbers is easy to fully pack in one trailer from set #1 and #2. However, the production of set #2 varies compared to set #1, and the process to find the optimal solution is relatively complex with the Solver. In set #3, the customer's demand varies noticeably so that it is difficult to deliver products in full trailer cars. The value of demand and production is attached as a table in APPENDIX A and APPENDIX B. The dimensions of the lumbers are exhibited in Table 4.1. Based on the product dimensions, the numbers of packs for each type of product were determined.

**Table 4.1 The dimensions of lumbers in foot and maximum number of packs loaded in a 53-foot truck trailer**

| Product No. | Height*Width (ft.$^2$) | Length (ft.) | Nb. of packs |
|---|---|---|---|
| 1 | 2x3 | 10 | 20 |
| 2 | 2x3 | 12 | 16 |
| 3 | 2x3 | 14 | 12 |
| 4 | 2x3 | 16 | 12 |
| 5 | 2x3 | 8 | 24 |
| 6 | 2x4 | 10 | 20 |
| 7 | 2x4 | 12 | 16 |
| 8 | 2x4 | 14 | 12 |
| 9 | 2x4 | 16 | 12 |
| 10 | 2x4 | 8 | 24 |
| 11 | 2x6 | 10 | 20 |
| 12 | 2x6 | 12 | 16 |
| 13 | 2x6 | 14 | 12 |
| 14 | 2x6 | 16 | 12 |
| 15 | 2x6 | 8 | 24 |

Before calculating cost and emission factors for transportation means and strategies, it was necessary to determine routes to deliver lumbers and to obtain the corresponding distance using Carbon RoadMap. The locations of customers and mills are shown in APPENDIX C. They are provided as precise coordinates with latitude and longitude.

In this case, two mills and twelve customers were considered, and forty-eight routes were generated. Transport Canada (2007) shows that the fuel consumption rate of trucks at speeds of 105 km/h was 40 L/100 km. The EIA (U.S. Energy Information Administration) estimated that combustion of one gallon of diesel fuel produced 22.38 pounds of $CO_2$ emissions (EIA, 2015). It is therefore approximately 1.073 kg per km of $CO_2$ eq. emitted by a heavy truck, with a gross weight of more than 15 tons, at speeds of 105 km per hour. The total $CO_2$ emissions for each route can be determined based on this value and traveled distance.

The cost mainly consists of three parts that are considered in this study, including fuel cost, driving cost, and maintenance cost. The diesel price provided by Natural Resources Canada was 98.5 Canadian dollar per litre in January 2016 (Natural Resources CANADA, 2017). Hence, the fuel consumption cost is about 0.39 Canadian dollar per km. It is assumed that the unit cost is 55 dollars per hour for driving, and the maintenance price is 0.5 dollars per km (W. Ford Torrey & Murray, 2015). As previously mentioned, the original average speed is 105 km per hour, and thus the driving cost should be 0.52 dollars per km. The cost and emissions generated of routes delivering products at speeds of 105 km per hour using road transportation are summarized in Table 4.2.

**Table 4.2 Transportation cost and emission of routes on speed of 105 km/h on road**

| Source | Destination | Distance (km) | **Emission (CO2 eq.)** | Fuel Cost (CAD) | Driving Cost (CAD) | Maintenance Cost (CAD) | **Total Cost (CAD)** | Time (hours) |
|---|---|---|---|---|---|---|---|---|
| St-Thomas | Montreal | 491.79 | 527.69 | 193.77 | 257.60 | 245.90 | 697.26 | 4.68 |
| | Toronto | 1031.93 | 1107.26 | 406.58 | 540.53 | 515.97 | 1463.08 | 9.83 |
| | Westfield | 913.85 | 980.56 | 360.06 | 478.68 | 456.93 | 1295.67 | 8.70 |
| | Portland | 979.04 | 1050.51 | 385.74 | 512.83 | 489.52 | 1388.09 | 9.32 |
| | Pittsburgh | 1458.73 | 1565.22 | 574.74 | 764.10 | 729.37 | 2068.20 | 13.89 |
| | Cleveland | 1433.01 | 1537.62 | 564.61 | 750.62 | 716.51 | 2031.74 | 13.65 |
| | Quebec | 336.18 | 360.72 | 132.45 | 176.09 | 168.09 | 476.64 | 3.20 |
| | Ottawa | 672.26 | 721.33 | 264.87 | 352.14 | 336.13 | 953.14 | 6.40 |
| | St Jerome | 526.03 | 564.43 | 207.26 | 275.54 | 263.02 | 745.81 | 5.01 |
| | Kingston | 778.57 | 835.41 | 306.76 | 407.82 | 389.29 | 1103.86 | 7.41 |
| | Montgomery | 977.46 | 1048.81 | 385.12 | 512.00 | 488.73 | 1385.85 | 9.31 |
| | Worcester | 924.75 | 992.26 | 364.35 | 484.39 | 462.38 | 1311.12 | 8.81 |
| La Doré | Montreal | 471.79 | 506.23 | 185.89 | 247.13 | 235.90 | 668.91 | 4.49 |
| | Toronto | 1011.94 | 1085.81 | 398.70 | 530.06 | 505.97 | 1434.74 | 9.64 |
| | Westfield | 893.85 | 959.10 | 352.18 | 468.21 | 446.93 | 1267.31 | 8.51 |
| | Portland | 959.05 | 1029.06 | 377.87 | 502.36 | 479.53 | 1359.75 | 9.13 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Pittsburgh | 1438.74 | 1543.77 | 566.86 | 753.63 | 719.37 | 2039.86 | 13.70 |
| | Cleveland | 1413.02 | 1516.17 | 556.73 | 740.15 | 706.51 | 2003.39 | 13.46 |
| | Quebec | 316.18 | 339.26 | 124.57 | 165.62 | 158.09 | 448.28 | 3.01 |
| | Ottawa | 652.27 | 699.89 | 256.99 | 341.67 | 326.14 | 924.79 | 6.21 |
| | St Jerome | 506.04 | 542.98 | 199.38 | 265.07 | 253.02 | 717.47 | 4.82 |
| | Kingston | 758.58 | 813.96 | 298.88 | 397.35 | 379.29 | 1075.52 | 7.22 |
| | Montgomery | 957.45 | 1027.34 | 377.24 | 501.52 | 478.73 | 1357.48 | 9.12 |
| | Worcester | 904.75 | 970.80 | 356.47 | 473.92 | 452.38 | 1282.76 | 8.62 |

As mentioned in the methodology in Section 3.2.2, fuel consumption is found to be reduced by 7.6% when speed decreases from 105 km/h to 95 km/h. Moreover, emissions have been shown to proportionally increase with the increase of fuel consumption (Kirby et al., 2000). Therefore, it is assumed that the emission and the fuel cost in this study is reduced by 7.6% when speed decreases from 105 km/h to 95 km/h. The parameters are shown in Table 4.3.

**Table 4.3 Transportation cost and emission of routes on speed of 95 km/h on road**

| Source | Destination | Distance (km) | **Emission (CO2 eq.)** | Fuel Cost (CAD) | Driving Cost (CAD) | Maintenance Cost (CAD) | **Total Cost (CAD)** | Time (hours) |
|---|---|---|---|---|---|---|---|---|
| St-Thomas | Montreal | 491.79 | 487.59 | 179.04 | 284.72 | 245.90 | 709.65 | 5.18 |
| | Toronto | 1031.93 | 1023.11 | 375.68 | 597.43 | 515.97 | 1489.08 | 10.86 |
| | Westfield | 913.85 | 906.04 | 332.69 | 529.07 | 456.93 | 1318.69 | 9.62 |
| | Portland | 979.04 | 970.67 | 356.43 | 566.81 | 489.52 | 1412.76 | 10.31 |
| | Pittsburgh | 1458.73 | 1446.26 | 531.06 | 844.53 | 729.37 | 2104.95 | 15.36 |
| | Cleveland | 1433.01 | 1420.76 | 521.70 | 829.64 | 716.51 | 2067.84 | 15.08 |
| | Quebec | 336.18 | 333.31 | 122.39 | 194.63 | 168.09 | 485.11 | 3.54 |
| | Ottawa | 672.26 | 666.51 | 244.74 | 389.20 | 336.13 | 970.07 | 7.08 |
| | St Jerome | 526.03 | 521.53 | 191.50 | 304.54 | 263.02 | 759.06 | 5.54 |
| | Kingston | 778.57 | 771.91 | 283.44 | 450.75 | 389.29 | 1123.48 | 8.20 |
| | Montgomery | 977.46 | 969.10 | 355.85 | 565.90 | 488.73 | 1410.48 | 10.29 |
| | Worcester | 924.75 | 916.85 | 336.66 | 535.38 | 462.38 | 1334.42 | 9.73 |
| La Doré | Montreal | 471.79 | 467.76 | 171.76 | 273.14 | 235.90 | 680.79 | 4.97 |
| | Toronto | 1011.94 | 1003.29 | 368.40 | 585.86 | 505.97 | 1460.23 | 10.65 |
| | Westfield | 893.85 | 886.21 | 325.41 | 517.49 | 446.93 | 1289.83 | 9.41 |
| | Portland | 959.05 | 950.85 | 349.15 | 555.24 | 479.53 | 1383.91 | 10.10 |
| | Pittsburgh | 1438.74 | 1426.44 | 523.78 | 832.95 | 719.37 | 2076.11 | 15.14 |
| | Cleveland | 1413.02 | 1400.94 | 514.42 | 818.06 | 706.51 | 2038.99 | 14.87 |
| | Quebec | 316.18 | 313.48 | 115.11 | 183.05 | 158.09 | 456.25 | 3.33 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Ottawa | 652.27 | 646.69 | 237.46 | 377.63 | 326.14 | 941.23 | 6.87 |
| | St Jerome | 506.04 | 501.71 | 184.23 | 292.97 | 253.02 | 730.22 | 5.33 |
| | Kingston | 758.58 | 752.10 | 276.17 | 439.18 | 379.29 | 1094.63 | 7.99 |
| | Montgomery | 957.45 | 949.27 | 348.57 | 554.31 | 478.73 | 1381.60 | 10.08 |
| | Worcester | 904.75 | 897.02 | 329.38 | 523.80 | 452.38 | 1305.56 | 9.52 |

Similarly, compared with normal road transport, eco-driving at an average speed of 105 km/h can achieve a 13.7% reduction of fuel consumption or a 13.7% reduction of carbon emission (Section 3.2.3). The parameters are summarized in Table 4.4.

**Table 4.4 Transportation cost and emission of routes with eco-driving**

| Source | Destination | Distance (km) | **Emission (CO2 eq.)** | Fuel Cost (CAD) | Driving Cost (CAD) | Maintenance Cost (CAD) | **Total Cost (CAD)** | Time (hours) |
|---|---|---|---|---|---|---|---|---|
| St-Thomas | Montreal | 491.79 | 455.40 | 167.22 | 310.60 | 245.90 | 723.72 | 4.68 |
| | Toronto | 1031.93 | 955.57 | 350.88 | 651.75 | 515.97 | 1518.59 | 9.83 |
| | Westfield | 913.85 | 846.22 | 310.73 | 577.17 | 456.93 | 1344.82 | 8.70 |
| | Portland | 979.04 | 906.59 | 332.90 | 618.34 | 489.52 | 1440.76 | 9.32 |
| | Pittsburgh | 1458.73 | 1350.78 | 496.00 | 921.30 | 729.37 | 2146.67 | 13.89 |
| | Cleveland | 1433.01 | 1326.97 | 487.25 | 905.06 | 716.51 | 2108.82 | 13.65 |
| | Quebec | 336.18 | 311.30 | 114.31 | 212.32 | 168.09 | 494.72 | 3.20 |
| | Ottawa | 672.26 | 622.51 | 228.58 | 424.59 | 336.13 | 989.30 | 6.40 |
| | St Jerome | 526.03 | 487.10 | 178.86 | 332.23 | 263.02 | 774.11 | 5.01 |
| | Kingston | 778.57 | 720.96 | 264.73 | 491.73 | 389.29 | 1145.74 | 7.41 |
| | Montgomery | 977.46 | 905.13 | 332.36 | 617.34 | 488.73 | 1438.43 | 9.31 |
| | Worcester | 924.75 | 856.32 | 314.44 | 584.05 | 462.38 | 1360.86 | 8.81 |
| La Doré | Montreal | 471.79 | 436.88 | 160.42 | 297.97 | 235.90 | 694.29 | 4.49 |
| | Toronto | 1011.94 | 937.06 | 344.08 | 639.12 | 505.97 | 1489.17 | 9.64 |
| | Westfield | 893.85 | 827.70 | 303.93 | 564.54 | 446.93 | 1315.39 | 8.51 |
| | Portland | 959.05 | 888.08 | 326.10 | 605.72 | 479.53 | 1411.34 | 9.13 |
| | Pittsburgh | 1438.74 | 1332.27 | 489.20 | 908.68 | 719.37 | 2117.25 | 13.70 |
| | Cleveland | 1413.02 | 1308.46 | 480.46 | 892.43 | 706.51 | 2079.40 | 13.46 |
| | Quebec | 316.18 | 292.78 | 107.51 | 199.69 | 158.09 | 465.29 | 3.01 |
| | Ottawa | 652.27 | 604.00 | 221.79 | 411.96 | 326.14 | 959.88 | 6.21 |
| | St Jerome | 506.04 | 468.59 | 172.06 | 319.60 | 253.02 | 744.69 | 4.82 |
| | Kingston | 758.58 | 702.44 | 257.93 | 479.10 | 379.29 | 1116.33 | 7.22 |
| | Montgomery | 957.45 | 886.60 | 325.55 | 604.71 | 478.73 | 1408.98 | 9.12 |
| | Worcester | 904.75 | 837.80 | 307.63 | 571.42 | 452.38 | 1331.43 | 8.62 |

Some adjustments were made to the solution from Carbon RoadMap for determining intermodal transportation routes, especially with respect to rail components and the connection between road and rail. Firstly, in this case study, the mill La Doré is located in proximity to a way station where the lumbers can be directly loaded into the rail car. However, this way station (at the mill) is not entered in the intermodal network. Carbon RoadMap generated routes from St-Félicien, located 21 km away from La Doré. This distance should therefore be added into the railway component and deleted from the road component. Secondly, there are three customers located at nearby rail terminals: Westfield, Cleveland Terminal, and Ottawa (Walkly yard), where delivered lumbers can be taken back to the warehouses. These are adjusted as it is done with La Doré way station instead of St-Félicien station. Both cost and emission are divided into road and rail parts. The calculation of the road section is identical to the road transportation. For intermodal, transit price should be considered. It is assumed that 50 Canadian dollars are charged if it is necessary to transport lumbers from railcar to freight truck and vice versa. The carload price is referred to the CN pricing documents which are available on the CN website (Canadian National Railway Company, 2017). These parameters are shown in Table 4.5.

**Table 4.5 Transportation cost and emission of routes on intermodal transportation**

| Source | Destination | Road (km) | Rail (km) | carload price (CAD) | Transit price (CAD) | **Emission (CO2 eq.)** | **Cost (CAD)** | Time (hours) |
|---|---|---|---|---|---|---|---|---|
| St-Thomas | Montreal | 19.03 | 453.82 | 3440.00 | 100.00 | 297.25 | 3566.98 | 23.87 |
| | Toronto | 17.27 | 1006.62 | 5963.00 | 100.00 | 632.57 | 6087.49 | 51.50 |
| | Westfield | 10.00 | 952.53 | 8082.50 | 50.00 | 591.77 | 8146.68 | 48.22 |
| | Portland | 12.32 | 845.80 | 7750.00 | 100.00 | 529.16 | 7867.47 | 43.41 |
| | Pittsburgh | 11.74 | 1442.41 | 8193.75 | 100.00 | 892.47 | 8310.40 | 73.23 |
| | Cleveland | 10.00 | 1372.41 | 6012.50 | 50.00 | 847.90 | 6076.68 | 69.22 |
| | Quebec | 11.78 | 337.62 | 3414.00 | 100.00 | 218.59 | 3530.70 | 17.99 |
| | Ottawa | 10.00 | 641.00 | 4376.00 | 50.00 | 401.74 | 4440.18 | 32.65 |
| | St Jerome | 12.70 | 495.25 | 3860.00 | 100.00 | 315.73 | 3978.01 | 25.88 |
| | Kingston | 20.09 | 744.34 | 4791.00 | 100.00 | 475.60 | 4919.48 | 38.41 |
| | Montgomery | 17.35 | 982.82 | 5200.00 | 100.00 | 618.14 | 5324.60 | 50.31 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Worcester | 13.16 | 990.28 | 8062.50 | 100.00 | 618.19 | 8181.16 | 50.64 |
| La Doré | Montreal | 9.04 | 449.23 | 3420.00 | 50.00 | 283.73 | 3482.82 | 23.55 |
| | Toronto | 7.28 | 1002.03 | 5943.00 | 50.00 | 619.05 | 6003.32 | 51.17 |
| | Westfield | 0.01 | 947.93 | 6646.25 | 0.00 | 578.25 | 6646.26 | 47.90 |
| | Portland | 2.33 | 841.20 | 7722.50 | 50.00 | 515.63 | 7775.80 | 43.08 |
| | Pittsburgh | 1.74 | 1437.82 | 6515.00 | 50.00 | 878.94 | 6567.47 | 72.91 |
| | Cleveland | 0.01 | 1367.82 | 4078.75 | 0.00 | 834.38 | 4078.76 | 68.89 |
| | Quebec | 1.78 | 333.02 | 3395.00 | 50.00 | 205.05 | 3447.52 | 17.67 |
| | Ottawa | 0.01 | 636.40 | 4407.00 | 0.00 | 388.21 | 4407.01 | 32.32 |
| | St Jerome | 2.71 | 490.66 | 3841.00 | 50.00 | 302.21 | 3894.84 | 25.56 |
| | Kingston | 10.10 | 739.74 | 4771.00 | 50.00 | 462.08 | 4835.32 | 38.08 |
| | Montgomery | 7.35 | 978.22 | 3927.50 | 50.00 | 604.60 | 3987.92 | 49.98 |
| | Worcester | 3.17 | 985.68 | 6576.25 | 50.00 | 604.67 | 6630.74 | 50.31 |

### 4.1.3 Optimization

The optimization model #1 using single-product loading patterns has totaled 24720 variables and 480 constraints in this case study. The following steps were repeated for all three sets of demand and production:

Step 1:

The values of demand, production, transportation cost and emission per km were organized into a spreadsheet and regarded as parameters of the model. The objective and constraints were then formulated by referring cell values. Only the values of demand and production needed to be modified regarding different sets. The model was then built in OpenSolver and was optimized by Gurobi engine. Alternatively, the spreadsheet was converted to a linear programming file (.lp), which was imported to Gurobi Optimizer for model optimization.

Step 2:

The model was solved using the methods for deriving Pareto Front introduced in the methodology chapter. If the ε-constraint method was employed, the model was optimized without the constraints of emissions to obtain the maximum value of emissions. The objective of (3-22) was then used to obtain the lower bound of emissions. The range of emissions was divided into ten equals and these values were assigned to emission constraints (3-7) in the solver. Alternatively, the values of weight from 0 to 1 with a step size of 0.1 was assigned to the objective (3-23) in the solver.

Solver produced a branch and bound tolerance between the current obtained optimal solution and the best possible solution when processing model optimization. If this tolerance reached 5% or less, the optimization was stopped and the results were obtained.

Step 3:

The pairs of values of cost and emissions derived from step 2 were recorded, and the total transportation cost in function of the total emissions was plotted. If the distance between two points was significantly larger than that of the others or if the curve was not smooth, one or more points were sampled between them by adjusting the value of emission constraints or the weight. For instance, if the distance between two points with the weights of 0.2 and 0.3 is found to be considerably larger than others, additional optimization using a weight of 0.25 will be conducted.

Three sets of data and Pareto Front were obtained in accordance with the abovementioned steps. In the next procedure, models using multi-product loading patterns were optimized. The heuristic model #3 with full shipment loading was established and optimized by LocalSolver. Since there were a plethora of combinations of various products packed in one trailer, the heuristic approach was not able to guarantee the optimality of results in a limited time period. As a result, heuristic model #3 only solved set #1 of demand and production.

The simplified model #4 was modified from the heuristic model #3 by regrouping wood products based on their lengths. The dimensions of lumbers are shown in Table 4.1. Regarding the length of products, the pack of 16-foot lumbers was grouped with that of 8-foot lumbers. 12-foot and 14-foot lumbers were grouped together since they are similar in length and can be fit in a 53-foot trailer. 10-foot lumbers were individually packed. The constraints (3-19) and (3-20) of the grouping were therefore expressed as follows:

$$\sum_{p\in a} X_{pijmt} \leq 20L_{aijmt} \quad a = \{1,6,11\}, \forall i,j,m,t \tag{4-1}$$

$$\sum_{p\in b1} X_{pijmt} \leq 16L_{bijmt} \quad b1 = \{2,7,12\}, b = \{2,3,7,8,12,13\},\ \forall i,j,m,t \tag{4-2}$$

$$\sum_{p\in b2} X_{pijmt} \leq 12L_{bijmt} \quad b2 = \{3,8,13\}, b = \{2,3,7,8,12,13\},\ \forall i,j,m,t \tag{4-3}$$

$$\sum_{p\in c1} X_{pijmt} + \sum_{p\in c2} 2X_{pijmt} \leq 24L_{cijmt} \quad c1 = \{5,10,15\},\ c2 = \{4,9,14\}, c = \{4,5,9,10,14,15\}, \forall i,j,m,t \tag{4-4}$$

This model was then processed with the same steps employed in model #1 using the single-product loading pattern, and the corresponding Pareto Front from the pairs of results was derived.

## 4.2 Results and discussion

Figure 4.1 illustrates the Pareto Front regarding the strategies of low-speed driving, eco-driving and intermodal transportation between total transportation cost (in Canadian dollars) and total emissions (in kg CO2 eq.) for three sets of parameters. The values of points derived from model optimization are attached as a table in APPENDIX D. In general, the shapes of Pareto Front of three sets are similar, particularly those for the first two sets. However, the third set is shifted to the upper right and is parallel to the other two sets, which suggests that both cost and emission in the third set are greater than its counterparts in the same level. The reason contributing to this result is that the third set of demand is difficult to be fully packed in car trailers. The total cost dramatically drops with the growth of emission before a certain point, and which can be regarded as the most interesting Pareto optimal solution or the trade-off point. The solution before this point is less competitive because of high costs before slightly decreasing until the emission peaks up to the maximum value.

In Figure 4.1, the triangle markers represent the Pareto optimal points of cost and emissions if only one transportation mean is allowed to be used in the plan. The results of intermodal transportation are marked in green, which is the costliest while emitting the least compared to other transportation means for the same set of data. On the contrary, the results of normal road transport coloured in purple appear that it is the least costly while emitting the most. According to the experimental results, the cost of intermodal transportation is 4.26 times as much as that of normal road transport, while its emission is almost half (0.57) of the latter. The red markers indicate points of eco-driving. Its carbon emission is 15 percent less than that of normal road transport, while it costs only 4 percent more than normal road transport. The points of low-speed driving are denoted in blue, which cost less and produce more emissions than eco-driving. Its cost is 2 percent more than normal road transport and its emission is 7 percent more than the latter.

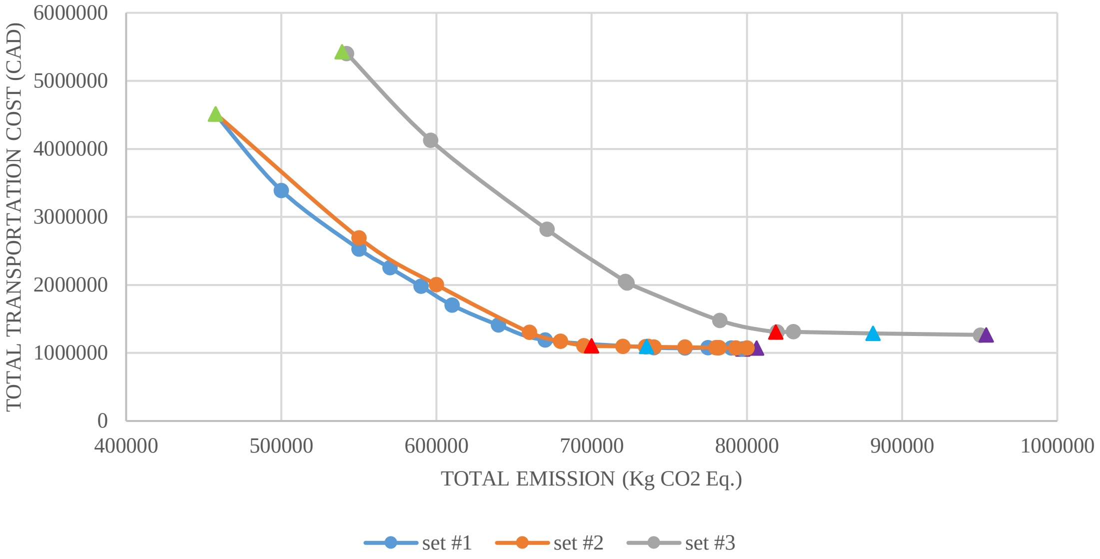


**Figure 4.1 Pareto Front of transportation cost and emission of model #1**

If the pair of transportation cost and emissions of a normal road trip without any changes in transport logistics are set as reference, Table 4.6, Table 4.7 and Table 4.8 demonstrate the percentage of trips by each transportation mean (normal road route, intermodal transportation, low-speed driving and eco-driving) depending on the different solutions found for three sets of data. It shows what the model recommends as the pressure to lower emissions increases. For instance, for reducing 5% of the carbon footprint with an increase of 1% of transportation cost for set #1, normal road transport trips account for 46% of the total shipment, low-speed driving trips represent 53% and eco-driving trips comprise the remaining 1%. If an additional 2% of total emission is reduced meanwhile one more percentage point of cost is added, the products are mostly delivered by eco-driving, as only 4% of total trips are allocated to normal road trips and low-speed trips.

**Table 4.6 Percentage of trips with each transportation mean for set #1**

| Sample | Cost | Emission | Normal road trip | Intermodal | Low speed | Eco-driving |
|---|---|---|---|---|---|---|
| 1 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 0.00 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 2 | 1.00 | 1.00 | 0.97 | 0.00 | 0.03 | 0.00 |
| 3 | 1.01 | 0.95 | 0.46 | 0.00 | 0.53 | 0.01 |
| 4 | 1.02 | 0.93 | 0.02 | 0.00 | 0.01 | 0.96 |
| 5 | 1.12 | 0.84 | 0.00 | 0.06 | 0.00 | 0.93 |
| 6 | 1.33 | 0.80 | 0.00 | 0.15 | 0.00 | 0.85 |
| 7 | 1.61 | 0.77 | 0.00 | 0.25 | 0.00 | 0.75 |
| 8 | 2.13 | 0.72 | 0.00 | 0.78 | 0.00 | 0.22 |
| 9 | 2.39 | 0.69 | 0.00 | 0.53 | 0.00 | 0.47 |
| 10 | 3.20 | 0.63 | 0.00 | 0.78 | 0.00 | 0.22 |
| 11 | 4.26 | 0.57 | 0.00 | 1.00 | 0.00 | 0.00 |

**Table 4.7 Percentage of trips with each transportation mean for set #2**

| Sample | Cost | Emission | Normal road trip | Intermodal | Low speed | Eco-driving |
|---|---|---|---|---|---|---|
| 1 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 0.00 |
| 2 | 1.00 | 0.99 | 0.98 | 0.00 | 0.01 | 0.01 |
| 3 | 1.01 | 0.97 | 0.53 | 0.00 | 0.14 | 0.33 |
| 4 | 1.02 | 0.91 | 0.01 | 0.00 | 0.57 | 0.42 |
| 5 | 1.03 | 0.87 | 0.01 | 0.00 | 0.00 | 0.98 |
| 6 | 1.04 | 0.86 | 0.04 | 0.00 | 0.02 | 0.95 |
| 7 | 1.10 | 0.84 | 0.01 | 0.00 | 0.00 | 0.99 |
| 8 | 1.22 | 0.82 | 0.00 | 0.06 | 0.00 | 0.94 |
| 9 | 1.87 | 0.74 | 0.00 | 0.23 | 0.00 | 0.77 |
| 10 | 2.52 | 0.68 | 0.01 | 0.79 | 0.00 | 0.19 |
| 11 | 4.22 | 0.57 | 0.00 | 1.00 | 0.00 | 0.00 |

**Table 4.8 Percentage of trips with each transportation mean for set #3**

| Sample | Cost | Emission | Normal road trip | Intermodal | Low speed | Eco-driving |
|---|---|---|---|---|---|---|
| 1 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 0.00 |
| 2 | 1.00 | 1.00 | 0.88 | 0.00 | 0.04 | 0.08 |
| 3 | 1.02 | 0.93 | 0.00 | 0.00 | 0.59 | 0.40 |
| 4 | 1.04 | 0.87 | 0.00 | 0.00 | 0.00 | 0.99 |
| 5 | 1.04 | 0.86 | 0.00 | 0.00 | 0.00 | 0.99 |
| 6 | 1.04 | 0.86 | 0.00 | 0.02 | 0.00 | 0.97 |
| 7 | 1.17 | 0.82 | 0.00 | 0.10 | 0.00 | 0.90 |
| 8 | 1.61 | 0.76 | 0.00 | 0.24 | 0.00 | 0.76 |
| 9 | 1.63 | 0.76 | 0.00 | 0.24 | 0.00 | 0.75 |
| 10 | 2.24 | 0.71 | 0.00 | 0.44 | 0.00 | 0.56 |
| 11 | 3.28 | 0.63 | 0.00 | 0.74 | 0.00 | 0.26 |

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
| 12 | 4.29 | 0.57 | 0.00 | 1.00 | 0.00 | 0.00 |
| 13 | 4.31 | 0.57 | 0.00 | 1.00 | 0.00 | 0.00 |

These tables reveal that with the increase of carbon emission reduction, normal road transport is gradually replaced by intermodal transportation, low-speed, or eco-driving. Meanwhile, the total transportation cost will increase accordingly. If the emission decreases by less than 7% with the increase of cost set at less than 2%, low-speed driving and eco-driving should be combined with normal road transport as the optimal transportation means. Furthermore, if the emission reduction is between 7% - 18% while the increase of transportation cost is controlled under 20%, the eco-driving strategy can effectively reduce the carbon footprint compared to other strategies. Regardless of the transportation cost, the intermodal transportation is shown to be the most efficient strategy to reduce the emissions. The combination of different transportation strategies can be adjusted according to the preference of decision makers depending on of the level of investment and carbon emission reduction targeted.

Figure 4.2 illustrates the Pareto Front of model #3 using multi-product loading patterns with the full shipment solved by using LocalSolver. The values of the results are attached in APPENDIX E. The blue line represents the actual Pareto Front given by experimental results and the green line represents the expected Pareto Front. Several points found by the model are observed as non-Pareto-optimal, especially for the point in the shape of the triangle marked in red. A possible explanation for this occurrence is the restriction of computer processing speed and the seemingly infinite number of variables and constraints. This reinforces the fact that the optimal solution produced by LocalSolver is still far from the ideal solution.

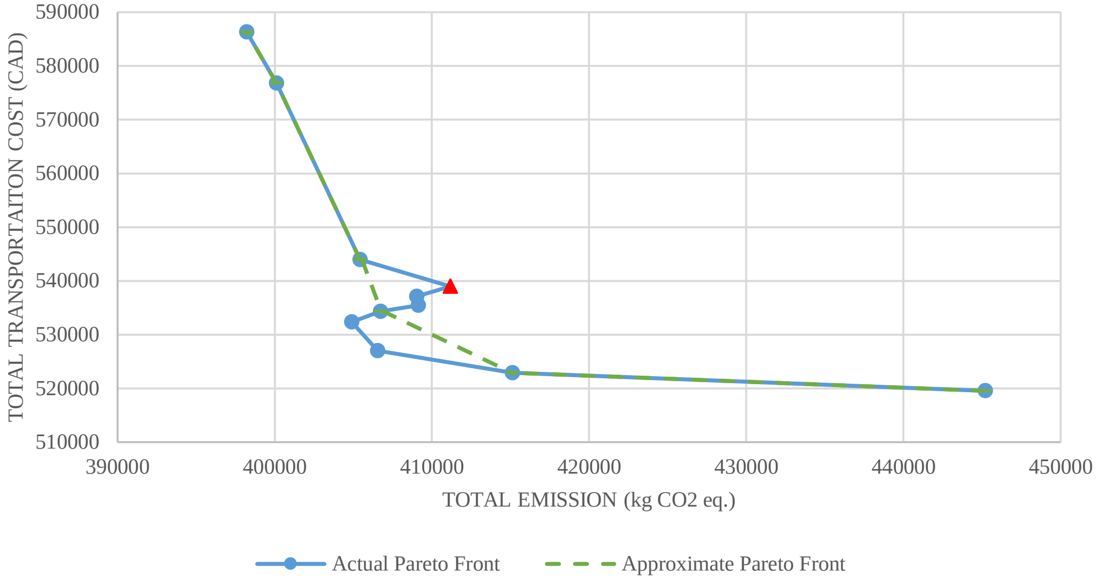


**Figure 4.2 Pareto Front of heuristic model #3 using multi-product loading patterns with full shipment of data set #1**

Figure 4.3 illustrates the Pareto Front of the simplified model #4 using multi-product loading patterns combined with low-speed driving, eco-driving, and intermodal transportation. The values of results are summarized in a table attached in APPENDIX F. We observe that the trend of cost coupled with the decrease of emissions is similar for all three sets of data. The Pareto-optimal points representing each transportation mean are respectively marked as triangles in different colours similar to the results of model #1.

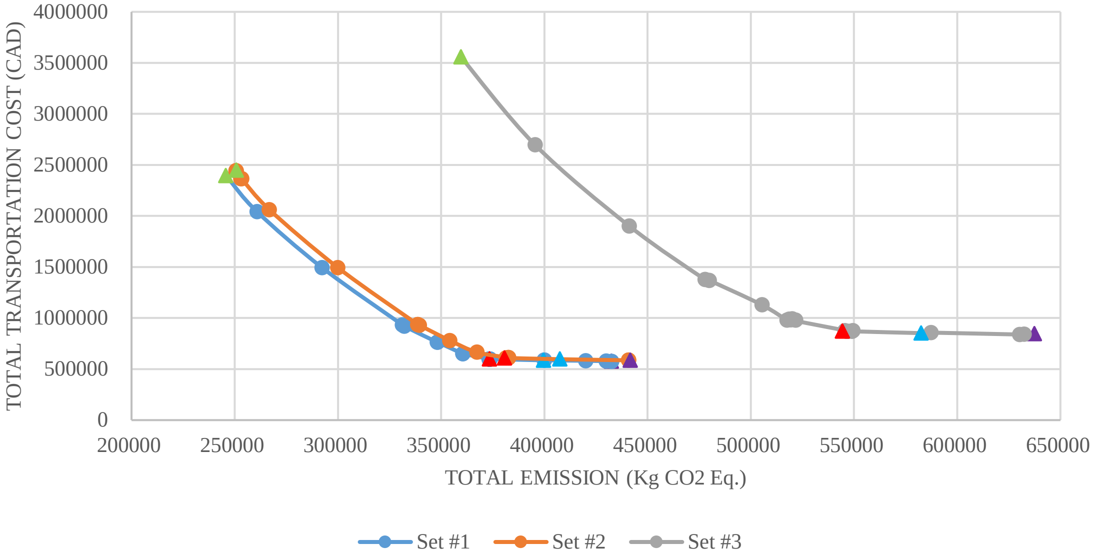


**Figure 4.3 Pareto Front of simplified model #4 with multi-product loading patterns with full shipment**

Figure 4.4 reveals the comparison of the optimization results of model #1 and those of simplified model #4 using multi-product loading patterns. Compared with the optimization results of model #1, it is more cost-efficient and produces fewer emissions at the same level in simplified model #4. It is proven that the optimizing loading pattern method provides more options to ship by combining products in an economical and eco-friendly condition. It is shown in the numerical results that both transportation cost and emission of simplified model #4 using multi-product loading patterns decreased to roughly 54% of those of model #1 for set #1 and #2 respectively. For set #3, it can reduce 33% of cost and emission shown in simplified model #4 compared to model #1.

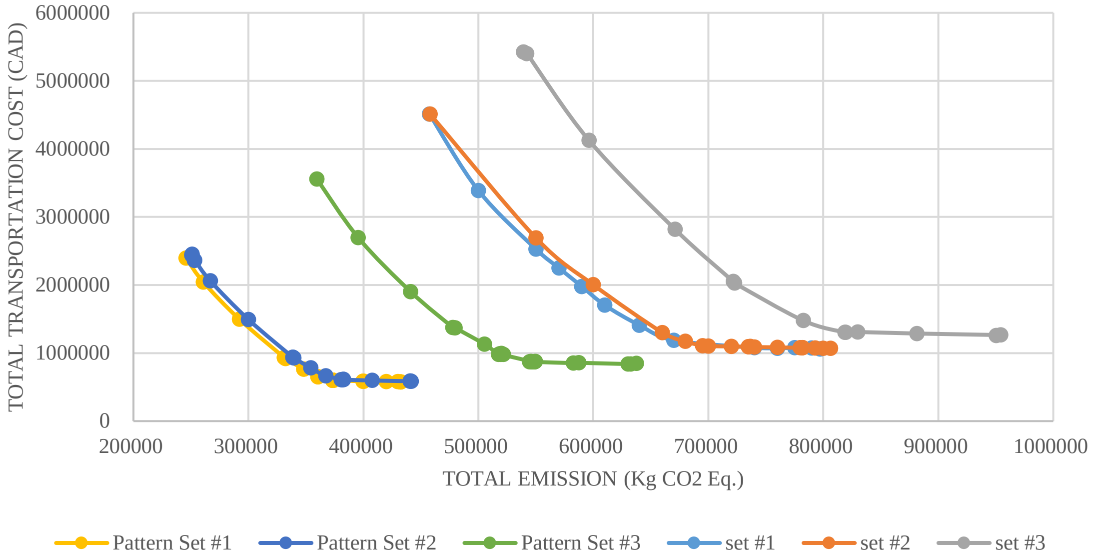


**Figure 4.4 Comparison of Pareto Front of model #1 and simplified model #4 using multi-product loading patterns**

Compared to simplified model #4 (see Figure 4.5), this solution has a lower total transportation cost. On the contrary, the range of possible improvements in emission reduction is within approximately 50000 kg $CO_2$ eq. in model #3, much lower than that of model #4 as 200000 kg $CO_2$ eq. It shows that the shipping costs are less if there are more available patterns to choose from. The emission range in model #3 is smaller than that of the simplified model, while its least emission is greater. It could suggest that if there are more options for loading patterns, it is more likely to produce lower costs. Due to the differences in the processes of Gurobi and LocalSolver, used to solve simplified and heuristic models, it is a great challenge to find an acceptable result in the heuristic model.

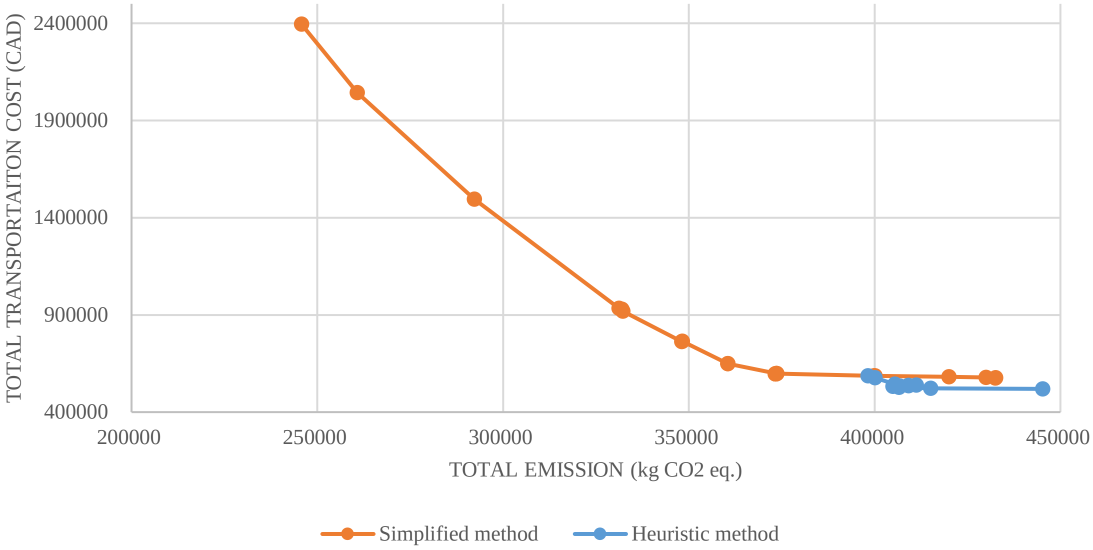


**Figure 4.5 Comparison of simplified and heuristic models using multi-product loading patterns**

# CHAPTER 5. CONCLUSION

The purpose of this study is to analyze the potential strategies to reduce carbon emissions. The main approach is to conduct the transportation cost optimization under the cap and trade scheme. Some strategies in previous studies are introduced and four are presented in this paper, namely those of low-speed driving, eco-driving, intermodal transportation, and optimizing loading pattern. Heuristic and simplified models are provided to assess the impact of multi-product loading patterns on emissions reduction. Pareto Front of transportation cost and emissions for different strategies is plotted according to the optimization results by optimizers like OpenSolver, Gurobi, and LocalSolver. The Pareto optimal points represent the most practical method of real-world application.

A related case study was conducted to illustrate the approach analyzing the potential of different strategies using data collected by studies, public government documents, and real-world resources. To enhance the findings of this paper, three different sets of demand from twelve clients and production from two mills were provided. Some of their locations were near rail terminals, while others were not.

The case study results show that the eco-driving strategy is the best strategy to reducing emissions despite incurring slightly greater costs. If the eco-driving method is employed as the primary transportation mean, it can reduce up to 18% of carbon emissions coupled with an increase in transportation cost within 20%. The intermodal transportation is the eco-friendliest approach, which can reduce up to 43% of emissions compared to normal road transport, while the corresponding increase in cost is considerable. The choices of multi-product loading patterns are worth considering in transportation planning since it can bring forth considerable benefits with regards to both total cost and emission reduction. The combination of different strategies can be likewise considered in transportation planning with accordance to preference. However, the possibility or the difficulty of implementation in the real world has to be further addressed in future research.

The optimization model constructed in this study may be applied in other conditions. It is a bi-objective model with objective of cost and emission in tactical planning level. The model could be extended or adapted for operational planning purposes, by adding VRP-type routing constraints as well as additional constraints to accommodate time window and driver hours. Since it is not specific to the forest products industry, this model can be also applied to other industries reliant on heavy-duty truck and rail transport with appropriate alternatives like loading patterns.

There are several suggestions on future studies given as follows: as the result shown in the case study and the aforementioned discussion, optimizing loading patterns has a high potential to improve cost and environmental efficiency. However, due to the complexity of heuristic models in this study, the Pareto optimality results are not optimal in terms of precisely assessing the potential of reducing emissions. This problem can be solved by improving heuristic and simplified approaches in order to facilitate the calculation of emission reduction and cost savings. Moreover, the current carbon price in Quebec and California's market is around 17 Canadian dollars, higher than the general price of approximately $3 (International Carbon Action Partnership, 2017b). In reality, the decision on the choice of strategy undoubtedly depends on how strong the economic incentive is to reduce carbon emissions or on the decision makers' willingness to reduce their emissions at the expense of increased logistical costs.  Finally, it is not necessary to fully load the car trailer in order to avoid the results of set #3 in the case study.

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# APPENDIX A. Demands from customers in case study

| | | | Product | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Set | Week | Customer | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 1 | 1 | 1 | 4 | 5 | 7 | 9 | 4 | 4 | 10 | 6 | 16 | 3 | 4 | 7 | 2 | 11 | 0 |
| | | 2 | 7 | 10 | 12 | 8 | 8 | 8 | 15 | 18 | 43 | 2 | 5 | 5 | 12 | 23 | 1 |
| | | 3 | 1 | 4 | 5 | 2 | 1 | 4 | 6 | 7 | 15 | 2 | 2 | 1 | 3 | 6 | 2 |
| | | 4 | 1 | 0 | 8 | 3 | 2 | 4 | 3 | 8 | 6 | 3 | 1 | 1 | 2 | 8 | 0 |
| | | 5 | 5 | 2 | 5 | 4 | 2 | 4 | 4 | 3 | 14 | 4 | 3 | 3 | 3 | 8 | 0 |
| | | 6 | 2 | 2 | 4 | 1 | 1 | 2 | 3 | 3 | 5 | 2 | 1 | 2 | 1 | 9 | 1 |
| | | 7 | 2 | 2 | 2 | 3 | 0 | 3 | 2 | 4 | 5 | 1 | 0 | 2 | 2 | 2 | 2 |
| | | 8 | 2 | 1 | 1 | 2 | 1 | 1 | 7 | 2 | 9 | 1 | 0 | 2 | 7 | 7 | 0 |
| | | 9 | 2 | 1 | 2 | 0 | 1 | 0 | 4 | 5 | 6 | 1 | 1 | 4 | 4 | 2 | 0 |
| | | 10 | 3 | 0 | 2 | 1 | 0 | 3 | 0 | 1 | 8 | 1 | 0 | 0 | 2 | 3 | 0 |
| | | 11 | 4 | 1 | 5 | 3 | 2 | 3 | 5 | 9 | 13 | 1 | 0 | 5 | 3 | 2 | 0 |
| | | 12 | 2 | 3 | 1 | 0 | 1 | 2 | 1 | 3 | 6 | 2 | 0 | 1 | 0 | 4 | 0 |
| | 2 | 1 | 4 | 4 | 5 | 8 | 6 | 5 | 9 | 6 | 23 | 1 | 4 | 4 | 8 | 11 | 0 |
| | | 2 | 10 | 10 | 15 | 7 | 2 | 12 | 14 | 15 | 35 | 6 | 1 | 9 | 12 | 31 | 2 |
| | | 3 | 1 | 3 | 4 | 5 | 2 | 5 | 5 | 4 | 11 | 1 | 1 | 2 | 3 | 5 | 1 |
| | | 4 | 3 | 0 | 3 | 7 | 0 | 2 | 2 | 6 | 10 | 1 | 1 | 1 | 4 | 5 | 0 |
| | | 5 | 2 | 4 | 5 | 2 | 2 | 4 | 5 | 7 | 3 | 2 | 0 | 1 | 4 | 6 | 0 |
| | | 6 | 2 | 4 | 6 | 3 | 1 | 2 | 5 | 3 | 7 | 2 | 1 | 2 | 2 | 4 | 0 |
| | | 7 | 0 | 1 | 3 | 1 | 1 | 1 | 1 | 2 | 9 | 0 | 0 | 1 | 3 | 6 | 1 |
| | | 8 | 3 | 0 | 3 | 1 | 1 | 3 | 4 | 3 | 5 | 1 | 0 | 1 | 5 | 6 | 2 |
| | | 9 | 1 | 0 | 0 | 1 | 0 | 3 | 2 | 7 | 3 | 3 | 0 | 0 | 2 | 4 | 0 |
| | | 10 | 2 | 1 | 6 | 0 | 1 | 0 | 3 | 6 | 12 | 1 | 2 | 2 | 5 | 3 | 0 |
| | | 11 | 2 | 2 | 3 | 1 | 1 | 5 | 6 | 11 | 9 | 4 | 2 | 5 | 4 | 9 | 0 |
| | | 12 | 1 | 1 | 5 | 2 | 0 | 2 | 4 | 5 | 5 | 1 | 1 | 0 | 3 | 4 | 1 |
| | 3 | 1 | 3 | 4 | 9 | 6 | 2 | 4 | 7 | 8 | 20 | 2 | 3 | 5 | 9 | 13 | 2 |
| | | 2 | 7 | 6 | 14 | 10 | 5 | 9 | 19 | 20 | 35 | 6 | 4 | 8 | 8 | 24 | 0 |
| | | 3 | 1 | 0 | 5 | 2 | 2 | 4 | 2 | 6 | 6 | 3 | 2 | 1 | 1 | 4 | 0 |
| | | 4 | 2 | 2 | 7 | 1 | 1 | 3 | 6 | 9 | 12 | 4 | 0 | 4 | 2 | 9 | 1 |
| | | 5 | 3 | 1 | 2 | 6 | 1 | 3 | 6 | 7 | 8 | 2 | 2 | 2 | 4 | 1 | 2 |
| | | 6 | 6 | 0 | 4 | 2 | 1 | 2 | 2 | 7 | 10 | 4 | 3 | 0 | 3 | 9 | 0 |
| | | 7 | 3 | 0 | 3 | 2 | 1 | 2 | 5 | 3 | 8 | 0 | 0 | 2 | 5 | 5 | 0 |
| | | 8 | 1 | 3 | 1 | 3 | 1 | 1 | 0 | 3 | 11 | 1 | 1 | 1 | 4 | 8 | 1 |
| | | 9 | 2 | 2 | 2 | 0 | 1 | 0 | 2 | 1 | 6 | 2 | 0 | 2 | 3 | 6 | 0 |
| | | 10 | 1 | 1 | 4 | 2 | 0 | 5 | 3 | 2 | 10 | 2 | 1 | 5 | 4 | 4 | 1 |
| | | 11 | 3 | 7 | 4 | 4 | 4 | 5 | 2 | 9 | 10 | 2 | 0 | 1 | 5 | 9 | 3 |
| | | 12 | 0 | 0 | 6 | 3 | 0 | 2 | 4 | 2 | 4 | 1 | 2 | 0 | 2 | 2 | 0 |
| | 4 | 1 | 4 | 6 | 10 | 4 | 5 | 9 | 4 | 8 | 14 | 3 | 3 | 3 | 8 | 22 | 2 |
| | | 2 | 7 | 3 | 11 | 8 | 7 | 10 | 13 | 15 | 39 | 7 | 5 | 13 | 12 | 22 | 2 |
| | | 3 | 3 | 4 | 2 | 2 | 1 | 1 | 4 | 8 | 15 | 0 | 1 | 6 | 7 | 4 | 0 |
| | | 4 | 3 | 2 | 6 | 4 | 1 | 1 | 3 | 4 | 8 | 0 | 0 | 1 | 2 | 6 | 0 |
| | | 5 | 2 | 4 | 1 | 2 | 2 | 2 | 2 | 6 | 12 | 2 | 1 | 1 | 5 | 7 | 0 |
| | | 6 | 3 | 2 | 2 | 5 | 1 | 4 | 6 | 4 | 10 | 1 | 1 | 0 | 2 | 8 | 0 |
| | | 7 | 1 | 2 | 7 | 2 | 0 | 2 | 2 | 3 | 4 | 1 | 1 | 0 | 1 | 5 | 1 |
| | | 8 | 3 | 1 | 3 | 2 | 2 | 1 | 2 | 6 | 6 | 5 | 1 | 0 | 5 | 5 | 1 |
| | | 9 | 0 | 4 | 3 | 2 | 0 | 2 | 0 | 6 | 3 | 1 | 0 | 1 | 1 | 1 | 0 |
| | | 10 | 4 | 0 | 2 | 1 | 0 | 2 | 1 | 1 | 7 | 1 | 2 | 3 | 2 | 3 | 3 |
| | | 11 | 3 | 1 | 8 | 3 | 0 | 6 | 10 | 6 | 22 | 4 | 3 | 4 | 5 | 13 | 0 |
| | | 12 | 4 | 0 | 1 | 1 | 0 | 5 | 1 | 3 | 5 | 1 | 1 | 0 | 2 | 2 | 0 |
| | 5 | 1 | 6 | 5 | 7 | 3 | 2 | 5 | 4 | 13 | 26 | 2 | 0 | 1 | 7 | 11 | 0 |
| | | 2 | 6 | 5 | 16 | 7 | 2 | 8 | 10 | 15 | 39 | 3 | 3 | 6 | 11 | 24 | 2 |
| | | 3 | 3 | 2 | 3 | 0 | 2 | 2 | 2 | 6 | 11 | 1 | 0 | 1 | 7 | 3 | 0 |

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 4 | 4 | 3 | 3 | 3 | 0 | 5 | 5 | 8 | 11 | 4 | 1 | 3 | 4 | 5 | 0 |
| | | 5 | 4 | 1 | 9 | 5 | 4 | 6 | 2 | 11 | 10 | 4 | 1 | 4 | 4 | 6 | 1 |
| | | 6 | 3 | 3 | 1 | 3 | 2 | 1 | 2 | 4 | 9 | 2 | 3 | 2 | 2 | 5 | 2 |
| | | 7 | 4 | 2 | 1 | 0 | 0 | 0 | 8 | 6 | 5 | 0 | 1 | 2 | 0 | 2 | 0 |
| | | 8 | 3 | 3 | 2 | 0 | 2 | 4 | 4 | 3 | 9 | 4 | 1 | 1 | 3 | 5 | 0 |
| | | 9 | 2 | 0 | 1 | 1 | 0 | 0 | 3 | 6 | 5 | 3 | 0 | 0 | 3 | 5 | 0 |
| | | 10 | 1 | 0 | 3 | 2 | 0 | 3 | 1 | 5 | 5 | 1 | 0 | 0 | 3 | 6 | 0 |
| | | 11 | 2 | 2 | 8 | 5 | 2 | 8 | 8 | 4 | 12 | 5 | 2 | 6 | 4 | 13 | 2 |
| | | 12 | 1 | 1 | 4 | 1 | 0 | 3 | 3 | 6 | 9 | 0 | 1 | 0 | 0 | 7 | 0 |
| | 6 | 1 | 2 | 4 | 8 | 5 | 2 | 5 | 12 | 15 | 14 | 4 | 3 | 3 | 8 | 12 | 1 |
| | | 2 | 9 | 7 | 8 | 6 | 6 | 10 | 10 | 26 | 35 | 5 | 2 | 6 | 7 | 18 | 4 |
| | | 3 | 4 | 6 | 2 | 2 | 2 | 4 | 3 | 3 | 7 | 3 | 1 | 1 | 5 | 8 | 0 |
| | | 4 | 0 | 1 | 4 | 1 | 1 | 1 | 2 | 6 | 13 | 2 | 4 | 1 | 3 | 5 | 1 |
| | | 5 | 8 | 2 | 6 | 5 | 1 | 2 | 4 | 3 | 14 | 6 | 2 | 2 | 1 | 3 | 0 |
| | | 6 | 5 | 1 | 7 | 2 | 1 | 1 | 2 | 4 | 9 | 2 | 2 | 0 | 4 | 7 | 0 |
| | | 7 | 1 | 2 | 5 | 2 | 1 | 5 | 5 | 4 | 9 | 2 | 0 | 3 | 2 | 2 | 1 |
| | | 8 | 3 | 1 | 2 | 2 | 1 | 2 | 2 | 3 | 8 | 1 | 0 | 1 | 1 | 4 | 1 |
| | | 9 | 1 | 0 | 1 | 1 | 2 | 0 | 4 | 5 | 12 | 2 | 1 | 1 | 1 | 5 | 0 |
| | | 10 | 2 | 1 | 4 | 4 | 0 | 0 | 2 | 6 | 6 | 1 | 1 | 0 | 1 | 6 | 0 |
| | | 11 | 1 | 2 | 3 | 5 | 0 | 4 | 6 | 12 | 18 | 1 | 2 | 3 | 8 | 4 | 0 |
| | | 12 | 2 | 1 | 1 | 1 | 0 | 3 | 2 | 2 | 5 | 2 | 0 | 3 | 0 | 3 | 0 |
| | 7 | 1 | 3 | 5 | 12 | 5 | 3 | 4 | 9 | 13 | 24 | 3 | 0 | 5 | 11 | 12 | 0 |
| | | 2 | 8 | 5 | 9 | 11 | 5 | 13 | 10 | 17 | 32 | 9 | 4 | 7 | 14 | 18 | 1 |
| | | 3 | 3 | 6 | 3 | 2 | 0 | 3 | 4 | 6 | 8 | 1 | 2 | 1 | 1 | 5 | 1 |
| | | 4 | 1 | 5 | 5 | 0 | 0 | 5 | 5 | 7 | 11 | 3 | 2 | 2 | 2 | 8 | 3 |
| | | 5 | 4 | 1 | 4 | 1 | 1 | 2 | 2 | 6 | 13 | 1 | 0 | 3 | 3 | 4 | 0 |
| | | 6 | 1 | 1 | 1 | 2 | 0 | 3 | 4 | 5 | 6 | 0 | 1 | 3 | 4 | 3 | 1 |
| | | 7 | 2 | 2 | 5 | 0 | 0 | 2 | 2 | 7 | 10 | 0 | 3 | 4 | 3 | 4 | 1 |
| | | 8 | 1 | 1 | 2 | 4 | 3 | 2 | 7 | 5 | 6 | 3 | 0 | 2 | 5 | 3 | 1 |
| | | 9 | 3 | 4 | 1 | 1 | 1 | 1 | 4 | 2 | 10 | 1 | 0 | 0 | 3 | 2 | 0 |
| | | 10 | 2 | 0 | 1 | 1 | 0 | 0 | 4 | 5 | 8 | 2 | 0 | 2 | 0 | 4 | 0 |
| | | 11 | 9 | 4 | 4 | 5 | 3 | 4 | 3 | 11 | 7 | 3 | 1 | 0 | 4 | 14 | 0 |
| | | 12 | 2 | 1 | 1 | 2 | 3 | 1 | 2 | 4 | 4 | 1 | 0 | 0 | 2 | 1 | 1 |
| | 8 | 1 | 6 | 6 | 13 | 6 | 4 | 6 | 6 | 10 | 19 | 4 | 5 | 4 | 2 | 8 | 2 |
| | | 2 | 10 | 10 | 15 | 7 | 4 | 8 | 22 | 19 | 34 | 11 | 4 | 6 | 9 | 23 | 0 |
| | | 3 | 0 | 1 | 5 | 5 | 0 | 2 | 3 | 7 | 6 | 1 | 0 | 2 | 2 | 5 | 2 |
| | | 4 | 2 | 3 | 2 | 0 | 4 | 1 | 4 | 6 | 12 | 4 | 2 | 2 | 2 | 6 | 0 |
| | | 5 | 0 | 0 | 7 | 1 | 4 | 4 | 2 | 4 | 19 | 3 | 2 | 4 | 5 | 5 | 0 |
| | | 6 | 2 | 2 | 2 | 1 | 0 | 5 | 6 | 4 | 6 | 1 | 0 | 1 | 3 | 5 | 1 |
| | | 7 | 2 | 0 | 0 | 4 | 2 | 0 | 3 | 3 | 6 | 2 | 0 | 3 | 3 | 4 | 2 |
| | | 8 | 4 | 2 | 2 | 4 | 1 | 5 | 1 | 5 | 10 | 3 | 2 | 2 | 2 | 7 | 1 |
| | | 9 | 3 | 2 | 1 | 0 | 0 | 4 | 0 | 3 | 9 | 0 | 0 | 1 | 4 | 3 | 1 |
| | | 10 | 2 | 2 | 6 | 0 | 0 | 2 | 3 | 0 | 7 | 0 | 0 | 0 | 2 | 6 | 0 |
| | | 11 | 2 | 4 | 5 | 1 | 1 | 1 | 3 | 6 | 27 | 2 | 3 | 1 | 5 | 7 | 0 |
| | | 12 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 6 | 9 | 1 | 0 | 2 | 2 | 1 | 1 |
| 2 | 1 | 1 | 7 | 5 | 8 | 4 | 5 | 4 | 13 | 10 | 24 | 5 | 4 | 6 | 7 | 14 | 2 |
| | | 2 | 4 | 7 | 15 | 7 | 1 | 13 | 17 | 12 | 30 | 5 | 4 | 4 | 8 | 18 | 2 |
| | | 3 | 1 | 3 | 3 | 3 | 1 | 2 | 5 | 12 | 9 | 0 | 12 | 4 | 6 | 5 | 1 |
| | | 4 | 1 | 1 | 12 | 2 | 0 | 5 | 4 | 6 | 15 | 0 | 1 | 2 | 2 | 5 | 0 |
| | | 5 | 5 | 0 | 2 | 1 | 2 | 4 | 4 | 5 | 12 | 1 | 0 | 2 | 4 | 7 | 0 |
| | | 6 | 2 | 0 | 5 | 6 | 1 | 2 | 3 | 1 | 2 | 2 | 0 | 1 | 2 | 4 | 0 |
| | | 7 | 5 | 1 | 3 | 0 | 2 | 4 | 4 | 3 | 6 | 0 | 0 | 0 | 3 | 8 | 1 |
| | | 8 | 4 | 8 | 2 | 1 | 0 | 2 | 4 | 3 | 9 | 1 | 0 | 1 | 3 | 6 | 0 |
| | | 9 | 0 | 1 | 2 | 0 | 3 | 3 | 2 | 8 | 7 | 2 | 2 | 0 | 12 | 1 | 2 |

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10 | 5 | 3 | 4 | 3 | 0 | 0 | 0 | 12 | 8 | 1 | 0 | 2 | 3 | 5 | 0 |
| | | 11 | 2 | 5 | 3 | 2 | 2 | 3 | 4 | 9 | 14 | 4 | 4 | 3 | 3 | 5 | 0 |
| | | 12 | 8 | 1 | 4 | 2 | 8 | 0 | 2 | 2 | 5 | 3 | 4 | 0 | 3 | 3 | 0 |
| | 2 | 1 | 8 | 9 | 9 | 5 | 4 | 5 | 4 | 13 | 14 | 4 | 2 | 5 | 5 | 20 | 0 |
| | | 2 | 4 | 8 | 23 | 9 | 8 | 8 | 16 | 21 | 32 | 10 | 0 | 7 | 10 | 23 | 2 |
| | | 3 | 3 | 1 | 2 | 2 | 0 | 4 | 3 | 6 | 10 | 1 | 1 | 3 | 4 | 5 | 10 |
| | | 4 | 2 | 1 | 2 | 5 | 9 | 3 | 5 | 4 | 12 | 8 | 0 | 1 | 11 | 1 | 0 |
| | | 5 | 3 | 2 | 3 | 2 | 0 | 6 | 3 | 10 | 8 | 1 | 3 | 4 | 3 | 8 | 0 |
| | | 6 | 2 | 1 | 2 | 3 | 0 | 2 | 5 | 3 | 7 | 5 | 1 | 1 | 1 | 5 | 0 |
| | | 7 | 0 | 1 | 1 | 0 | 2 | 2 | 4 | 0 | 8 | 3 | 4 | 1 | 3 | 5 | 1 |
| | | 8 | 2 | 1 | 1 | 1 | 0 | 0 | 4 | 9 | 8 | 0 | 1 | 2 | 3 | 4 | 0 |
| | | 9 | 3 | 1 | 6 | 0 | 1 | 1 | 0 | 1 | 1 | 7 | 0 | 1 | 0 | 11 | 0 |
| | | 10 | 0 | 1 | 4 | 2 | 0 | 1 | 1 | 1 | 6 | 2 | 0 | 1 | 4 | 9 | 1 |
| | | 11 | 2 | 3 | 6 | 3 | 1 | 5 | 9 | 10 | 15 | 4 | 1 | 3 | 4 | 12 | 1 |
| | | 12 | 1 | 5 | 3 | 3 | 11 | 3 | 5 | 2 | 2 | 0 | 0 | 1 | 1 | 2 | 0 |
| | 3 | 1 | 10 | 9 | 4 | 6 | 0 | 6 | 10 | 14 | 19 | 4 | 4 | 4 | 7 | 13 | 2 |
| | | 2 | 8 | 9 | 17 | 8 | 4 | 8 | 14 | 18 | 32 | 4 | 3 | 10 | 8 | 19 | 2 |
| | | 3 | 1 | 1 | 4 | 0 | 1 | 3 | 2 | 3 | 6 | 0 | 3 | 1 | 3 | 3 | 6 |
| | | 4 | 0 | 2 | 5 | 1 | 2 | 2 | 2 | 3 | 15 | 4 | 0 | 1 | 5 | 3 | 1 |
| | | 5 | 1 | 2 | 6 | 5 | 1 | 5 | 5 | 11 | 8 | 5 | 2 | 2 | 3 | 9 | 1 |
| | | 6 | 2 | 2 | 4 | 5 | 0 | 3 | 2 | 5 | 13 | 0 | 2 | 2 | 2 | 7 | 0 |
| | | 7 | 0 | 1 | 1 | 3 | 2 | 1 | 0 | 4 | 5 | 2 | 0 | 4 | 0 | 4 | 0 |
| | | 8 | 3 | 0 | 2 | 4 | 1 | 5 | 3 | 8 | 6 | 2 | 1 | 1 | 5 | 5 | 1 |
| | | 9 | 0 | 1 | 4 | 0 | 1 | 3 | 2 | 0 | 2 | 3 | 1 | 4 | 1 | 1 | 0 |
| | | 10 | 2 | 1 | 2 | 0 | 1 | 6 | 3 | 3 | 12 | 1 | 1 | 0 | 1 | 8 | 0 |
| | | 11 | 8 | 6 | 6 | 2 | 4 | 1 | 6 | 15 | 13 | 3 | 1 | 3 | 4 | 9 | 1 |
| | | 12 | 4 | 1 | 3 | 1 | 1 | 2 | 2 | 2 | 6 | 2 | 0 | 1 | 1 | 4 | 0 |
| | 4 | 1 | 7 | 0 | 6 | 6 | 3 | 6 | 9 | 14 | 29 | 6 | 2 | 4 | 8 | 15 | 1 |
| | | 2 | 6 | 7 | 21 | 7 | 8 | 9 | 19 | 12 | 30 | 2 | 2 | 2 | 12 | 14 | 0 |
| | | 3 | 2 | 2 | 5 | 3 | 0 | 1 | 5 | 5 | 11 | 1 | 1 | 3 | 2 | 8 | 2 |
| | | 4 | 2 | 2 | 3 | 1 | 3 | 2 | 2 | 8 | 6 | 1 | 1 | 4 | 0 | 6 | 0 |
| | | 5 | 1 | 2 | 3 | 3 | 1 | 4 | 4 | 2 | 11 | 2 | 1 | 1 | 3 | 5 | 2 |
| | | 6 | 2 | 1 | 2 | 3 | 1 | 3 | 6 | 3 | 9 | 2 | 2 | 2 | 2 | 10 | 0 |
| | | 7 | 2 | 2 | 0 | 1 | 1 | 2 | 1 | 9 | 8 | 0 | 0 | 1 | 3 | 6 | 0 |
| | | 8 | 0 | 0 | 4 | 1 | 2 | 6 | 2 | 3 | 10 | 1 | 12 | 2 | 4 | 10 | 12 |
| | | 9 | 0 | 3 | 2 | 1 | 0 | 3 | 1 | 2 | 2 | 1 | 0 | 1 | 2 | 4 | 1 |
| | | 10 | 1 | 2 | 0 | 3 | 3 | 0 | 8 | 3 | 8 | 1 | 1 | 1 | 7 | 5 | 1 |
| | | 11 | 3 | 7 | 0 | 3 | 1 | 4 | 4 | 5 | 10 | 6 | 3 | 1 | 3 | 5 | 2 |
| | | 12 | 5 | 1 | 1 | 1 | 0 | 1 | 0 | 3 | 3 | 1 | 1 | 2 | 1 | 4 | 0 |
| | 5 | 1 | 2 | 4 | 12 | 2 | 4 | 8 | 9 | 7 | 28 | 2 | 1 | 2 | 5 | 7 | 1 |
| | | 2 | 5 | 5 | 20 | 12 | 5 | 11 | 12 | 14 | 33 | 4 | 7 | 7 | 12 | 27 | 1 |
| | | 3 | 7 | 4 | 4 | 2 | 2 | 4 | 8 | 9 | 8 | 2 | 5 | 7 | 4 | 5 | 2 |
| | | 4 | 1 | 0 | 1 | 3 | 1 | 0 | 6 | 4 | 7 | 5 | 2 | 1 | 5 | 8 | 1 |
| | | 5 | 5 | 1 | 4 | 1 | 1 | 9 | 5 | 5 | 12 | 3 | 0 | 5 | 3 | 4 | 1 |
| | | 6 | 1 | 3 | 8 | 1 | 2 | 1 | 2 | 4 | 10 | 2 | 2 | 1 | 3 | 6 | 0 |
| | | 7 | 3 | 2 | 2 | 0 | 0 | 1 | 3 | 4 | 5 | 0 | 1 | 6 | 3 | 4 | 0 |
| | | 8 | 4 | 2 | 0 | 2 | 3 | 3 | 2 | 4 | 13 | 2 | 0 | 3 | 1 | 5 | 1 |
| | | 9 | 4 | 2 | 2 | 3 | 0 | 1 | 2 | 1 | 9 | 7 | 7 | 1 | 7 | 2 | 0 |
| | | 10 | 0 | 0 | 4 | 0 | 1 | 3 | 3 | 2 | 11 | 2 | 0 | 12 | 1 | 19 | 5 |
| | | 11 | 4 | 5 | 5 | 2 | 3 | 3 | 7 | 13 | 15 | 1 | 1 | 2 | 8 | 6 | 0 |
| | | 12 | 1 | 1 | 2 | 2 | 0 | 1 | 0 | 2 | 3 | 0 | 0 | 1 | 0 | 0 | 2 |
| | 6 | 1 | 4 | 5 | 10 | 6 | 5 | 7 | 8 | 14 | 27 | 5 | 0 | 3 | 6 | 13 | 1 |
| | | 2 | 11 | 9 | 9 | 4 | 4 | 11 | 11 | 14 | 32 | 6 | 3 | 6 | 13 | 19 | 3 |
| | | 3 | 2 | 0 | 2 | 4 | 1 | 4 | 5 | 7 | 7 | 2 | 0 | 1 | 7 | 5 | 0 |

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| | | 4 | 3 | 4 | 4 | 2 | 1 | 18 | 4 | 12 | 11 | 1 | 8 | 2 | 3 | 5 | 2 |
| | | 5 | 4 | 2 | 4 | 5 | 1 | 3 | 1 | 7 | 6 | 1 | 3 | 2 | 3 | 10 | 0 |
| | | 6 | 0 | 4 | 4 | 2 | 1 | 4 | 4 | 1 | 3 | 3 | 1 | 4 | 3 | 7 | 0 |
| | | 7 | 1 | 3 | 3 | 2 | 10 | 1 | 3 | 7 | 5 | 1 | 1 | 1 | 1 | 2 | 0 |
| | | 8 | 0 | 2 | 3 | 1 | 0 | 1 | 3 | 4 | 10 | 2 | 0 | 1 | 3 | 4 | 0 |
| | | 9 | 0 | 3 | 1 | 1 | 1 | 1 | 1 | 2 | 4 | 2 | 3 | 1 | 3 | 3 | 0 |
| | | 10 | 2 | 1 | 4 | 2 | 1 | 2 | 3 | 5 | 9 | 0 | 1 | 0 | 1 | 3 | 0 |
| | | 11 | 1 | 1 | 3 | 5 | 2 | 2 | 4 | 4 | 8 | 3 | 3 | 3 | 5 | 10 | 0 |
| | | 12 | 2 | 0 | 1 | 12 | 12 | 1 | 0 | 2 | 16 | 0 | 1 | 0 | 3 | 6 | 0 |
| | 7 | 1 | 2 | 8 | 14 | 5 | 3 | 8 | 7 | 9 | 19 | 6 | 10 | 8 | 12 | 18 | 0 |
| | | 2 | 6 | 3 | 14 | 11 | 4 | 10 | 10 | 19 | 40 | 12 | 3 | 5 | 12 | 16 | 2 |
| | | 3 | 2 | 3 | 4 | 3 | 0 | 3 | 6 | 7 | 11 | 0 | 1 | 1 | 4 | 8 | 0 |
| | | 4 | 3 | 3 | 3 | 2 | 4 | 7 | 4 | 6 | 7 | 2 | 1 | 3 | 3 | 5 | 1 |
| | | 5 | 2 | 2 | 4 | 1 | 0 | 4 | 5 | 8 | 8 | 2 | 3 | 3 | 4 | 9 | 0 |
| | | 6 | 3 | 3 | 4 | 4 | 0 | 3 | 1 | 7 | 9 | 2 | 0 | 4 | 3 | 12 | 7 |
| | | 7 | 3 | 5 | 2 | 1 | 2 | 3 | 2 | 2 | 7 | 1 | 1 | 3 | 3 | 4 | 1 |
| | | 8 | 1 | 2 | 3 | 1 | 1 | 2 | 3 | 8 | 9 | 2 | 1 | 1 | 6 | 9 | 0 |
| | | 9 | 2 | 0 | 2 | 1 | 0 | 0 | 2 | 4 | 8 | 1 | 1 | 3 | 1 | 1 | 0 |
| | | 10 | 2 | 2 | 4 | 1 | 1 | 1 | 3 | 4 | 7 | 0 | 0 | 1 | 3 | 4 | 0 |
| | | 11 | 1 | 3 | 4 | 4 | 2 | 5 | 8 | 12 | 11 | 6 | 0 | 2 | 8 | 9 | 1 |
| | | 12 | 1 | 0 | 3 | 1 | 0 | 1 | 1 | 4 | 6 | 1 | 2 | 1 | 4 | 3 | 1 |
| | 8 | 1 | 3 | 7 | 10 | 6 | 4 | 6 | 4 | 12 | 27 | 5 | 0 | 1 | 8 | 11 | 2 |
| | | 2 | 5 | 6 | 10 | 8 | 4 | 5 | 13 | 19 | 40 | 8 | 3 | 9 | 13 | 16 | 3 |
| | | 3 | 4 | 3 | 5 | 2 | 1 | 2 | 4 | 5 | 6 | 3 | 1 | 6 | 5 | 10 | 1 |
| | | 4 | 3 | 1 | 1 | 1 | 3 | 3 | 5 | 8 | 11 | 0 | 1 | 1 | 4 | 7 | 0 |
| | | 5 | 1 | 2 | 7 | 4 | 1 | 1 | 4 | 9 | 9 | 4 | 1 | 0 | 2 | 10 | 8 |
| | | 6 | 1 | 1 | 6 | 2 | 0 | 3 | 7 | 4 | 13 | 0 | 0 | 1 | 4 | 7 | 0 |
| | | 7 | 0 | 2 | 2 | 1 | 2 | 3 | 7 | 7 | 13 | 1 | 3 | 1 | 4 | 1 | 0 |
| | | 8 | 2 | 0 | 8 | 1 | 0 | 2 | 2 | 4 | 12 | 2 | 2 | 1 | 0 | 4 | 0 |
| | | 9 | 1 | 1 | 4 | 1 | 1 | 4 | 2 | 2 | 3 | 1 | 0 | 1 | 1 | 2 | 1 |
| | | 10 | 1 | 1 | 2 | 0 | 0 | 1 | 1 | 6 | 12 | 1 | 1 | 1 | 4 | 4 | 1 |
| | | 11 | 8 | 4 | 6 | 4 | 0 | 7 | 6 | 13 | 15 | 2 | 0 | 1 | 4 | 9 | 0 |
| | | 12 | 0 | 0 | 3 | 4 | 0 | 2 | 3 | 4 | 5 | 0 | 1 | 1 | 1 | 3 | 0 |
| 3 | 1 | 1 | 9 | 9 | 8 | 5 | 10 | 4 | 10 | 10 | 0 | 7 | 5 | 11 | 4 | 0 | 11 |
| | | 2 | 5 | 10 | 0 | 5 | 5 | 0 | 2 | 0 | 10 | 7 | 7 | 10 | 2 | 10 | 12 |
| | | 3 | 10 | 5 | 8 | 10 | 10 | 11 | 11 | 5 | 6 | 9 | 1 | 5 | 7 | 10 | 11 |
| | | 4 | 9 | 3 | 8 | 9 | 7 | 9 | 6 | 6 | 0 | 8 | 11 | 12 | 10 | 2 | 12 |
| | | 5 | 9 | 10 | 10 | 8 | 11 | 11 | 9 | 5 | 0 | 9 | 1 | 8 | 10 | 8 | 12 |
| | | 6 | 8 | 12 | 6 | 12 | 11 | 7 | 9 | 7 | 4 | 5 | 12 | 9 | 7 | 10 | 3 |
| | | 7 | 3 | 1 | 7 | 11 | 12 | 10 | 10 | 12 | 6 | 11 | 11 | 11 | 9 | 8 | 3 |
| | | 8 | 10 | 8 | 12 | 8 | 11 | 11 | 9 | 5 | 3 | 11 | 5 | 11 | 9 | 7 | 10 |
| | | 9 | 12 | 3 | 12 | 9 | 10 | 11 | 12 | 7 | 10 | 12 | 1 | 9 | 12 | 10 | 12 |
| | | 10 | 3 | 9 | 7 | 12 | 1 | 11 | 5 | 9 | 5 | 10 | 5 | 11 | 1 | 9 | 12 |
| | | 11 | 10 | 9 | 6 | 6 | 12 | 10 | 11 | 6 | 10 | 5 | 7 | 9 | 8 | 9 | 11 |
| | | 12 | 7 | 9 | 3 | 1 | 1 | 12 | 7 | 9 | 2 | 10 | 12 | 3 | 10 | 11 | 12 |
| | 2 | 1 | 7 | 9 | 4 | 5 | 10 | 7 | 0 | 10 | 0 | 5 | 9 | 7 | 7 | 10 | 10 |
| | | 2 | 8 | 3 | 0 | 10 | 10 | 0 | 10 | 0 | 0 | 8 | 9 | 3 | 10 | 10 | 1 |
| | | 3 | 9 | 10 | 7 | 8 | 7 | 10 | 5 | 10 | 0 | 9 | 1 | 10 | 9 | 10 | 3 |
| | | 4 | 8 | 9 | 10 | 9 | 3 | 5 | 7 | 10 | 10 | 12 | 5 | 11 | 10 | 10 | 11 |
| | | 5 | 3 | 8 | 10 | 9 | 10 | 7 | 7 | 8 | 0 | 10 | 5 | 10 | 8 | 8 | 12 |
| | | 6 | 9 | 10 | 7 | 11 | 3 | 3 | 11 | 2 | 4 | 11 | 12 | 9 | 6 | 4 | 5 |
| | | 7 | 1 | 9 | 10 | 9 | 7 | 11 | 9 | 6 | 1 | 11 | 11 | 10 | 3 | 7 | 1 |
| | | 8 | 3 | 11 | 9 | 10 | 11 | 10 | 10 | 7 | 1 | 10 | 12 | 11 | 11 | 10 | 11 |
| | | 9 | 8 | 11 | 10 | 11 | 10 | 3 | 3 | 9 | 7 | 12 | 12 | 1 | 11 | 9 | 12 |

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| | | 10 | 12 | 10 | 10 | 10 | 12 | 11 | 10 | 9 | 1 | 12 | 12 | 10 | 7 | 7 | 12 |
| | | 11 | 7 | 10 | 9 | 10 | 12 | 11 | 7 | 6 | 0 | 6 | 9 | 7 | 4 | 4 | 9 |
| | | 12 | 10 | 11 | 9 | 12 | 1 | 11 | 9 | 9 | 8 | 10 | 12 | 1 | 9 | 8 | 12 |
| | 3 | 1 | 8 | 10 | 7 | 6 | 9 | 10 | 4 | 0 | 10 | 10 | 10 | 8 | 6 | 10 | 7 |
| | | 2 | 4 | 5 | 0 | 10 | 10 | 0 | 0 | 10 | 0 | 3 | 7 | 9 | 3 | 10 | 10 |
| | | 3 | 12 | 9 | 9 | 9 | 8 | 10 | 8 | 5 | 7 | 10 | 5 | 10 | 10 | 6 | 11 |
| | | 4 | 7 | 9 | 5 | 9 | 3 | 12 | 7 | 7 | 10 | 12 | 9 | 11 | 11 | 5 | 1 |
| | | 5 | 9 | 9 | 9 | 9 | 12 | 7 | 10 | 3 | 0 | 9 | 1 | 7 | 11 | 6 | 12 |
| | | 6 | 11 | 12 | 5 | 9 | 12 | 11 | 11 | 10 | 2 | 10 | 3 | 12 | 9 | 5 | 11 |
| | | 7 | 10 | 9 | 7 | 12 | 10 | 7 | 10 | 10 | 10 | 12 | 1 | 9 | 10 | 8 | 11 |
| | | 8 | 5 | 1 | 12 | 11 | 11 | 5 | 10 | 7 | 10 | 12 | 5 | 11 | 9 | 9 | 12 |
| | | 9 | 3 | 12 | 11 | 1 | 12 | 11 | 3 | 7 | 10 | 12 | 11 | 11 | 8 | 9 | 11 |
| | | 10 | 1 | 11 | 5 | 10 | 5 | 9 | 7 | 9 | 10 | 11 | 3 | 9 | 8 | 5 | 12 |
| | | 11 | 8 | 10 | 2 | 8 | 12 | 7 | 10 | 3 | 1 | 9 | 12 | 10 | 4 | 10 | 12 |
| | | 12 | 12 | 5 | 0 | 11 | 10 | 11 | 11 | 10 | 9 | 11 | 12 | 11 | 3 | 11 | 12 |
| | 4 | 1 | 5 | 8 | 9 | 3 | 6 | 5 | 0 | 10 | 0 | 8 | 7 | 10 | 10 | 5 | 11 |
| | | 2 | 3 | 10 | 0 | 10 | 6 | 2 | 10 | 0 | 10 | 2 | 8 | 0 | 0 | 0 | 5 |
| | | 3 | 10 | 8 | 8 | 3 | 11 | 10 | 10 | 4 | 4 | 3 | 12 | 3 | 6 | 7 | 11 |
| | | 4 | 3 | 5 | 7 | 9 | 10 | 9 | 7 | 10 | 5 | 12 | 1 | 11 | 8 | 9 | 11 |
| | | 5 | 9 | 10 | 5 | 10 | 10 | 10 | 9 | 10 | 0 | 7 | 12 | 10 | 10 | 10 | 12 |
| | | 6 | 9 | 8 | 7 | 12 | 12 | 7 | 7 | 9 | 1 | 8 | 9 | 10 | 3 | 10 | 12 |
| | | 7 | 3 | 11 | 7 | 11 | 5 | 11 | 11 | 10 | 2 | 11 | 12 | 12 | 9 | 10 | 1 |
| | | 8 | 9 | 5 | 1 | 9 | 12 | 8 | 9 | 10 | 10 | 10 | 11 | 10 | 9 | 5 | 1 |
| | | 9 | 10 | 12 | 8 | 5 | 3 | 7 | 7 | 5 | 8 | 12 | 9 | 12 | 9 | 8 | 3 |
| | | 10 | 10 | 12 | 11 | 11 | 3 | 10 | 10 | 9 | 0 | 9 | 1 | 10 | 11 | 11 | 1 |
| | | 11 | 10 | 10 | 10 | 9 | 1 | 10 | 4 | 6 | 10 | 11 | 8 | 10 | 10 | 0 | 12 |
| | | 12 | 11 | 12 | 11 | 1 | 5 | 12 | 5 | 10 | 10 | 12 | 12 | 5 | 11 | 5 | 12 |
| | 5 | 1 | 10 | 5 | 10 | 5 | 6 | 8 | 4 | 0 | 10 | 10 | 10 | 4 | 6 | 10 | 11 |
| | | 2 | 4 | 6 | 1 | 3 | 9 | 5 | 0 | 0 | 10 | 10 | 6 | 7 | 10 | 0 | 10 |
| | | 3 | 11 | 3 | 7 | 10 | 10 | 9 | 7 | 10 | 8 | 12 | 9 | 11 | 10 | 2 | 1 |
| | | 4 | 3 | 11 | 9 | 7 | 3 | 8 | 7 | 8 | 3 | 8 | 11 | 8 | 7 | 10 | 12 |
| | | 5 | 9 | 3 | 10 | 9 | 12 | 7 | 10 | 6 | 0 | 11 | 10 | 3 | 6 | 7 | 12 |
| | | 6 | 9 | 3 | 7 | 5 | 10 | 12 | 7 | 7 | 10 | 3 | 10 | 9 | 6 | 4 | 1 |
| | | 7 | 3 | 9 | 7 | 7 | 11 | 12 | 3 | 10 | 10 | 11 | 12 | 3 | 9 | 9 | 12 |
| | | 8 | 4 | 9 | 9 | 11 | 11 | 10 | 7 | 10 | 4 | 10 | 3 | 10 | 11 | 11 | 3 |
| | | 9 | 3 | 10 | 7 | 9 | 3 | 1 | 5 | 9 | 10 | 3 | 12 | 11 | 9 | 10 | 11 |
| | | 10 | 12 | 12 | 12 | 10 | 12 | 12 | 5 | 5 | 7 | 3 | 1 | 5 | 10 | 7 | 3 |
| | | 11 | 10 | 11 | 9 | 11 | 7 | 8 | 6 | 6 | 10 | 5 | 11 | 10 | 7 | 10 | 11 |
| | | 12 | 11 | 1 | 5 | 12 | 11 | 9 | 5 | 3 | 10 | 7 | 1 | 5 | 12 | 7 | 11 |
| | 6 | 1 | 10 | 9 | 10 | 6 | 7 | 6 | 4 | 0 | 0 | 11 | 8 | 9 | 7 | 10 | 3 |
| | | 2 | 10 | 7 | 0 | 10 | 6 | 1 | 1 | 0 | 0 | 10 | 10 | 5 | 3 | 0 | 11 |
| | | 3 | 9 | 3 | 9 | 3 | 11 | 7 | 8 | 10 | 4 | 5 | 10 | 3 | 10 | 10 | 1 |
| | | 4 | 12 | 8 | 7 | 7 | 11 | 9 | 8 | 4 | 0 | 10 | 11 | 8 | 9 | 5 | 12 |
| | | 5 | 9 | 10 | 7 | 7 | 11 | 10 | 10 | 8 | 4 | 11 | 10 | 11 | 7 | 5 | 10 |
| | | 6 | 7 | 3 | 6 | 7 | 3 | 11 | 9 | 8 | 7 | 10 | 3 | 11 | 8 | 8 | 11 |
| | | 7 | 12 | 3 | 10 | 11 | 12 | 3 | 9 | 11 | 2 | 3 | 1 | 10 | 9 | 7 | 12 |
| | | 8 | 11 | 10 | 7 | 8 | 3 | 10 | 10 | 7 | 5 | 5 | 11 | 12 | 12 | 7 | 12 |
| | | 9 | 9 | 5 | 10 | 11 | 11 | 12 | 12 | 8 | 10 | 5 | 11 | 1 | 10 | 7 | 11 |
| | | 10 | 5 | 12 | 9 | 3 | 5 | 9 | 8 | 6 | 10 | 9 | 12 | 11 | 5 | 9 | 11 |
| | | 11 | 9 | 10 | 4 | 9 | 11 | 10 | 9 | 6 | 10 | 9 | 1 | 7 | 1 | 10 | 1 |
| | | 12 | 10 | 5 | 11 | 12 | 11 | 12 | 7 | 8 | 10 | 11 | 12 | 3 | 11 | 7 | 11 |
| | 7 | 1 | 10 | 9 | 4 | 8 | 10 | 7 | 0 | 3 | 0 | 6 | 10 | 5 | 4 | 0 | 1 |
| | | 2 | 10 | 6 | 0 | 0 | 8 | 10 | 6 | 10 | 10 | 10 | 10 | 10 | 3 | 0 | 5 |
| | | 3 | 3 | 9 | 11 | 9 | 10 | 10 | 6 | 10 | 5 | 3 | 12 | 8 | 9 | 10 | 11 |

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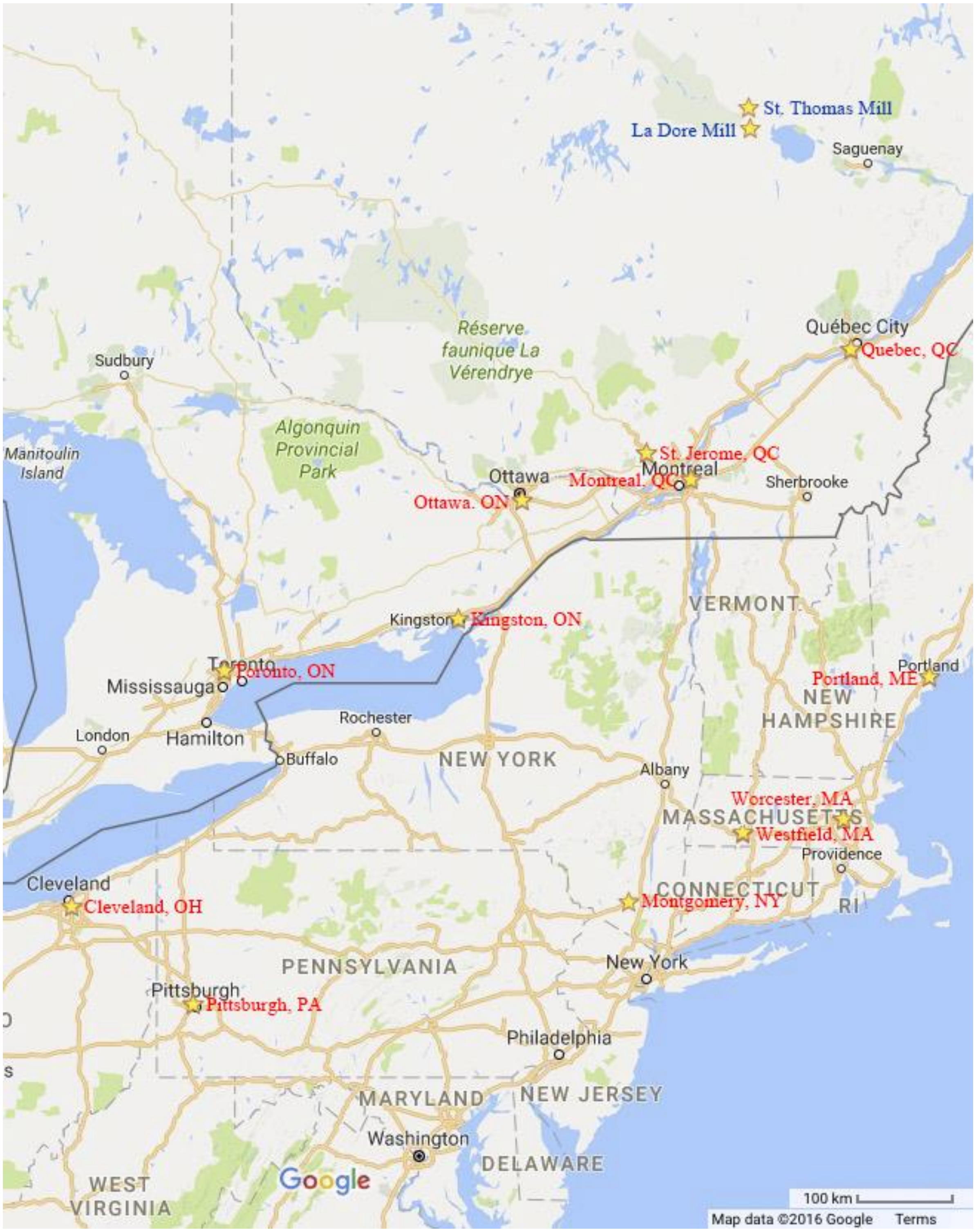
| | | 4 | 10 | 10 | 9 | 5 | 12 | 11 | 3 | 8 | 0 | 5 | 12 | 11 | 9 | 3 | 5 |
| | | 5 | 10 | 3 | 10 | 11 | 5 | 5 | 3 | 8 | 3 | 11 | 11 | 7 | 8 | 1 | 12 |
| | | 6 | 9 | 9 | 6 | 11 | 12 | 3 | 8 | 6 | 3 | 5 | 5 | 3 | 6 | 8 | 3 |
| | | 7 | 7 | 11 | 5 | 7 | 9 | 12 | 9 | 7 | 10 | 11 | 1 | 10 | 12 | 10 | 3 |
| | | 8 | 9 | 12 | 9 | 10 | 10 | 10 | 8 | 6 | 5 | 1 | 3 | 12 | 7 | 9 | 1 |
| | | 9 | 3 | 11 | 7 | 1 | 3 | 12 | 7 | 8 | 6 | 12 | 12 | 11 | 6 | 8 | 1 |
| | | 10 | 7 | 5 | 11 | 9 | 10 | 9 | 10 | 12 | 10 | 11 | 11 | 11 | 7 | 8 | 12 |
| | | 11 | 10 | 9 | 6 | 8 | 9 | 8 | 5 | 5 | 10 | 8 | 9 | 10 | 10 | 0 | 3 |
| | | 12 | 11 | 5 | 11 | 5 | 10 | 7 | 11 | 12 | 3 | 9 | 12 | 11 | 10 | 10 | 12 |
| | 8 | 1 | 10 | 7 | 1 | 5 | 8 | 8 | 9 | 0 | 0 | 8 | 5 | 8 | 5 | 2 | 3 |
| | | 2 | 10 | 10 | 3 | 1 | 8 | 0 | 2 | 0 | 0 | 6 | 5 | 10 | 10 | 0 | 12 |
| | | 3 | 7 | 3 | 8 | 10 | 1 | 9 | 5 | 10 | 7 | 7 | 11 | 9 | 8 | 11 | 11 |
| | | 4 | 7 | 11 | 8 | 3 | 10 | 9 | 9 | 5 | 10 | 9 | 9 | 11 | 3 | 8 | 11 |
| | | 5 | 12 | 8 | 9 | 3 | 5 | 8 | 4 | 4 | 3 | 10 | 9 | 12 | 6 | 5 | 3 |
| | | 6 | 3 | 9 | 11 | 11 | 11 | 8 | 7 | 3 | 10 | 3 | 11 | 10 | 10 | 8 | 12 |
| | | 7 | 3 | 1 | 11 | 10 | 11 | 10 | 11 | 4 | 0 | 1 | 12 | 7 | 5 | 6 | 12 |
| | | 8 | 11 | 11 | 9 | 9 | 11 | 10 | 8 | 10 | 3 | 3 | 3 | 9 | 9 | 9 | 1 |
| | | 9 | 3 | 12 | 5 | 10 | 11 | 3 | 11 | 10 | 5 | 12 | 12 | 3 | 12 | 8 | 11 |
| | | 10 | 12 | 3 | 9 | 12 | 11 | 10 | 7 | 5 | 9 | 1 | 3 | 3 | 9 | 10 | 11 |
| | | 11 | 10 | 9 | 3 | 3 | 9 | 8 | 5 | 2 | 1 | 11 | 11 | 7 | 6 | 10 | 1 |
| | | 12 | 9 | 12 | 11 | 3 | 11 | 11 | 8 | 5 | 7 | 10 | 12 | 11 | 3 | 9 | 5 |
| | 9 | 1 | 8 | 2 | 7 | 6 | 3 | 2 | 8 | 8 | 31 | 5 | 2 | 1 | 9 | 14 | 0 |
| | | 2 | 16 | 12 | 13 | 7 | 4 | 12 | 13 | 11 | 38 | 7 | 4 | 11 | 9 | 16 | 2 |
| | | 3 | 0 | 3 | 8 | 0 | 2 | 6 | 3 | 5 | 6 | 2 | 2 | 4 | 1 | 7 | 1 |
| | | 4 | 3 | 0 | 3 | 2 | 2 | 1 | 5 | 10 | 5 | 5 | 2 | 3 | 3 | 7 | 0 |
| | | 5 | 3 | 1 | 5 | 3 | 0 | 1 | 5 | 9 | 17 | 2 | 2 | 4 | 2 | 10 | 0 |
| | | 6 | 1 | 1 | 3 | 3 | 4 | 2 | 0 | 6 | 9 | 1 | 0 | 0 | 4 | 4 | 0 |
| | | 7 | 1 | 2 | 1 | 1 | 0 | 1 | 2 | 2 | 11 | 1 | 0 | 4 | 3 | 6 | 1 |
| | | 8 | 0 | 3 | 5 | 3 | 2 | 1 | 5 | 2 | 7 | 1 | 2 | 0 | 3 | 4 | 0 |
| | | 9 | 0 | 1 | 2 | 1 | 0 | 1 | 3 | 3 | 6 | 2 | 0 | 1 | 1 | 2 | 0 |
| | | 10 | 2 | 1 | 4 | 5 | 0 | 4 | 2 | 5 | 5 | 0 | 1 | 2 | 1 | 4 | 0 |
| | | 11 | 3 | 3 | 3 | 2 | 3 | 3 | 4 | 9 | 15 | 2 | 4 | 2 | 4 | 11 | 2 |
| | | 12 | 1 | 2 | 3 | 0 | 0 | 1 | 1 | 2 | 8 | 0 | 0 | 1 | 2 | 5 | 1 |

# APPENDIX B. Production of mills in case study

| | | | Product | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Set | Week | Mill | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 1 | 1 | La Dore | 28 | 25 | 45 | 29 | 16 | 35 | 47 | 70 | 125 | 24 | 15 | 26 | 44 | 80 | 8 |
| | | St. Thomas | 11 | 10 | 19 | 13 | 7 | 12 | 16 | 23 | 42 | 8 | 4 | 7 | 11 | 20 | 2 |
| | 2 | La Dore | 28 | 25 | 45 | 29 | 16 | 35 | 47 | 70 | 125 | 24 | 15 | 26 | 44 | 80 | 8 |
| | | St. Thomas | 11 | 10 | 19 | 13 | 7 | 12 | 16 | 23 | 42 | 8 | 4 | 7 | 11 | 20 | 2 |
| | 3 | La Dore | 28 | 25 | 45 | 29 | 16 | 35 | 47 | 70 | 125 | 24 | 15 | 26 | 44 | 80 | 8 |
| | | St. Thomas | 11 | 10 | 19 | 13 | 7 | 12 | 16 | 23 | 42 | 8 | 4 | 7 | 11 | 20 | 2 |
| | 4 | La Dore | 28 | 25 | 45 | 29 | 16 | 35 | 47 | 70 | 125 | 24 | 15 | 26 | 44 | 80 | 8 |
| | | St. Thomas | 11 | 10 | 19 | 13 | 7 | 12 | 16 | 23 | 42 | 8 | 4 | 7 | 11 | 20 | 2 |
| | 5 | La Dore | 28 | 25 | 45 | 29 | 16 | 35 | 47 | 70 | 125 | 24 | 15 | 26 | 44 | 80 | 8 |
| | | St. Thomas | 11 | 10 | 19 | 13 | 7 | 12 | 16 | 23 | 42 | 8 | 4 | 7 | 11 | 20 | 2 |
| | 6 | La Dore | 28 | 25 | 45 | 29 | 16 | 35 | 47 | 70 | 125 | 24 | 15 | 26 | 44 | 80 | 8 |
| | | St. Thomas | 11 | 10 | 19 | 13 | 7 | 12 | 16 | 23 | 42 | 8 | 4 | 7 | 11 | 20 | 2 |
| | 7 | La Dore | 28 | 25 | 45 | 29 | 16 | 35 | 47 | 70 | 125 | 24 | 15 | 26 | 44 | 80 | 8 |
| | | St. Thomas | 11 | 10 | 19 | 13 | 7 | 12 | 16 | 23 | 42 | 8 | 4 | 7 | 11 | 20 | 2 |
| | 8 | La Dore | 28 | 25 | 45 | 29 | 16 | 35 | 47 | 70 | 125 | 24 | 15 | 26 | 44 | 80 | 8 |
| | | St. Thomas | 11 | 10 | 19 | 13 | 7 | 12 | 16 | 23 | 42 | 8 | 4 | 7 | 11 | 20 | 2 |
| 2 | 1 | La Dore | 36 | 28 | 51 | 25 | 20 | 34 | 50 | 67 | 113 | 20 | 25 | 20 | 45 | 65 | 7 |
| | | St. Thomas | 14 | 11 | 19 | 10 | 8 | 13 | 19 | 25 | 43 | 8 | 10 | 8 | 17 | 25 | 3 |
| | 2 | La Dore | 24 | 28 | 50 | 28 | 29 | 32 | 48 | 64 | 99 | 36 | 11 | 24 | 40 | 84 | 12 |
| | | St. Thomas | 9 | 11 | 19 | 11 | 11 | 12 | 18 | 24 | 37 | 14 | 4 | 9 | 15 | 32 | 5 |
| | 3 | La Dore | 32 | 28 | 47 | 28 | 15 | 36 | 41 | 69 | 110 | 24 | 15 | 27 | 32 | 68 | 12 |
| | | St. Thomas | 12 | 11 | 18 | 11 | 6 | 14 | 16 | 26 | 42 | 9 | 6 | 10 | 12 | 26 | 5 |
| | 4 | La Dore | 25 | 24 | 38 | 27 | 19 | 33 | 49 | 56 | 110 | 20 | 21 | 20 | 38 | 74 | 17 |
| | | St. Thomas | 10 | 9 | 15 | 10 | 7 | 13 | 19 | 21 | 42 | 8 | 8 | 8 | 15 | 28 | 7 |
| | 5 | La Dore | 30 | 24 | 52 | 24 | 18 | 36 | 48 | 56 | 124 | 24 | 21 | 39 | 42 | 75 | 12 |
| | | St. Thomas | 12 | 9 | 20 | 9 | 7 | 14 | 18 | 21 | 47 | 9 | 8 | 15 | 16 | 28 | 5 |
| | 6 | La Dore | 24 | 28 | 39 | 37 | 32 | 44 | 38 | 64 | 111 | 21 | 20 | 20 | 41 | 70 | 5 |
| | | St. Thomas | 9 | 11 | 15 | 14 | 12 | 17 | 15 | 24 | 42 | 8 | 8 | 8 | 16 | 27 | 2 |
| | 7 | La Dore | 23 | 28 | 49 | 28 | 14 | 38 | 42 | 72 | 114 | 28 | 19 | 28 | 51 | 79 | 11 |
| | | St. Thomas | 9 | 11 | 19 | 11 | 6 | 15 | 16 | 27 | 43 | 11 | 7 | 11 | 19 | 30 | 4 |
| | 8 | La Dore | 24 | 23 | 52 | 28 | 13 | 32 | 47 | 75 | 133 | 22 | 11 | 20 | 40 | 68 | 13 |
| | | St. Thomas | 9 | 9 | 20 | 11 | 5 | 12 | 18 | 28 | 50 | 9 | 4 | 8 | 15 | 26 | 5 |
| 3 | 1 | La Dore | 76 | 71 | 70 | 77 | 81 | 86 | 81 | 65 | 45 | 84 | 63 | 88 | 72 | 76 | 97 |
| | | St. Thomas | 24 | 22 | 22 | 24 | 26 | 27 | 26 | 21 | 14 | 26 | 20 | 28 | 23 | 24 | 31 |
| | 2 | La Dore | 68 | 89 | 76 | 92 | 77 | 72 | 71 | 69 | 26 | 93 | 88 | 72 | 76 | 78 | 80 |
| | | St. Thomas | 22 | 28 | 24 | 29 | 24 | 23 | 22 | 22 | 8 | 29 | 28 | 23 | 24 | 25 | 25 |
| | 3 | La Dore | 72 | 82 | 58 | 84 | 92 | 80 | 73 | 65 | 64 | 97 | 64 | 95 | 74 | 76 | 98 |
| | | St. Thomas | 23 | 26 | 18 | 27 | 29 | 25 | 23 | 21 | 20 | 31 | 20 | 30 | 23 | 24 | 31 |
| | 4 | La Dore | 74 | 89 | 68 | 75 | 68 | 81 | 72 | 75 | 48 | 84 | 82 | 83 | 77 | 64 | 74 |
| | | St. Thomas | 23 | 28 | 21 | 24 | 21 | 26 | 23 | 24 | 15 | 27 | 26 | 26 | 24 | 20 | 23 |
| | 5 | La Dore | 72 | 67 | 75 | 80 | 84 | 81 | 53 | 60 | 74 | 75 | 77 | 69 | 83 | 70 | 79 |
| | | St. Thomas | 23 | 21 | 24 | 25 | 27 | 26 | 17 | 19 | 23 | 24 | 24 | 22 | 26 | 22 | 25 |
| | 6 | La Dore | 91 | 68 | 72 | 76 | 82 | 80 | 76 | 61 | 50 | 80 | 80 | 73 | 74 | 68 | 85 |
| | | St. Thomas | 29 | 22 | 23 | 24 | 26 | 25 | 24 | 19 | 16 | 25 | 25 | 23 | 23 | 22 | 27 |
| | 7 | La Dore | 80 | 80 | 72 | 68 | 87 | 84 | 61 | 76 | 52 | 74 | 87 | 88 | 73 | 54 | 56 |
| | | St. Thomas | 25 | 25 | 23 | 21 | 27 | 26 | 19 | 24 | 17 | 23 | 27 | 28 | 23 | 17 | 18 |
| | 8 | La Dore | 78 | 77 | 71 | 64 | 86 | 76 | 69 | 47 | 44 | 65 | 83 | 80 | 69 | 69 | 75 |
| | | St. Thomas | 25 | 24 | 22 | 20 | 27 | 24 | 22 | 15 | 14 | 21 | 26 | 25 | 22 | 22 | 24 |

# APPENDIX C. Locations of mills and customers

| | | Address | Latitude | Longitude |
|---|---|---|---|---|
| Mill | La Doré Mill | 4600, avenue des Jardins, La Doré (Québec) G8J 1B4 Canada | 48.726448 | -72.623493 |
| | St-Thomas Mill | 300, avenue du Moulin, Saint-Thomas-Didyme, Québec, G0W 1P0 Canada | 48.915311 | -72.649263 |
| Customer | Montréal, PQ | 220, chemin du Tremblay, Boucherville, QC J4B 8H7 | 45.564233 | -73.420782 |
| | Toronto, ON | 486 Steeles Ave W, Vaughan, ON M9W 6Y3 | 43.752712 | -79.626222 |
| | Westfield, MA | 50 Campanelli Dr, Westfield, MA 01085, États-Unis | 42.169732 | -72.734272 |
| | Portland, ME | 297 Presumpscot St, Portland, ME 04103 | 43.691868 | -70.258981 |
| | Pittsburgh, PA | 2810 Preble Ave, Pittsburgh, PA 15233 | 40.464703 | -80.035385 |
| | Cleveland, OH | 4150 E 56th St, Cleveland, OH 44105 | 41.446306 | -81.650391 |
| | Québec, QC | 3258 Chemin de la Gare, Ville de Québec, QC G1W 0B7, Canada | 46.753742 | -71.301799 |
| | Ottawa, ON | 2056 Bank St, Ottawa, ON K1V 7Z8, Canada | 45.365096 | -75.660236 |
| | St-Jérome, QC | 2159 Boulevard du Curé-Labelle, Saint-Jérôme, QC J7Y 1T1, Canada | 45.80274 | -74.011453 |
| | Kingston, ON | 59 Bath Rd, Kingston, ON K7L 5G3, Canada | 44.241504 | -76.514383 |
| | Montgomery, NY | 601 Neelytown Rd, Montgomery, NY 12549 | 41.495142 | -74.244549 |
| | Worcestern, MA | 1 Worcester Rd, Framingham, MA 01701 | 42.303681 | -71.393934 |


St. Thomas Mill
La Dore Mill
Saguenay
Réserve faunique La Vérendrye
Québec City
Quebec, QC
Sudbury
Algonquin Provincial Park
Manitoulin Island
St. Jerome, QC
Ottawa
Montreal, QC
Montreal
Sherbrooke
Ottawa, ON
VERMONT
Kingston
Kingston, ON
Toronto
Toronto, ON
Portland
Portland, ME
Mississauga
NEW HAMPSHIRE
Rochester
London
Hamilton
Buffalo
NEW YORK
Albany
Worcester, MA
MASSACHUSETTS
Westfield, MA
Providence
Cleveland
Cleveland, OH
CONNECTICUT
Montgomery, NY
RI
PENNSYLVANIA
New York
Pittsburgh
Pittsburgh, PA
Philadelphia
MARYLAND
NEW JERSEY
Washington
DELAWARE
Google
WEST VIRGINIA
100 km
Map data ©2016 Google
Terms

# APPENDIX D. Results of model #1 using single-product loading patterns

| Set No. | 1 | | 2 | | 3 | |
|---|---|---|---|---|---|---|
| Sample No. | Cost | Emission | Cost | Emission | Cost | Emission |
| 1 | 1057720 | 797391 | 1068715 | 806343 | 1259301 | 950481 |
| 2 | 1057981 | 796999 | 1070905 | 800000 | 1264784 | 954333 |
| 3 | 1073981 | 790000 | 1072969 | 792876 | 1286919 | 881342 |
| 4 | 1076727 | 774999 | 1077944 | 782080 | 1309969 | 829944 |
| 5 | 1070845 | 760000 | 1076786 | 781555 | 1305117 | 819473 |
| 6 | 1079090 | 739988 | 1077089 | 781545 | 1303782 | 818686 |
| 7 | 1188310 | 669997 | 1076841 | 781501 | 1476753 | 782626 |
| 8 | 1409880 | 640000 | 1076673 | 780000 | 2027917 | 722756 |
| 9 | 1703110 | 609999 | 1084295 | 760000 | 2049818 | 721822 |
| 10 | 1978881 | 589998 | 1088413 | 740000 | 2816239 | 671158 |
| 11 | 2250670 | 569997 | 1095432 | 736375 | 4126558 | 596144 |
| 12 | 2527989 | 549999 | 1093948 | 735373 | 5402015 | 542112 |
| 13 | 3388681 | 499999 | 1093348 | 734998 | 5423512 | 539293 |
| 14 | 4509306 | 457572 | 1093054 | 734819 | - | - |
| 15 | - | - | 1097839 | 720000 | - | - |
| 16 | - | - | 1101883 | 700000 | - | - |
| 17 | - | - | 1107318 | 694896 | - | - |
| 18 | - | - | 1171827 | 680000 | - | - |
| 19 | - | - | 1301357 | 659996 | - | - |
| 20 | - | - | 2002980 | 599999 | - | - |
| 21 | - | - | 2692551 | 549980 | - | - |
| 22 | - | - | 4512247 | 457893 | - | - |

# APPENDIX E. Results of heuristic model #3 using multi-product loading patterns with full shipment

| Sample No. | Cost | Emission |
|---|---|---|
| 1 | 519550 | 445199 |
| 2 | 522886 | 415117 |
| 3 | 526992 | 406543 |
| 4 | 532344 | 404906 |
| 5 | 534304 | 406724 |
| 6 | 535490 | 409128 |
| 7 | 537142 | 409043 |
| 8 | 538978 | 411178 |
| 9 | 543965 | 405424 |
| 10 | 576801 | 400107 |
| 11 | 586302 | 398220 |

# APPENDIX F. Results of simplified model #4 using multi-product loading patterns with full shipment

| Set No. | 1 | | 2 | | 3 | |
|---|---|---|---|---|---|---|
| Sample No. | Cost | Emission | Cost | Emission | Cost | Emission |
| 1 | 575611 | 432480 | 587479 | 440872 | 846940 | 637453 |
| 2 | 575927 | 432532 | 586724 | 441617 | 840410 | 632453 |
| 3 | 578212 | 429990 | 586045 | 440837 | 838803 | 630274 |
| 4 | 581515 | 419997 | 596909 | 407626 | 857150 | 587273 |
| 5 | 586336 | 400097 | 609187 | 381511 | 852380 | 582609 |
| 6 | 585684 | 399649 | 611038 | 382654 | 870353 | 548962 |
| 7 | 585958 | 399838 | 610498 | 382617 | 870208 | 546821 |
| 8 | 597876 | 373684 | 607765 | 380790 | 873869 | 548990 |
| 9 | 597116 | 373509 | 611056 | 382597 | 875174 | 549407 |
| 10 | 597140 | 373427 | 665026 | 367310 | 870672 | 546435 |
| 11 | 597153 | 373399 | 780039 | 354215 | 869997 | 544396 |
| 12 | 597182 | 373332 | 929470 | 339497 | 877343 | 545671 |
| 13 | 597211 | 373266 | 936545 | 338644 | 981830 | 519360 |
| 14 | 597491 | 373441 | 935805 | 338710 | 979626 | 521668 |
| 15 | 597449 | 373536 | 1494429 | 299930 | 991711 | 520034 |
| 16 | 597876 | 373684 | 2062188 | 266752 | 987130 | 518601 |
| 17 | 649873 | 360484 | 2364282 | 253369 | 978827 | 517590 |
| 18 | 649902 | 360502 | 2363771 | 252917 | 1129113 | 505382 |
| 19 | 763596 | 348233 | 2439698 | 250710 | 1369292 | 479803 |
| 20 | 763346 | 348076 | 2443009 | 250653 | 1377112 | 477838 |
| 21 | 919104 | 332209 | 2449395 | 250896 | 1900791 | 441152 |
| 22 | 929078 | 331978 | - | - | 2696623 | 395487 |
| 23 | 933451 | 331220 | - | - | 3557579 | 359605 |
| 24 | 1494898 | 292262 | - | - | - | - |
| 25 | 2042599 | 260789 | - | - | - | - |
| 26 | 2394751 | 245757 | - | - | - | - |