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A Hierarchical Intermodal Network Optimization Model for the Gasification of Recycled Plastic in Southern Ontario: The Case of McKeil Marine

by

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Abstract

In this research, we apply the *hierarchical fixed charge uncapacitated facility location model* to optimize the supply chain network of a gasification plant. The model determines the optimal location of shredding facilities on the network that are required to supply plastic feedstock to the gasification plant in Hamilton, Ontario. To construct the model, we will determine an optimized transportation network for the gasification plant, which faces a fixed demand during the period of one-year. The transportation routes to the plant and the associated costs are determined with the use of geographic information systems software. Our research finds (1) the optimal number of shredding facilities and their locations (2) the production of each facility and allocation of demand in a one-year period and (3) an optimized transportation network that attempts to utilize intermodal transportation in order to minimize the cost function of the entire network. The model determines that transporting the plastic via truck and locating a single shredding facility in Hamilton is more cost effective than decoupling the shredding process from the plant or transporting the plastic via an alternative modality. This leads the author to the conclusion that the network's scale is too small and that there is not a large enough volume of plastic flowing through the network to justify the utilization of an intermodal transportation network.

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List of Abbreviations

bhp	- Break Horsepower
C$	- Canadian Dollars
CAPEX	- Capital Expenditures
CFLM	- Capacitated Facility Location Model
EBITDA	- Earnings Before Interest, Taxes, Depreciation and Amortization
ESRI	- Environmental Systems Research Institute
ft	- Feet
ft^3	- Square Foot
GIFT	- Geographic Intermodal Freight Transportation Model
GL	- Great Lakes
GIS	- Geographic Information System
GIS-T	- Geographic Information Systems – Transportation
GTA	- Greater Toronto Area
HFCUFLM	- Hierarchical Fixed Charge Uncapacitated Facility Location Model
hr	- Hour
ISO	- International Standardization Organization
lbs	- Pounds
MGO	- Marine Gas Oil
m	- Metres
m^2	- Metres Squared
m^3	- Cubic Metres
mt	- Metric tonnes
mtkm	- Tonne Kilometre
MILP	- Mixed-Integer Linear Programming
MRF	- Material Recovery Facility
NTAD	- National Transportation Atlas Database
OBBP	- Ontario Blue Box Programme
OPEX	- Operational Expenditures
RIT	- Rochester Institute of Technology
RPM	- Revolutions Per Minute
UFLM	- Uncapacitated Facility Location Model
WDO	- Waste Diversion Ontario

Chapter 1 Introduction

1.1 Green Logistics

In recent years, the moral push for environmental awareness and corporate responsibility has been reinforced by a wave of innovations that have made environmentally-conscious decisions economically feasible. The field of logistics has played a pivotal role in the success of many green initiatives due to the easily quantifiable savings that result from decisions based on proven logistical practices. Green logistics furthers the fundamental principle of logistics – the co-ordination of all activities required to move a certain product through its given supply chain at a minimal cost – by accounting for the important variables of environmental and social concerns. Instead of impeding economic growth, the green movement seeks to improve upon the traditional role of markets, *the allocation of scarce resources,* by redefining scarcity. Rethinking production and a product's lifecycle are fundamental principles to the idea of radical resource productivity – a concept that is heralded by the green movement as a method for reducing waste without depressing economic growth. Instead of acting as a deterrent to growth, introducing recycling into the lifecycle of manufactured products has radically increased the profits of many firms globally because of the reduced costs realized from reusing materials. Not surprisingly, this is also beneficial to the environment, which is important considering the negative impacts of environmental degradation. The advantage of green logistics is that it affords firms the ability to approach problems as interconnected issues, not isolated events. Building a supply chain based on the whole system rather than isolated sections will lead to greater optimization, greater efficiency and greater profits for firms in markets that are becoming increasingly competitive given the nature of economic globalization.

1.2 McKeil Marine

McKeil Marine is a Canadian-based company that provides innovative marine transportation solutions to customers across the Great Lakes, Eastern Seaboard and Canadian Arctic. The McKeil fleet consists of a variety of specialized tugboats and barges that can be customized in order to support specific logistical solutions. The company is continuously looking to modernize to maintain its competitive edge. McKeil is currently looking for innovative ideas for new business opportunities, which not only include existing freight movements but also pursuing new cargoes that have not historically moved on water. "Certain initiatives within the green movement are a positive force for change," says McKeil's Chairman and CEO B. McKeil. "The company and the country have benefited immensely from several green initiatives that we have been fortunate enough to have been involved in" (2012). In 2012, the sales and marketing department of McKeil Marine was approached with the idea of moving large volumes of recycled plastic over routes on Lake Ontario. The plastic is intended to be feedstock for a proposed gasification plant that converts the recycled plastic into crude oil. This thesis will establish an optimized supply chain network for the gasification plant and explore the positive and negative aspects of the potential intermodal network in order to accurately inform the necessary parties within McKeil Marine of the project's financial viability.

Figure 1.1: A map depicting the Golden Horseshoe region of Southern Ontario **(**Ontario Ministry of Infrastructure, 2012, 76**)**

1.3 Recycling in Ontario and Gasification

Environmental concerns coupled with health risks and diminishing space have brought the topic of waste management to the forefront of the municipal agenda across the globe, especially in large, agglomerated urban areas. Figure 1.1 displays the "Golden Horseshoe" region of Southern Ontario in Canada – a densely populated region of the country that faces a variety of waste management issues.

In 2011, the population of the Golden Horseshoe was approximately 9,090,000 people, living within a total area 31,562 km^2 (Ontario Ministry of Infrastructure, 2012, 60). While relatively small in area given Canada's total size of 9,984,670 km^2, the population residing in the Golden Horseshoe is approximately 27% of the country's total population of 33,476,688 (The City of Toronto, 2012,1). The high population density of the region creates a situation whereby a large amount of waste is being produced in a relatively limited amount of space given factors such as urban sprawl, environmentally-protected zones and health concerns over locating disposal sites.

In 2010, the Ontario Blue Box Program (OBBP) recovered 58,621 tonnes of plastic (Stewardship Ontario, 2011, 28). This accounted for an estimated recovery rate of only 25% of the total plastic produced in Ontario (Ibid**).** Plastic recovered by the OBBP can be used in viable markets instead of being sent to a landfill where the plastic will take up space for a much longer time than material that has a faster rate of decomposition.

The recycling of plastic has generated a large multifaceted industry that uses a variety of methods to fulfil its goals. One such method, chemical recycling, refers to technological processes that transform plastic materials into smaller molecules, usually gases or liquids that can then be used to produce petrochemicals or new plastics (Mastellone, 1999). Specifically, we will focus on gasification, the conversion of plastic feedstock into fuels or combustible gases. Within the last decade, several companies have begun to market ready-made gasification systems. Agilyx, an industry leader in gasification, provides turnkey continuous batch systems that operate 24 hours per day. In 2011, Agilyx was chosen as one of the companies in the Global Clean Tech 100, which recognizes the top 100 clean technology companies that are most likely to make a significant impact in the next 5-10 years.

While the base model offered by Agilyx processes 30 tonnes of plastic per day, its systems are scalable and the company has begun to develop a system that will process 98 tonnes of plastic feedstock per day resulting in the production of 553 barrels of light sweet crude oil. This oil is sought by producers of ASTM spec Ultra Low Sulphur Diesel, Diesel, Gasoline, Jet-A fuel along with other transportation fuels and petroleum products (Agilyx, 2012). A simplified drawing of the Agilyx system is displayed in Figure 1.2. For the purposes of this thesis we will base our input and output approximations for a gasification plant on the large Agilyx system.

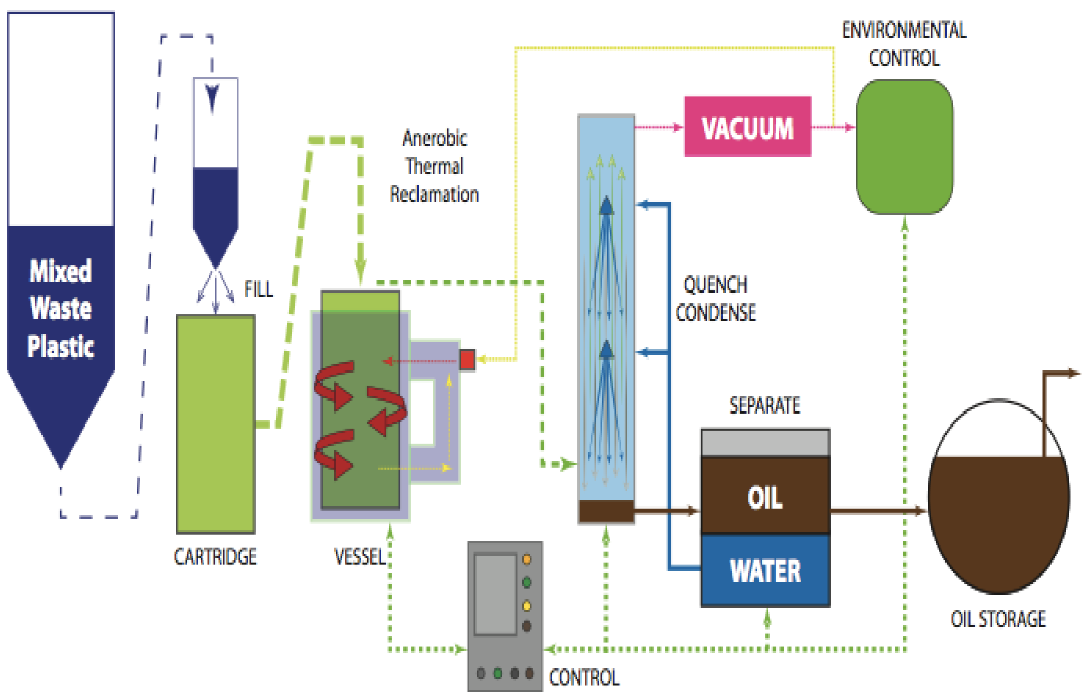

Figure 1.2: A simplified diagram of an Agilyx gasification system (Agilyx, 2012).

To fulfil diverse roles, plastic products vary in their chemical makeup. There are seven types of plastic resins that encompass the full spectrum of plastic products. To operate at optimal efficiency, Agilyx systems require plastic feedstock containing resins two, four, five and six although the system can process one, three and seven with less than optimal outputs (Agilyx, 2012). This is an important requirement to consider given the majority of plastic collected in Ontario’s Golden Horseshoe region is comprised of resin one and two (Stewardship Ontario, 2011, 34).

According to D. Merriman, Director of Waste Diversion Programs at Waste Diversion Ontario (WDO), plastic that is collected from households and certain businesses is brought to a Material Recovery Facility (MRF) and is either sold or given to a downstream private business that sorts and bails the plastic into resins one through seven and then sells the separated bails to buyers (2012). Prices are determined by various plastic commodity exchanges. If the price for a certain plastic resin is lower in domestic markets than in foreign markets, the plastic will be marketed and sold to foreign markets. This is not an ideal situation given that one of the objectives of recycling is to reduce carbon footprints rather than exacerbate them. Furthermore, current legislation in Ontario prohibits the use of plastic collected by the OBBP, from being disposed of (Waste Diversion Act, 2002). Currently, the Government of Ontario defines gasification as a form of disposal. As a result, gasification plants have been built in the United States within close proximity of the Canadian border to circumnavigate the laws outlined by the Waste Diversion Act. The Plastic2Oil gasification plant located in Niagara Falls, New York is an example of a company using plastic feedstock sourced from Ontario in a gasification system (Plastic2Oil, 2012). The WDO is continuously looking for methods to enhance Ontario’s recycling capacity and gasification may have the potential to become a successful addition to WDO’s current initiatives. Therefore, this thesis will proceed under the assumption that the feedstock from Ontario’s MRF are available for use in gasification.

1.4 Intermodal Transportation

One of the difficulties associated with recycling any material is the creation of a supply chain network to collect, process and remanufacture the recycled products. The OBBP has been highly successful in organizing the initial collection stage that begins with households and businesses. Mandated in the Ontario Blue Box Program Plan of 2003, which is subject to the Ontario Waste Diversion Act of 2002, is a detailed explanation of the tendering process for the transportation of recycled goods from households and businesses to the various MRFs whose ownership and operation by either a private or public entity are also subject to a tendering process (Waste Diversion Ontario, 2003, 25).

Within the Golden Horseshoe region are 13 publically-operated MRFs that collect the suitable resins of plastic required as feedstock for the Agilyx gasification system. The public MRFs will be used as the origin nodes of the hierarchical network proposed in this thesis because of their collective ability to fulfil the tonnage requirements of the Agilyx gasification facility and their obligation to disclose data resulting from their position as public entities. All of the facilities are located in close proximity to major highways and eight of the facilities may be ideally located to take advantage of an intermodal transportation network comprised of truck and barge.

Intermodal movements describe the transportation of goods using two or more modes of transportation that are linked end-to-end in order to move goods or people from an origin to a destination. The proximity of Lake Ontario to many of the major cities in the Golden Horseshoe region creates an attractive incentive for potentially shipping large volumes of plastic over water. T. Paterson, Assistant Manager of Marketing and Business Development at McKeil Marine, contends that on a short-haul route, such as the barge route considered by this thesis, a tug and barge are more cost effective than a ship. This is a result of a smaller crew, lower operational costs and the opportunity cost that a ship forgoes by working on a more lucrative job better suited to its unique attributes (2012). However, the size of a barge is an important consideration in the preliminary planning stages of potential job. A barge operator wants to maximize the use of the company's scarce resources. By allocating a tug and barge that are too small for a particular job, the operator may lose out on securing cargo or be forced to charge a higher-than-market price to accommodate additional trips. By allocating a tug and barge that are too large, the operator may not be able to reconcile the operating cost of the tug and barge unit with the market freight rate.

There are benefits associated with barge movements if enough volume is being moved in a network. With regards to the economies of scale, a barge can transport far more tonnage than a single truck and as a result, the cost of transportation per tonne decreases. Furthermore, a barge is far more fuel-efficient than a truck based on the burn rate per tonne kilometre. Not only is this economically advantageous because of the increasing price of fuel, but it also results in fewer greenhouse gas emissions. Depending on the size of a barge, a considerable number of trucks can be removed from the road network. For example, the barge being considered for use in this network can carry 1,994 tonnes of shredded plastic whereas a truck can only carry 22.3 tonnes. One barge load effectively eliminates 89 truckloads. As in any urban area, the Golden Horseshoe faces considerable congestion issues. Therefore, the use of a barge is an attractive method for reducing trucks from areas of high congestion. At the same time, a barge can act as moveable warehouse space. A barge can serve as both a floating warehouse and a mode of transportation due to its ability to use a variety of tugboats, which act as the barge's propulsion system. In one possible scenario considered in this thesis, one tug can serve as the propulsion system for two barges – one barge being loaded and one barge in transit. The barges can be rotated in the system in order to maximize the use of the tug.

Capt. G. Seymour, Vessel Manager at McKeil Marine is enthusiastic about any job that incorporates barges because of their relative shallow draft and manoeuvrability. "The shallow draft of smaller barges creates a number of interesting options. You can create your own dock with the use of a Jack-Up barge in areas that would otherwise be impossible to access. This opens up a number of opportunities to any supply chain" (2012). The opportunities created by Jack-Up barges are important to consider given the minimal number of industrial-use docks operating in the Greater Toronto Area (GTA), the Golden Horseshoe's most populated consensus metropolitan area. Docks that have not been maintained are normally inaccessible. The use of barges for transportation and Jack-Up barges for docking will establish accessibility.

1.5 Aim of the Thesis

The objectives of this thesis are circumscribed by the motivations of McKeil Marine. While McKeil does not have a financial stake in the gasification facility, truck routing or plastic shredding facilities – all of which are required to create the network – the company is adopting the role of a full spectrum logistics provider in the hopes that a sizeable amount of the plastic flowing from the origin nodes to the gasification facility will move on water. The first step in finding the solution involves constructing weighted routes from each of the origin nodes to the destination node. Moreover, the hopper device that delivers the plastic feedstock into the Agilyx system can only process plastic that is shredded to a two-inch particle size. This creates an additional parameter whereby a facility location model is required to determine the optimal location of the shredding facility or facilities and the amount of plastic the facility or facilities is required to process. Once the placement of the facility or facilities is determined, the total cost of a route from the origin nodes to the candidate transhipment nodes and onto destination node can be determined.

If any volume of plastic is dedicated to the barge route, it is then the task of the thesis to determine if the volume is large enough to actually justify a trip or multiple trips with a barge. While this network is oriented to accommodate the requirements of a specific supply chain, it is the intentions of the company to develop similar models for other clients. Therefore, the main objective of this thesis can be summarized into the following research question: Does the use of an intermodal supply chain minimize the transportation cost of a specifically constructed network? Additionally, does the minimized cost function discovered for the transportation network assist in the economic viability of the overall project?

1.6 Methodology

In order to develop the complex intermodal network required to satisfy the various constraints associated with this project, the Economic and Social Research Institute's (ESRI) Geographic Information System (GIS) software called ArcGIS will be used to determine the lowest cost routes of the recycled plastic from 13 publically-operated MRFs to a gasification facility at a predetermined location in Hamilton, Ontario. The established routes for both the trucks and the barge used in the network will be a function of distance in kilometres and cost in tonne kilometres. G. McNeil, the General Manager of CV Logistics, provides estimates of truck rates. T. Paterson, Assistant Manager for Marketing and Business Development at McKeil Marine, provides estimates for barge rates. The reason for choosing the 13 publically-operated facilities as the origin nodes is based on the fact that public entities have an obligation to collect and present data to the public in the form of annual reports and municipal datacalls. After observing the data calls, it is apparent that the public MRFs maintain enough yearly throughput to support the requirements of an Agilyx gasification facility processing 98 tonnes of plastic per day.

Once the optimal routes have been forecasted by ArcGIS, four distinct industrial zoned properties will be chosen as candidate sites for plastic shredding facilities. The shredding of plastic is of paramount importance to the carriers because it allows for both the trucks and barge used in this network to carry more cargo on each voyage due to the reduction in the cargo's stowage factor. Additionally, the hopper feeder used by the Agilyx system requires the plastic to be shredded into a two-inch particle size. Each site offers a unique attribute that will test a certain aspect of the network:

- Candidate site one is located in the Port of Oshawa and is situated with direct access to the water in order to test the possibility of barge route on the supply chain.

- Candidate site two is located in close proximity to a major roadway (The 401 Highway) that is navigated by a number of routes from various MRFs. It was chosen to determine if the reduction of the stowage factor and therefore the reduction in transportation costs resulting from decoupling the shredding process from the gasification facility plant are economically sensible.

- Candidate site three is located at the gasification plant and acts as a benchmark against all of the other candidate sites.

- Candidate site four is located in a remote location relative to any of the MRFs or routes established on the network. It is a dummy facility that is used to determine the veracity of the facility location model.

Furthermore, the candidate sites adhere to industrial zoning requirements and size requirements. The properties must be large enough to accommodate a commercial shredder and the warehouse space for the plastic. It was determined that a facility of 6,000 square feet will suit the requirements of the proposed network.[1]

Four possible shredding facilities will be used as the transhipment nodes in a *hierarchical fixed charge uncapacitated facility location model* (HFCUFLM). The model will determine the optimal number of facilities, their locations and the allocation of plastic from each of the MRFs to the shredding facilities and then onto the gasification plant. The model is designed to minimize the combined cost of transportation and the fixed cost of the shredding facilities. Once the optimal transhipment network is established, the operational and capital costs incurred by McKeil Marine will be subtracted from the total revenue collected by the company. Furthermore, the estimated costs of the total operation will be subtracted from the estimated revenue of the gasification facility in order to determine the economic feasibility of the project.

Experiments are subject to human error. In order to verify and validate the findings of the experiment in this thesis, alternative methods for discovering the outcomes produced by step one and two are required. To evaluate the findings of ArcGIS, an alternative experiment must be conducted. In the alternative experiment, an origin node is selected and the cost of every path from the origin node to a transhipment node is calculated by hand. This process is repeated from the transhipment node to the destination node so that the total cost of moving cargo on the

[1] The reasoning behind this statement is explained in section 4.2.

path from the origin node to transhipment and onto the destination node can be determined. The outcome of the sample experiment will be compared to the outcome determined by ArcGIS in order to see if discrepancies arise. If there is no variation in the paths determined by both experiments, it can be proven that there is not enough evidence to disprove the ArcGIS method.

There are 13 origin nodes, four potential transhipment nodes and one destination node. In total, there are 91 potential paths on the theoretical network. This constitutes a relatively small number of possible routes compared to the reality of many supply chains and can be tested by basic mathematical computations. The mathematical process involves adding the all of the routes originating at a specific origin node and combining the cost of transportation with the yearly fixed cost of leasing each of the four candidate transhipment facilities. The outcomes of this experiment can be compared with the outcomes discovered by the HFCUFLM in order to determine the merit of the model. The address of the 13 MRFs, four potential transhipment facilities and gasification plant are exhibited in Table 1 and their locations are displayed on the maps – altered by the author –in Figure 1.3 and 1.4.

Table 1: The Addresses of the Networks' Nodes

Origin Nodes	Potential Transhipment Nodes	Destination Node
Kingston - 96 Lappans Lane, ON K7K 6Z4	**Oshawa** 1050 Farewell Street, ON L1H 6N6	**Hamilton** 208 Hillyard St, ON L8L 6B6
Trenton - 270 West Street, ON K8V 2N3		
Northumberland - 280 Edwardson Road, ON K0K 2G0		
Peterborough - 390 Pido Rd, ON K9J 6X7	**Whitby** 5 Carlow, ON L1N 9T7	
Whitby - 4590 Garrard, ON L1H 7K4		
East Gwillimbury - 90 Bales Dr, ON L0G 1V0		
Dufferin - 35 Vanley Crescent, ON M3J 2C3	**Hamilton** 208 Hillyard St, ON L8L 6B6	
Brampton - 7795 Torbram Rd, ON L6T 0B6		
Guelph - 110 Dunlop Dr, ON N1E 3J3		
Waterloo - 925 Erb Street West, ON N2J 3Z4	**London** 522 Newbold St, ON N6E 1K6	
Simcoe - 28 Grigg Dr, ON N3Y 4L1		
Hamilton - 1575 Burlington St E, ON L8H		
Niagara Falls - 4935 Kent Ave, ON L2H 1J5		

(Author, 2012).

Figure 1.3: A map exhibiting the locations of the 13 MRFs (AECOM, 2011, 6).

Figure 1.4: A map exhibiting the locations 4 transhipment facilities and the gasification plant (AECOM, 2011, 6).

1.7 Structure

The thesis will be divided into six sections following the introduction. Section one beginning with Chapter 2 will cover the theoretical explanations of GIS software and its application to the study of transportation science as well as an overview of facility location models and their relationship to this thesis. Chapter 3 will offer a series of concise hypotheses for the three steps constituting the experiment conducted in this thesis. Chapter 4 will chronologically detail the steps required to setup experiment and explain how each of the steps contributed to the optimal calibration of the gasification plant's supply chain. Chapter 5 will provide the results of the experiment. Chapter 6 will analyze the results of the experiment and lead into the conclusions of the research explained in Chapter 7.

Chapter 2 Theoretical Framework

2.1 Geographic Information Systems

Since their rudimentary inception in the late 19th century, Geographic Information Systems have radically evolved from the manually drawn maps used by cartographers who were seeking to discover correlations between geographic data. One of the most notable examples from history, J. Snow's mapping of the 1854 cholera outbreak in London, offers an impeccable example of the application of a primitive GIS (Snow, 1855). Snow recorded the place of residence of each known case of cholera on a map of London and was able to determine that a public water pump was the source of the outbreak based on the pattern of infections he observed on his map. K.E. Foote and M. Lynch describes the contemporary GIS as an integrating technology that allows the precise layering of thematic maps and their concurring data on a base map that aligns all of the layers with the use of an implicit or explicit coordinate reference system such as the lines of latitude and longitude (1995). Their description is visually depicted in Figure 2.1, which demonstrates the potential insights for the integration of thematic layers. Essentially, a GIS combines multiple data sources based on geographic features and allows for the display, examination, management and manipulation of the spatial data.

The reason GIS software is relevant to this thesis, McKeil Marine and the transportation industry as a whole, relates to the software's ability to process a multitude of unique variables inherent in any supply chain and analyze the interactions of the variables in a simplified digital format that is presented in an attractive visual layout. Not only is the visual layout produced by ArcGIS more attractive than the classic spreadsheet approach, alterations to the experiment are easier because the format is more user friendly.

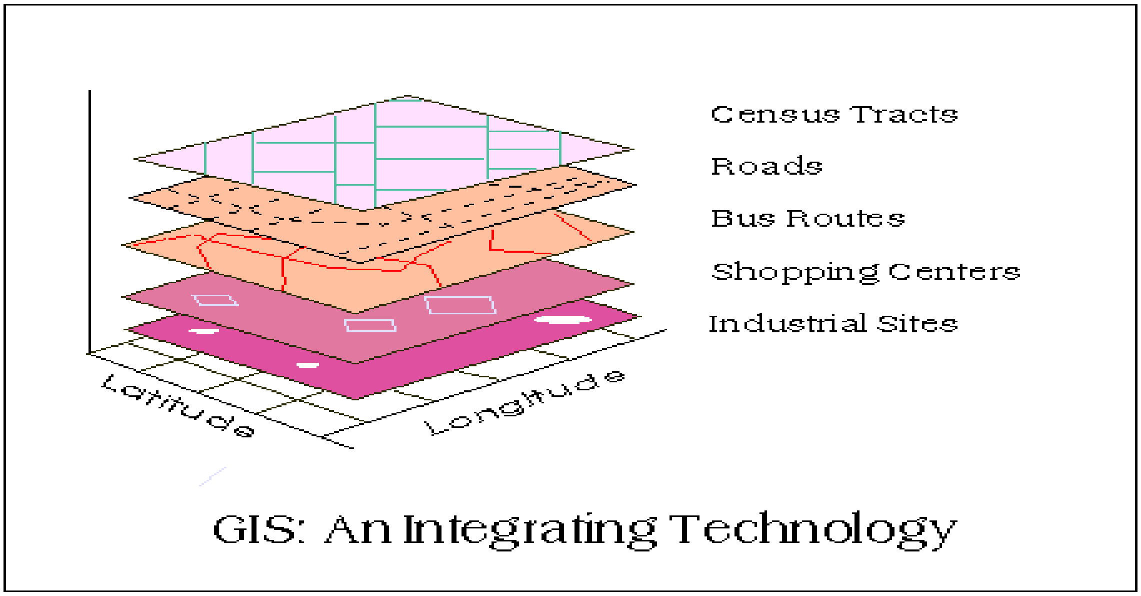

Figure 2.1: A visual example of thematic map layering on a common grid system in order to digitally analyze spatial data (Foote and Lynch, 1995).

2.1.1 The Components of GIS

Before a more in-depth explanation of how GIS software relates to the goals of McKeil Marine pursuant to this thesis, the basic foundations of the software must be clarified to explicate a fundamental knowledge of the processes and methods at work. In order to compute and analyze geographic data, GIS software requires that maps and aerial images be digitized so that real-world features can be represented as digital attributes in a GIS environment. The process of digitization is now fully automated and involves scanning maps or aerial images of the earth’s surface. The scanned images are then automatically converted into digital data (T. Sutton et al, 2009, 4). Digital data is presented in two forms, raster and vector data. Raster data is displayed as a matrix of cells. When an aerial image is taken, the pixels of the photo act as the framework for the cells in the raster matrix. The software correlates real features within each pixel with cells of the raster matrix. For example, the network constructed for McKeil Marine required aerial images of the Golden Horseshoe Region. Satellite images of the region were digitized into raster data. Features such as Lake Ontario, agricultural land and urban land were expressed by a large number of pixels on the images. The software converted the images into a raster matrix whereby pixels containing Lake Ontario were defined as water in the correlating cells of the raster matrix.

The second type of digital data, vector data, uses points and lines based on x, y coordinates of whichever coordinated reference system a constructed network is using. This thesis uses the North American Datum of 1983. Real world features such as roads or waterways can be created as vector data and overlaid as line shapefiles on top of a raster background. Both the raster and vector data accurately represent locations on the earth’s surface because the data is rectified to the North American Datum of 1983 which conforms the digital environment to real-world positions and distances. Vector files can accommodate attributes and allow for spatial analysis to occur. For example, vector shapefiles representing roads can be attributed with an average speed. A highway may maintain a speed of 100 kilometres per hour and a city street may maintain an average speed of 50 kilometres per hour. The software can analyze and process the distance and the speed limit of each roadway to determine the shortest route or the quickest route. This thesis requires the software to determine the quickest route because cost has a greater dependence on time in this network.

Buildings, such as the shredding facilities considered by the network, are made from polygons that comprise of a series of interconnected lines. Figure 2.2 depicts the difference between raster and vector data (Case and Doscher, 2012). Once a transportation network such as the North American Roadways has been completely digitized, it can be saved as a vector thematic map layer. It can then be combined with other thematic map layers such as the North American Waterways to allow the software to analyze specific user requests. In this thesis, GIS software is used to analyze and compare transportation routes over road and water to determine a minimized cost of transportation for an entire supply chain network.

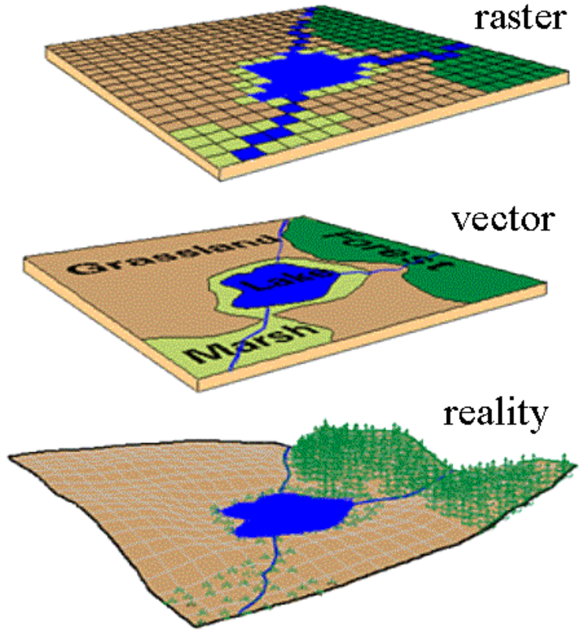

Figure 2.2: A depiction how real world features appear as raster and vector data (Case and Crile, 2012).

2.1.2 Routing with the Use of GIS Software

This thesis sets out to establish the optimal routes for a supply chain network servicing a gasification facility. The cost of each route is required in order to act as deterministic variables for a facility location model that will determine the best location(s) for a transhipment facility or facilities in the network. The routes considered by the facility location model will be inputted as the total yearly cost of moving an origin node's entire yearly volume of bailed plastic. To find the total yearly cost, ArcGIS was used to analyze the quickest routes from an origin node to a transhipment node and onto a destination node. The routes were based on distance and the average speed attributed to a road based on its class i.e. highways, rural roads etc. and known attributes i.e. traffic congestion, construction etc. It is within the capacity of ArcGIS to determine vehicle schedules, which would certainly lead to further optimization of the network and a reduced minimized cost. However, the objectives of McKeil Marine are fulfilled without the implementation of vehicle schedules for the trucks and barge being used on the network. The goal was to determine where the cargo flows occur. Once those flows are established, further refinements can be made with regards to vehicle scheduling. With that said, it is worth noting the capabilities of GIS and the actual aspects of GIS that were used in this thesis.

The most important ability of GIS in respect to its application to the transportation industry is the software's ability to associate deterministic variables to digitized topological data that represents real structures or locations on the earth's surface (Simkowitz, 1989, 72). For example, a digital road can be supported by a database of attributes that define the road's traffic volumes, average speed etc. The technology is therefore invaluable to planning, managing and supporting transportation operations because it can forecast optimal routes quickly, effectively and accurately. The ability of the software to take into account so many factors and analyze them simultaneously would normally be impossible or at least extremely difficult.

Traditional vehicle routing relies on a variety of mathematical techniques. The conventional, and most frequently used techniques are subject to distinct origin and destination points. An efficient route is one that minimizes weighted distance between the points. The weightings are normally based on distance, time, cost ascribed to each route and the loading / unloading times (Keenen, 2008, 203). Keenan outlines three important considerations for determining routing: locations, paths and the vehicles used on the paths. Locations formulate the framework for the routes because they describe origin nodes, transhipment nodes and destination nodes. Paths describe the linkages between the locations and are a function of distance and speed. Vehicles dictate the speed and capacity of the flow of goods along routes. Costs along the routes are normally dependant on vehicles and expenditures such as their fuel burn rate etc.

ArcGIS was used to determine the distances of the routes used on the network created for McKeil Marine. The software computed the quickest paths along the available transportation networks based on the quickest time a vehicle could travel from an origin point to a destination point. The quickest path was the target because trucking rates were quoted on an hourly basis. Once the quickest routes were established, the traditional mathematical techniques described by Keenen were used to determine the tonne kilometre rate of each route considered on the network created for McKeil.

Researchers Devlin et al. offer an example of ArcGIS software being successfully utilized to determine optimal routes (2008, 64). The researchers focused on creating an optimized network for the haulage of timber in Ireland. The software allowed the researchers to increase the number of full truckloads and minimize the damage done to peat-based, forest access roads by finding alternative routes over more stable roads. The authors' discoveries minimized, among other things, maintenance costs on forest roads resulting from heavy traffic and maximized full truckloads, which in turn increased revenues for the logging companies. The authors developed a weighting system for each road class (highway, rural road, forest road) that allowed them to refine Edsger Dijkstra's graph search algorithm for discovering the shortest path problem in order to successfully develop new routes that achieved the authors' objectives (1959, 270). While the objectives of our network differ from the objectives in the research of Devlin et al., the methods for realizing the unique objectives are similar.

Another study that closely relates to topics addressed in this thesis was undertaken in India. The explosive growth of urban populations in India has put a significant amount of pressure on the municipal infrastructure of many cities. Waste management is one of the most important roles of a municipality and because of the complexities inherent in implementing an effective waste management system, it is one of the most difficult services to execute. In order to reduce costs while simultaneously increasing the performance of limited waste management resources, the municipality of Asansol in the Indian province of West Bengal developed, by using GIS software, a routing model for carrying out waste services (Ghose et al., 2008, 1292). The model was based on the parameters of population density along routes in the city, the amount of waste generated along the total road network, the storage bins used by the city and the capacity of the collection facilities. To increase efficiency for the entire waste management system, the model optimizes the routes of the collection vehicles, the load balancing, fuel consumption and the work schedules of the workers and vehicles. The network had not yet been put into action at the time of publishing however, the authors were confidant that the model would be successful.

2.1.3 ArcGIS and Intermodal Transportation Networks

As supply chain networks continue to evolve, intelligent transportation systems are required to minimize the costs and maximize the revenues born by networks. The initial literature regarding Geographic Information Systems for Transportation (GIS-T) specifically focusing on intermodal freight was provided by two independent studies. Authors G.C. Standifer and C.M. Walton published their research at the University of Texas, Austin (2000). F. Southworth and B. E. Peterson published their findings for the Centre for Transportation Analysis in Oak Ridge Tennessee (2000). Standifer and Walton set out to prove that digital data conflation – the process of applying attributes to specific sections of a designed network – and network design – the creation of decision rules and paths representing actual paths in real life networks – assist supply chain managers in making the most cost effective decisions for their businesses. Through a series of case studies, the authors demonstrate the positive benefits of digital network creation and data conflation (using ArcView – the predecessor of ArcGIS) based on real variables such as speed limitations, ton / mile and a variety of other case specific variables. Integrated into their model is Dijkstra's graph search algorithm for discovering the shortest path problem to ensure that a supply chain is achieving the lowest possible cost (1959, 270).

Standifer and Walton's research introduced the unique computing processes of GIS software to the concept of intermodal transportation. Prior to their research, GIS software had only been utilized in determining transportation routes of individual modalities. The singular approach to routing missed out on the various opportunities inherent in diversifying transportation along a supply chain. McKeil Marine's current business model is geared towards intermodal transportation. As a provider of transportation solutions over water, McKeil must cooperate with both truck and rail companies in order to service many, if not all of their customers' needs.

Southworth and Peterson's research focused on the macro-economic aspects of a GIS network. The authors constructed a digital network to simulate the cross-continental movement of five million origin-to-destination freight shipments with the use of digitally-constructed intermodal routes. The aim of the research was to discover the optimal routes and modal combinations for delivering goods from the West Coast of the United States to the various regions of the country. The authors found that the routes projected in by the software differed from real-world practices. Empirical evidence indicated that routes generated outside of a GIS setting were more efficient and cost effective. However, the authors noted that when parameters of their routes were changed within their GIS network, the results changed dramatically. Rather than invalidate the use of GIS software, the authors' finding may be attributed to inexperience of using new technology and the technical limitations of the early software. Recent studies of route optimization using GIS software have proven the software's substance.

Several difficulties arise when modeling intermodal freight networks. Ever present are the uncertainties relating to both the cost and time delays incurred by transferring freight between the different modes of transportation used on a network. This issue is addressed in Standifer and Walton's work and a variety of solutions are researched and presented by Ziliaskopoulos and Wardell (2000, 488-505). ArcGIS has the ability to account for time and cost penalties associated with transferring cargo. However, this thesis faced several additional constraints that required the use of a facility location model to fulfil the mandate outlined by McKeil Marine.

2.1.4 The Utilization of ArcGIS for Intermodal Networks on the Great Lakes and St. Lawrence Seaway & Further Considerations

Recent studies pertaining to GIS-T with respect to intermodal freight networks have been advanced at the Rochester Institute of Technology (R.I.T.). Using ArcGIS, researchers have constructed digital networks known as Geospatial Intermodal Freight Transportation Networks (GIFT) that not only determine optimal routes for intermodal flows but also account for costs related to negative externalities associated with the networks (Falzarano et al. 2007). Falzarano et al. faced the challenge of constructing transshipment nodes that accurately represented the cost and time penalties associated with transferring freight between different modalities. Furthermore, the researchers had to overcome the issue of linking several transportation databases that had already been converted into vector files.

Further studies from the R.I.T. focused on refining the procedures developed by Falzarano et al. and specifically focused on intermodal transportation networks on the Great Lakes and St. Lawrence Seaway System (Winebrake et al., 2008). Winebrake et al. have a significant influence on this paper because the networks they developed are located in the Great Lakes region. While the Golden Horseshoe and Lake Ontario comprise only a small portion of the region, the datum and methods used by Winebrake's team for implementing an intermodal freight network in the region will act as a manual for manipulating the digital information required to create the network in this thesis.

The findings of the R.I.T. studies indicate that transporting cargo by barge is a cost-effective solution in the classical economic sense and becomes even more attractive when the negative externalities of transportation are factored into the equation. For example, the R.I.T. studies indicate that when a monetary value is ascribed to pollution, transporting cargo via barge becomes even more cost effective because a truck produces more pollution per tonne kilometre than a barge does (Winebrake et al. 2008, 18). The R.I.T. studies positively reinforce a number of studies that advocate the increased use of short sea shipping. For McKeil Marine, one of a limited number of barge operators on the Great Lakes and St. Lawrence Seaway, the academic research only serves to reinforce the reasons for the company's success.

As a result of congestion and other factors such as economies of scale, the utilization of barge transportation and short sea shipping is becoming more attractive (Medda & Trujillo, 2010, 286). One problem contributing to the lack of short sea shipping is that current logistical systems are limited in their scope and therefore may not maximize the potential of specific supply chains because of lack of awareness (Notteboom & Rodrigue, 2000, 501). Logistical strategies must therefore be devised to allow for the integration of short sea shipping into the regional and global movement freight. In order to integrate short sea shipping into the logistical strategy of supply chain, a factor analysis of best practices for short sea operators has been developed (Casaca & Marlow, 2009, 1-19).

Each individual mode of transportation in an intermodal network maintains practices that can be altered to maximize efficiency within a particular leg of a cargo's voyage. In order to maximize the efficiency of the sea leg of a voyage, barge operators have to assess the synergies between routing, scheduling and the financial implications of their decisions (Lam, 2010, 33). There are a number of automatic systems that can be used to maximize the sea leg portion voyage. For example, the integration of the sea leg portion into the logistical framework of the Geospatial Intermodal Freight Transport Network will be an important aspect of this paper. While Lam's study has a broader focus on several aspects of a voyage, Fagerholt specifically focuses on computer-based decision support systems for vessel scheduling (2002, 36-44). The findings of Fagerholt's study are relevant to several issues that are dealt with in this thesis. However the methodology used in his research may limit the application of his findings to this thesis.

One relevant consideration that will affect an intermodal network constructed by the GIS software is the size of barge being used in the network. Normally the marketing team from McKeil Marine will collaborate with the operations department in order to choose an existing vessel or seek advice on purchasing a new vessel that would fulfil the requirements of a specific job. Industry specialists from both McKeil's Marketing Department and Operations Department offered advice on the equipment that would best serve the barge route considered by the model.

The methodology used in this thesis only accounts for the internal operational and private costs born by the carriers. M. Janic notes that there are a number of externalized costs produced by any intermodal network (2007, 34-43). Costs such as air pollution, congestion, noise pollution and traffic accidents often go unaccounted for. While these penalties will not be considered in the network created for McKeil, further research may include cost penalties for each externality, which may significantly alter the optimal routes. For example, the GIFT model was designed to measure the outputs of pollution from each mode of transportation on a particular route. The model then assigns a monetary cost to the pollution. Pollution is considered a negative externality because it is not paid for directly by the polluter and unrelated third parties incur consequences such as adverse health effects. Once a monetary value is assigned to the emissions, optimal routes change accordingly to account for the new costs. Furthermore, government policies are increasingly forcing companies to internalize negative external costs produced by their activities.

2.2 The Facility Location Problem

One of McKeil Marine's current goals is to evolve from its traditional role of a carrier into a full-spectrum provider of logistical solutions. In doing so, McKeil not only diversifies its business practices, it also hopes to find solutions that incorporate barge transportation for companies that have been oblivious to the savings resulting from transporting their products over water. Many of McKeil's current customers have facilities advantageously located next to shipping lanes. These companies have benefited greatly from the savings in transportation costs provided by McKeil.

The decision to locate a facility within a supply chain network is both extremely important and difficult. Managers must not only find the optimal solutions for their objectives in the present but also anticipate long-term developments that may alter the efficiency and effectiveness of their supply chain. A poor location decision can effectively handicap an otherwise efficient supply chain. Locating a facility by either purchasing an existing site or constructing an entirely new building is capital intensive and normally produces a fixed cost in the short term because of the capital and physical difficulties associated with relocating. An inefficient location for a facility will result in substantial economic penalties for the duration of the facility's lifespan (Chopra & Meindl, 2010, 135).

The candidate facilities proposed in this thesis are to be leased rather than purchased. The leasing stipulation is designed to lower the initial setup costs of the supply chain and allows for more flexibility with regards to facility relocation in the short term. However, leases are fixed for a certain period of time and within that timeframe relocation is less of a possibility. Even with the lower capital requirements resulting from leasing a facility, the price of real estate fluctuates depending on location. For example; the price of leasing real estate per square metre will be higher in central Amsterdam than the price per square metre will be in rural Lindbergh. Therefore, even with the use of a leasing structure, location will have significant impact on the price of a facility and therefore the locating of candidate facilities.

To compound the difficulties associated with locating facilities, decisions are mostly made in uncertain environments because demand and cost may fluctuate significantly over time (Daskin et al., 2005, 40). To aid managers in their decision-making process, a number of models have been produced in order to allow for simulations that will assist in choosing the best location for a facility in an interrelated supply chain. Contemporary facility location models owe their origins to the work of Alfred Weber who wrote *Über Den Standort Der Industrien, Tübingen* (translated to *The Theory of the Location of Industries),* which explores the methods for locating a facility at a site where the combined total cost of transportation and labour is minimized (1909). In the mid-1950's, Walter Isard, the man heralded as the founding father of regional science, brought about the resurgence in the study of location theory and began to apply modern economic principals to his concepts and models (1956). Recently, the proliferation of supply chain management in normal business practices has spawned an innumerable number of facility location models that are uniquely designed for specific fields and individual scenarios. Owen and Daskin developed a taxonomy for contemporary facility location models to update the earlier attempts by scholars and to expatiate further research within the academic field (1998). The taxonomy continues to be updated to chronicle new developments that transpire regularly. Melkote and Daskin (2001), Klose and Drexl (2005), Daskin (2008) and Melo et al. (2009) all readdress the taxonomy and attempt to accurately update findings within the fragmented field. The classification schemes of the various authors will be consolidated and addressed briefly in section 2.2.1. It is important to research and explore each of the unique aspects associated with the various facility location models so that the right model can be constructed to properly serve the purposes of McKeil Marine.

2.2.1 A Taxonomy of the Facility Location Models

Facility location models can be subdivided into four categories: *analytic models*, *continuous models*, *network models* and *discrete models* (Daskin, 2008, 283). The model used in this thesis is a variation of a *discrete model* but for the benefit of the reader, a brief summary of the three additional facility location models will be provided.

Analytic models, the most basic of the facility location models, operate under the assumption that demand is distributed in some quantifiable way over a ubiquitous area which is predefined (Ibid). *Analytic models* can be solved with basic calculus. Slightly more advanced than *analytic models*; *continuous models* operate under the assumption that demand can only occur at discrete points on a circumscribed service area. A real world example of a *continuous model* was devised by the founding father of facility location theory - Alfred Weber. In Weber's *Theory of Industrial Locations* the author postulates a model whereby markets are fixed at specific locations and the transportation cost is derived by the combined weight and distance of the goods being moved (1909). *Network models* are more advanced than *analytic* and *continuous models* and only allow for facilities to be located on augmented networks consisting of focal points called nodes that are connected by a series of arcs that represent real-life linkages such as roads, railways or waterways. Demand can only occur on a node but facilities such as production plants can be located at any point on a node or arc. *Network models* are normally based on an underlying distance metric. The *1-median problem* devised by A.J. Goldman's is an example of a *network model* used specifically in the research of transportation science (1971). Finally, *discrete location models*, also known as *mixed-integer programming models,* are defined by the fact that there is a finite set of locations for potential facilities on a network comprised of nodes and arcs. Like a *network model*, demand mostly occurs at the nodes but transportation distances and their associated costs may or may not be arbitrary. More often than not, a *discrete location model* is supported by a distance matric and will follow some mathematical rule (Klose & Drexl, 2005, 5).

There are three subdivisions of *discrete models* that are important to explore because of the insight they offer into the field of location modeling. The first subset of models are known as *covering-based models*, the second set is known as *median-based models* and Daskin has labelled the third category *other models* (2008, 286). *Covering-based models* discover the number of facilities and location of facilities required to service a given area. Toregas et al. demonstrate an example of a *covering-based model* in their research on locating emergency services (1974, 1365-1366). In *covering-based models*, nodes are subject to binary constraints, that is, they are either covered or they are not. Daskin's *other models,* such as the *p-dispersion model,* maximize the minimum distance between any numbers of facilities. An example of the *p-dispersion model* in a real world scenario is demonstrated by the introduction of a new franchisee into a service area without taking away market share from an existing franchisee (Daskin, 2008, 285). *Median-based models* are used for distribution planning and are designed to minimize the transportation costs. An adaptation of a *median-based model* is used in this thesis. Within the term *median-based* are two distinct models, the *p-median* and the *fixed charge location model*. The *p-median* is based on the assumption that all of the potential sites are equivalent in terms of running cost and setup cost. The *fixed charge problem* adds an additional requirement to the objective function that considers unique facility costs. As a result, the number of facilities chosen to be in the network is an endogenous decision (Melo et al., 2009, 402).

The classic facility location models described above normally treat data as deterministic and do not take into consideration the suboptimal outcomes that result from solutions built on deterministic assumptions. Robust location models have been created in order to minimize the regret of a network should variables such as cost and demand fluctuate (Daskin et al., 2005, 56). An example of the robust optimization approach can be found in the research of Baron et al. who attempted to solve a location model with alternative levels of uncertainty (2011, 3-7).

2.2.2 Hierarchical Facility Location Models

Klose and Drexl describe a hierarchical network as a supply chain of different types of interacting facilities (2005, 14). Each type of facility in the network is associated with a specific tier. For example, tier one of the network established in this thesis encompasses the MRFs. Tier two encompasses the shredding facilities and tier three encompasses the gasification facility. In order to expand the research on hierarchical systems G. Sahin and H. Süral conducted a comprehensive review of the existing literature for hierarchical facility location models (2007). In their review, the authors created a classification scheme for the various forms of hierarchical location models based on specific characteristics that have been defined by a wide array of authors researching the subject. The first category in the classification system is the *flow pattern*. The *flow* along the network can either be a *single-flow* or *multi-flow* pattern. In a *multi-flow* pattern, every facility in the network can interact with every other facility. In a *single-flow* network, the flow of goods follows a consistent sequential pattern from tier one onto each tier in the network until the final tier is reached. The network in this thesis operates as a *single-flow* pattern because the recycled plastic moves sequentially from tier one to tier two and finally onto tier three.

Sahin and Süral report that the second defining characteristic of a hierarchical system is the *service variety* offered by the facilities at each tier of the network. The authors describe the *service* variety as either being *nested* or *non-nested*. In a network where the facilities are *nested*, each higher-level tier of facilities can perform the tasks of the lower level facilities. In a *non-nested* network, each tier of facilities provides a unique service that is not replicated in any other tier. The network constructed in this thesis is *non-nested* because each of the three levels of facilities offers a unique set of services – distribution, shredding and gasification.

As was discussed in section 2.2.2, there are a variety of objectives that can be fulfilled by a facility location model. Appropriately, the final classification category for a hierarchical facility location model is to define the *objectives of the model*. For example, the objectives of the model used in this thesis are to minimize the combined transportation and facility costs by determining the optimal transportation routes along a network as well simultaneously determining the optimal number and location of the facilities. These objectives are met by the objective function of a *hierarchical fixed charge uncapacitated facility location model*.

2.2.3 The Fixed Charge Problem and Transhipment

The *fixed charge facility location problem* is a basic template that acts as the foundation for many facility location problems encompassing a wide array of objectives. The problem describes a scenario where the quantity demanded and the locations of demand are known. For example, the demand at the gasification plant is known along with the fixed costs and the associated transportation costs of inbound and outbound flows from each of the four candidate facilities. The objective of the *fixed charge problem* is to find the optimal number of facilities, the location of the facilities and the capacity of each of the facilities so as to minimize the combined transportation and facility costs while still meeting all of the demand in the given scenario. There are two types of *fixed charge models*, the *uncapacitated facility location model* (UFLM) and the *capacitated facility location model* (CFLM). In an UFLM, each of the candidate facility locations is thought to have an unlimited capacity (Melo et al., 2009, 402**)**. Conversely, a CFLM problem takes into account the additional constraint(s) that limit the capacity of each facility or facilities (Ibid).

Computer scientist, Michael Balinski, was the first to devise a formula for the UFLM (1965, 286-293). The formula consists of inputs, decision variables an objective function and constraints.

Inputs and Sets:

I: Customer locations indexed by i
J: Candidate facility locations indexed by j
h_i: Demand at location $i \in I$
f_j: The fixed cost of locating a facility at candidate site $j \in J$
c_{ij}: Unit cost of transportation between candidate site $j \in J$ and customer location $i \in I$

Decision Variables:

$$X_j = \begin{cases} 1, & \text{if we locate at candidate site } j \in J \\ 0, & \text{if not} \end{cases}$$

Y_{ij} = the fraction of demand at customer location i ∈ I that is served by a facility at site j ∈ J

The Objective Function:

$$Min \sum_{j \in J} f_j X_j + \sum_{j \in J} \sum_{i \in I} h_i \, c_{ij} \, Y_{ij} \qquad (1.1)$$

Subject To:

$$\sum_{j \in J} Y_{ij} = 1 \qquad \forall i \in I \qquad (1.2)$$

$$Y_{ij} - X_j \leq 0 \qquad \forall i \in I;\ \forall j \in J \qquad (1.3)$$

$$X_j \in \{0,1\} \qquad \forall j \in J \qquad (1.4)$$

$$Y_{ij} \geq 0 \qquad \forall i \in I;\ \forall j \in J \qquad (1.5)$$

In the formula for the objective function (1.1) it is stated that the total transportation and facility location costs will be minimized. Constraint (1.2) stipulates that the demand at each node must be satisfied. Constraint (2.3) dictates that a demand node cannot be serviced by a facility unless that facility is opened. Constraint (2.4) is a binary constraint, which is indicated by a 1 if a facility is open or a 0 if it is closed. Constraint (2.5) is a non-negativity constraint, which means that the flow must be greater than 0. Since 1965, several adaptations have been applied to Balinski's original formula including an expansion to meet the capacity constraints apparent in the CFLM. The CFLM operates under the assumption that maximum capacity values are ascribed to facilities considered by a network (Chopra & Meindl, 2010, 135).

The capacitated facility location model will not be used in this thesis because the 33,691 tonnes of plastic considered by this network are divided over the course of an entire year. Even if only one facility were to process the entire amount, the space required to accommodate a week's worth of plastic, 3,000 square feet, is only half of the total square footage required for each of the four potential shredding facilities considered by the model. The mathematical equation below justifies the reasoning:

$$33{,}691 \text{ mt} \div 52 \text{ weeks} \qquad (2.1)$$

$$= \qquad 647 \text{ mt / week} \qquad (2.2)$$

$$647 \text{ mt / week x } 3.7 \text{ m}^3 \text{ (the stowage factor of plastic)}^2 \qquad (2.3)$$

$$= \qquad 2397 \text{ m}^3 \qquad (2.4)$$

In the requirements, outlined in section 4.2, for each of the candidate facilities, the minimum space necessary for a facility was set at 6,000 square feet. Half of 6,000 square feet is reserved for warehouse space and is equal to 278.709 cubic metres. The required height of each facility is 25 ft. in order to accommodate a forklift. The plastic needs to be stacked 8.6 ft. high. Based on the variables, each of the candidate facilities can accommodate 2397 m^3 of plastic per week based on:

$$278.709 \text{ m}^2 \text{ x } 8.6 \text{ ft.} \qquad (3.1)$$

[2] The stowage factor of 3.7 is discovered in equation 4.2 found in section 4.3.

$$= \quad 2397 \text{ m}^3 \tag{3.2}$$

The addition of a hierarchical structure to the problem faced in this thesis will alter the basic UFLM location formula devised by Balinski. Prior to discussing real world examples of the combined UFLP and a hierarchical network, it is important to establish a basic understanding of the transhipment problem that the network in this thesis will face. The transhipment problem is faced in any hierarchical network because a tiered structure will contain additional nodes apart from the origin and destination nodes. The objective of a transhipment problem is to determine how many units should be shipped over each arc in a network so that all of the demand is met at a minimal possible transportation cost. Anderson et al. create a concise and congenial example of a basic transhipment model (2011, 273-279).

Inputs and Sets:

X_{ij}: number of units shipped from node i to node j
C_{ij}: cost per unit of shipping from node i to node j
s_i: Supply at origin node i
d_j: Supply at destination node j

The Objective Function:

$$Min \sum_{\text{all arcs}} C_{ij}X_{ij} \tag{4.1}$$

Subject To:

$$\sum_{\text{arcs out}} X_{ij} - \sum_{\text{arcs in}} X_{ij} \leq S_i \quad \text{origin nodes } i \tag{4.2}$$

$$\sum_{\text{arcs out}} X_{ij} - \sum_{\text{arcs in}} X_{ij} = 0 \quad \text{Transhipment nodes} \tag{4.3}$$

$$\sum_{\text{arcs out}} X_{ij} - \sum_{\text{arcs in}} X_{ij} = d_j \quad \text{Destination nodes } j \tag{4.4}$$

$$X_{ij} \geq 0 \text{ for all } i \text{ and } j \tag{4.5}$$

An early attempt to construct a two level hierarchical network that incorporated a *fixed charge location model* with similarities to the model required by McKeil Marine was undertaken by J. P. Osleeb and S. J. Ratick (1983). The authors created an optimized freight network for the export of coal from the East Coast of the United States. J. Current expanded upon the early research by refining the methods for minimizing the cost of a network (1998). In his research, Current noted that solving the integer programming formula yields only one optimal solution for the network. When approached heuristically, a number of solutions can be rendered if the network has multiple objectives including those objectives not directly related to cost. Furthermore, Current considers the heuristic approach to be more flexible to change with regards to altering routes. The model constructed for McKeil Marine does not consider a heuristic approach but further research may be undertaken to evaluate the benefits of Current's findings.

2.2.4 Existing Literature of Facility Location for Waste Management

There are three studies that explore facility location problems with similar characteristics to the waste management / recycling problem apparent in the model developed for this thesis. Erkut et al. set about the task of optimizing the regional planning of a solid waste management strategy in central Macedonia (2008). The authors develop a *mixed-integer linear programming model* with multiple objectives that account for both environmental and economic considerations. The model seeks to locate various facilities at different stages of the hierarchical system. The facilities included potential sites for transfer stations, MRFs, incinerators, and sanitary landfills.

Barros et al. research an optimal network for the recycling of sand used in construction projects across the Netherlands (1998). The authors establish a two-level hierarchical network that determines how the recycled sand should be sourced from finished projects, transported, stored, cleaned, classified and delivered to new projects so that the total cost of the network is minimized. The model created by the authors, a *mixed integer linear program*, determines the optimal number of operational facilities from a number of candidate facilities at each level of the network and the location of the facilities given the actual capacity constraints of the candidate facilities.

In an attempt to reduce and harness methane emissions from municipal solid waste (MSW) in Russia, a utilization system was devised with the assistance of a *linear programming model* (Rodionov and Nakata, 2011, 1486). The study focuses on the municipality of St. Petersburg and the authors construct a system that attempts to reduce carbon dioxide and methane emissions while maximizing the annual energy generated from the system. The objective function of the model seeks to minimize the net costs of the MSW system. The revenue for the system is generated by selling by-products of the waste, such as the energy produced by converting the waste into energy, compost from appropriate biological material and recyclable material such as plastic. The costs borne by the system include the collection of waste, transportation to the necessary facilities, treatment of the waste and the landfilling of the treated material. Figure 2.3 displays a graphic representation of a portion of the network created by the authors (Ibid). The network is a hierarchical system similar to the one used in this thesis apart from the multiple destination nodes – we only have one gasification facility – and the multiple objectives of the transhipment nodes – our transhipment nodes have only one task, shredding.

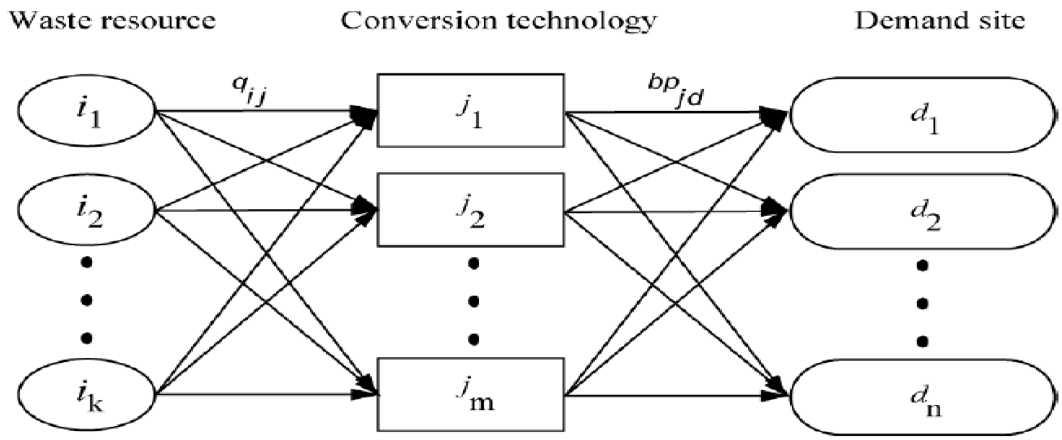

Figure 2.3: A representation of the network created by M. Rodionov and T. Nakata (2011, 1492).

2.3 A Job Cost Model for McKeil Marine

According to M Miceli, the lead Business Analyst at McKeil Marine, the main objective of a job costing model is to discern if a potential job is economically sensible. The target for any job McKeil looks at undertaking is approximately 10%-20% of earnings before, interest, taxes, depreciation and amortization (EBITDA). That means the projected revenue of a potential job needs to cover operating costs and overhead costs. "A model helps structure the costs and earnings of a job. It prevents a company from entering into a job that has an unreasonable amount of financial risk and reveals the point where a company begins to lose money. By using a job cost model, McKeil can be more competitive when we bid on potential projects because we have a very accurate forecast of all of the variables that determine revenue and cost" (2012).

Within the last year, McKeil Marine Ltd. has established a line of credit with an undisclosed financial institution. The commitment is structured as a revolving credit with a four-year maturity and a 10-year amortization rate with financing up to 85% of the value of an asset. The revolving credit facility allows McKeil to borrow money to finance the acquiring of new assets, pay down the loan and re-borrow money against the facility as long as the sum borrowed does not exceed the limit established in the contractual agreement with the bank. The loan is also subject to a number of confidential covenants that the bank has put in place in order to manage its risk. According to J. Merwin, the Vice President of Finance at McKeil, "the introduction of the revolving line of credit will not only reduce the time and effort involved with borrowing money, the line of credit will actually save us money on our bottom line because of the rates we have been able to secure."

An amortized loan refers to a debt that has a fixed payment schedule over a defined period of time. During the payment schedule, a portion of each payment is allocated to cover the interest accumulating on the debt while the remaining portion of the payment is used to reduce the principal (Brealy et al., 2011, 59-60). The structure of McKeil's loan is altered by the nature of the revolving facility. Each time McKeil Marine borrows against the facility, the sum borrowed is automatically structured into a 10-year amortized loan. The term of the revolving loan facility is four years, which means that money can be borrowed from the facility from the beginning of the 2012 fiscal year until the end of the 2016 fiscal year. A key covenant that can be disclosed in this thesis is McKeil's ability to finance an asset up to 85% of its value. The value of 85% will be broken down into the daily capital cost of both the tug and barge.

We will present a job cost model that treats the equipment used to service the network in this thesis as separate entities from the other vessels in McKeil's fleet. Furthermore, the normal job cost model constructed by McKeil's President S. Fletcher and M. Miceli will not be used because it contains sensitive information that is confidential. Based on the volume of plastic being transported in the network, it is hypothesised that if any plastic moves on water, it will be a relatively small amount and will constitute only a minimal number of movements a year rather than a steady revenue stream associated with a long-term contract. Therefore, the assets cannot rely on financing from this project alone. The job cost model will be created to account for daily spot market rates rather than a yearly breakdown in order to assess the economic feasibility of any cargo runs manifesting from this project. A. Strullatto, Assistant Vice President of DVB Bank's Dry Bulk Sector, has assisted in the creation of a simplified template for determining a vessel(s)' economic viability in respect to projected revenue, capital expenditures (CAPEX) and operational expenditures (OPEX). Both the figures for CAPEX and OPEX used in this model will be accurate but their breakdown will remain confidential. Without divulging confidential financial information, the OPEX comprise of five major expenses and are presented in Table 2. Fuel accounts for the largest per day expenditure. The exact percentage is difficult to determine because the market price for marine gas oil (MGO) fluctuates daily as do a vessel's sailing times. The burn rate of fuel is also a function of sailing time vs. time in a port because less fuel is burned if the vessel is not moving. All other expenses are accurately forecasted and incorporated into the job cost calculations but cannot be divulged. Used assets were determined to be more suitable for this project because of the projected low-margins. With used vessels, capital expenditures are kept low.

After reviewing the requirements of this particular job, the operations and marketing departments within McKeil have determined that the tug Ecosse and the barge OC 181 will be best suited to carry out the necessary work. Figure 2.4 displays the specifications of the Ecosse. Important characteristics of the Ecosse are that the vessel has an Inland Waters Class I, which allows the vessel to operate within Canadian waters subject to the regulations outlined by the Canadian Shipping Act 2001. The Ecosse has a fuel capacity of 12,000 Imperial gallons, which is equal to 54,553 litres and uses MGO. The figure of 14,000 break horsepower (bhp) refers to the amount of power generated by the engines without taking into account any of the auxiliary devices aboard a vessel that reduce the speed of the engine. The term bollard pull refers to the hypothetical thrust capabilities of a towing vessel that is achieved at zero speed of advance and the engine's full revolutions per minute (RPM). The bollard pull is often used as a benchmark for a tug's ability to pull or push a certain deadweight tonnage. Important pieces of equipment on the tug are its capstan and double drum 25 tonne winch. Both pieces of equipment can be used in towing, pushing or mooring by applying pressure to cables, ropes or hawser lines. Figure 2.5 displays the aft deck of the Ecosse. The double barrel winch is visible below the emergency lifeboat. Steel cables originating from the winch run along the aft deck and out through a fair lead on the port and starboard side. The cables then run forward along the port and starboard side's of the vessel and are attached to bits on the aft of the OC 181. The winch can tighten or loosen the cables accordingly and keep the tug's push knee tight against the barge for optimal control (Paterson, 2012). The fabrication and installation of a bin wall is required on the deck of the OC 181. The bin wall is designed to protect cargo and take advantage of cubic deck space[3]. The particulars of the barge are presented in Figure 2.6.

Table 2: A List of The CAPEX and OPEX Associated With a Tug and Barge

Operational Expenditures	**Capital Expenditures**
Fuel Sailing	Payments to the bank
Fuel Standby	
Lubes	
Crew Cost	
Crew Travel	
R&M	
Winter Works/ Dry Dock Accrual	
Misc. Operating	
Marine Service Fee Per Day	
Supplies	
Provisions	
Insurance	
Overhead	

(Author, 2012).

[3] The costs associated with the addition of the bin wall will be explained in section 4.4.

NADRO MARINE SERVICES LIMITED

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Ecosse

Specifications

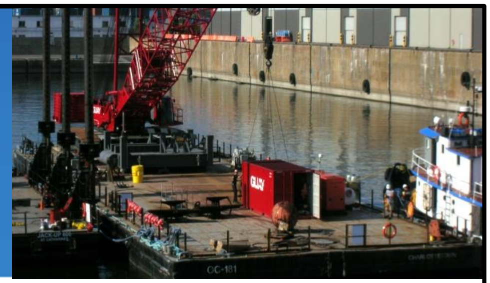
CONSTRUCTED:	Wheatly, ON
HULL:	O.A. Length 91′; Beam 26′; Draft – 8′6″ lite, 10′2″ loaded
HEIGHT OF EYE:	22′6″
TONNAGE:	142 Gross; 57 Net Reg.
DECK SPACE:	58′ x 25′
COAST GUARD CLASS:	Inland Waters I
COMPLIMENT:	12
FUEL CAPACITY:	12,000 Imp. Gal. Fuel Transfer Capabilities
PROPULSION:	2 – Detroit Diesel 16V 92 N Each @ 700 BHP
HORSE POWER:	1400 BHP; 1800HP with 60″ Kort Nozzles

BOLLARD PULL:	16 Ton
GENERATOR:	(2) 30 KW 3 Phase Gen. (DD 353 Series)
DECK EQUIPMENT:	After Steering Station Capstan Double Drum 25 Ton Tow Winch (DD 471)
NAVIGATION EQUIP.:	2 Radars Furuno AIS FA 150 Furuno DGPS GP37 ComNav Auto Pilot 2 VHF Radios
OTHER FEATURES:	Large Galley 5 State Rooms / Sleeps 8 3 Piece Washroom for Crew Private Washroom & Shower in Captains Room

Figure 2.4: The particulars of Nadro Marine's tug Ecosse (Nadro, 2012).

Figure 2.5: The Nadro tug Ecosse pushing the McKeil barge OC 181 (Patterson, 2012).

Project Fleet | OC 181



Principal Particulars

Flag:	Canadian
Port of Registry:	Charlottetown, P.E.I.

Dimensions

Grt:	957
Nrt:	957
Capacity:	2,100 MT
Length:	180’ (54.86 m)
Beam:	54’ (16.46 m)
Depth Molded:	12’ (3.66 m)

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MCKEIL

Figure 2.6: The particulars of McKeil Marine’s barge OC 181 (McKeil Marine, 2012).

Chapter 3 Hypotheses for the Network Optimization Model

The hypotheses will be separated into three distinct sections. The first section will address the expected outcomes of the various routes determined through the use of ArcGIS. The second section will discuss the expected outcomes of the HFCUFLM. The third and final section of the hypothesis will address the job cost model in relation to the two previous sections.

3.1 ArcGIS Routing

The research presented in the literature review validates the use of ArcGIS as a tool for determining optimal routes. However, the question faced by this paper is whether or not the software was used appropriately in the context of McKeil Marine's objectives. The software was used to determine the quickest paths on the transportation network because prices for both truck and barge were quoted on a per hour basis. Therefore, the shortest amount of time a vehicle spends traveling on the network will lead to the lowest cost. There are two components to a complete route on our network, the route from an origin node to a transhipment node and the route from transhipment to the destination node. Notwithstanding the origin node located in Hamilton, it is predicted that all of the routes will find the quickest path from a point of origin, be it from an origin node or transhipment node, to the nearest highway because a highway will facilitate the fastest route to the point of destination. Highways maintain a greater average speed than any other road type on the network. Speed is one of the many attribute taken into account by the software. The MRF in Hamilton is located only 4.1 kilometres from the candidate shredding facility in Hamilton and is not connected to the candidate facility via a highway. In all of the remaining 53 potential routes, it is predicted that a highway will be accessed in order to obtain the quickest route from a point of origin to a point of destination.

The single barge route differs from the road routes because there are no alternative options from the origin point of the route, located at the Port of Oshawa, to the gasification plant in Hamilton. The single route is a predetermined shipping lane that traverses the shortest distances between the two ports. It is predicted that the transportation cost, discussed in section 4.1, of moving one tonne of cargo over water will be less than moving one tonne via a truck because a barge can transport far more tonnage in a single trip than a truck can. Even though the cost per hour to utilize a barge will be higher than the cost per hour of a truck, the factor increase in cost is not expected to overtake the factor increase in the amount of volume a barge can transport. With that said, the loading and unloading of a barge is more costly and time consuming than the loading and unloading of a truck. Furthermore, the Port of Oshawa and the Port of Hamilton will require additional infrastructure cargo handling in order to avoid stevedoring costs and reduce the overall time the cargo spends in transition. The facility requirements will be factored into the fixed charge costs considered by the HFCUFLM and discussed in greater detail in section 3.2.

The use of ArcGIS in this thesis departs from similar studies because the findings of the software were combined with Keenen's basic mathematical methods in order to determine specific costs associated with each of the potential routes proposed for the network. In the research conducted by Winebrake et al., a standard tonne kilometre rate was applied to routes used by each mode of transportation. Winebrake et al. considered containerized cargo in their research, which is easier to create a standardized rate for than the bulk cargo considered in our network. The objective of this thesis was to determine, as accurately as possible, the real cost of transporting cargo for each modality so that the most cost effective solution could be determined. The routes on our network will also have to account for a reduction in stowage factor that occurs after shredding. This will alter the tonne kilometre rate and make standardization of route pricing impossible.

The idea of instituting an intermodal network within the Golden Horseshoe was approached cautiously but optimistically. If a sizeable amount of tonnage was generated by the various MRFs, than it stood to reason that plastic from any number of ideally situated facilities could move on water and take advantage of the tonne kilometre reduction resulting from the economies of scale that is inherent in transporting cargo via barge. However, a number of facts emerged early in the research process that made the use of a barge in this network appear untenable. The close proximity of the facilities utilized by the network and more importantly, a fundamental lack of cargo, are both factors that work against the establishment of an intermodal network. The OBBP collects approximately 58,000 tonnes of plastic. Of that amount, our network only considers 33,691 tonnes that is divided unevenly amongst the 13 MRFs. The disaggregation of the plastic between the 13 origin nodes compounds the issues relating to the lack of cargo. One barge load can move approximately 2,000 tonnes of shredded plastic. That accounts for approximately 6% of the entire year's worth of plastic generated by the program. If a barge route is financially viable, than plastic will have to be warehoused to fill the capacity of the barge in order to attain the relatively lower tonne kilometre rate associated with a full barge load. A less than full barge load would mean that the tonne kilometre rate of the barge would increase proportionate to the unfilled capacity because the costs to operate the barge remain the same regardless of the amount of cargo it transports.

3.2 The Facility Location Model

The HFCUFLM model considers both the yearly cost of transportation on each complete transportation route in addition to the cost of opening and running a shredding facility. The model's objective is to establish the lowest cost of transportation in accordance with the lowest facility cost by determining the optimal routes for moving cargo and which facility or facilities should be opened. There are four potential candidate-shredding facilities and 91 potential transportation routes. Transhipment facility one is located in Oshawa and was positioned in order to test the viability of a barge route within the supply chain. It is predicted that the model will not use the facility in Oshawa or its corresponding barge route to Hamilton. The reasoning supporting this conclusion is that there are additional facility costs applied to the facility in Oshawa. The additional costs are a result of an automated cargo handling system required to blow the shredded plastic onto the barge in the same way that woodchips are blown onto a woodchip barge. Figure 3.1 displays the automated loading system. In addition to the cost of a loading system, the Oshawa facility will also be attributed with the cost of the automated unloading system required in Hamilton. The reason for attributing both costs to the Oshawa facility is because it simplifies the model and doesn't alter the result. If the Oshawa facility is opened then the unloading equipment in Hamilton will be required as well. The combined cost of the automated system is C$1,000,000. The model will consider an additional C$100,000 to the cost of the Oshawa facility. This represents a financing structure whereby roughly 10% of the capital investment is paid down in year one.

The rational for using automated cargo handling systems is based on the gasification plant's economic lifespan of 20 years. Over the course of 20 years, the automated systems can be financed and depreciated in such a way that the cost of cargo handling will decrease every year. If the systems were not installed, the barges would be loaded and unloaded via stevedoring firms. The cost of stevedoring would gradually increase over the economic lifespan of the gasification facility and cargo-handling times will be consistently higher when stevedores are used. Over the course of 20 years, the additional cargo handling time may amount to a significant cost relative to the short transit time of the barge. The close proximity of all the facilities in the network combined with the method of quoting transportation costs on an hourly rate structure means that time is an important determinant of overall cost.

Transhipment facility two, located in Whitby, is situated along a main arterial of the transportation network. It is predicted that the transhipment facility in Whitby will not be opened because the time required to unload the plastic bails at the facility and reload the shredded plastic onto trucks will increase the overall cost of transportation in the network. The reduction in the tonne kilometre rate from Whitby to Hamilton resulting from the reduced stowage factor of the shredded plastic will not generate enough savings to justify the costs incurred by additional cargo handling time. Plastic delivered directly to the shredding facility in Hamilton is essentially at its final destination and can transferred to the gasification plant's hopper without incurring additional transportation costs. The close proximity of all of the candidate facilities means that time is a major factor for determining cost because transportation times have to be rounded up to the nearest hour (McNeil, 2012). As a result, distance is less of a factor than time in this model and the reduced tonne kilometre rate has less of an impact then a reduction in the overall time cargo spends in transit on the network.

Figure 3.1: The loading of a woodchip barge via an automated system (Nsandal, 2012).

The facility in London was purposely positioned in a remote location on the network. It is predicted that the London transhipment facility will not be opened and if it is, it will indicate that there is a problem with the formulation of the model. Based on all the factors considered in this section, it is hypothesized that the shredding facility in Hamilton will be the sole transhipment node opened on the network. The Hamilton shredding facility is in an advantageous position for minimizing the total time cargo spends in transit. While there are a number of facilities whose transportation costs will be minimized by the barge service, the additional facility costs manifested by the handling system required to service the barge will most likely make the barge route infeasible.

3.3 The Job Cost Model

The objective of the job cost model created for McKeil Marine was to eliminate the possibility for making an economic loss. Even if the determined hourly rate for the combined tug barge unit makes the utilization of a water route infeasible, it will ensure that McKeil does not lose money. The model acknowledges both the CAPEX and OPEX and is designed to set a target for revenue so that the company will always be aware of the monetary value it needs to earn to cover its expenses. Ideally, a margin of between 10% and 20% is added to the known expenditures in order to cover unforeseen expenditures and make a profit. Once the daily revenue becomes known, it is a matter of determining the volume of cargo that is allocated to the barge route. The volume is then divided by the capacity of the barge and the number of trips can be determined. It is predicted that no volume of plastic will be moved over water because the savings resulting from a reduced tonne kilometre rate of moving cargo via a barge do not make up for the fixed costs of the automated handling systems required to accommodate a barge.

Chapter 4 Experimental Setup

There are three unique steps that coalesce to answer the research questions outlined in the introduction. The first step requires the use of ESRI's ArcGIS software in order to determine the minimized cost routes used by the two types of vehicles in this network. The second step involves the use of a *hierarchical fixed charge uncapacitated facility location model*. The inputs for the model are derived from the weighted cost of the routes discovered in the first step by ArcGIS. The final step of the experiment focuses on the financial feasibility – from the perspective of McKeil Marine – of moving recycled plastic with a tug and barge. Modeling the overall feasibility of the project will be attempted by subtracting the known costs of the entire network from the estimated revenue generated by the gasification facility. Even if McKeil Marine is in a position to make a profit on the barge route, the gasification plant will not be opened if it is predicted to make an economic loss over the duration of its lifespan.

4.1 Establishing Network Routes with ArcGIS

The purpose of using ArcGIS in this research is twofold. The software has thematic maps of existing networks such as the southern Ontario road system as well as shipping routes along Lake Ontario. Segments of the networks such as highways, rural roads or waterways maintain accurate data of distances, average speed, congestion, construction etc. The software utilizes a variation of the shortest path algorithm created by Dijkstra to allow the user to define which attributes constitute the weighting of the route. The network consists of nodes that represent origin, transhipment and destination facilities. The addresses of the origin nodes, candidate transhipment nodes and destination node are presented in Table 1. Google Earth™ was used to determine the exact location of each facility along the lines of longitude and latitude. The coordinates were then inputted into ArcGIS and polygon shapefiles were constructed to represent the facilities at the coordinates discovered by Google Earth™. Connecting the digitally constructed nodes are arcs that are representations of real transportation infrastructure and are weighted based on attributes that are entered by a user i.e. average speed. When two nodes are selected, the software calculates the quickest route between the point of origin and the destination. The routes discovered by ArcGIS are then augmented with a basic mathematical equation presented in section 4.4 to determine the tonne kilometre rate that is used to discover the total cost of transporting a years worth of plastic from each of the 13 MRFs.

In order to take advantage of ArcGIS's abilities, a computerized network must first be constructed. The North American Datum of 1983 is used as the networks' reference system. Using the Network Analysis tool, existing vector-based shapefiles representing entire transportation networks are imported to the GIS environment. Shapefiles constitute several files that maintain metadata, geometry, attribute data, and positioning. Within the shapefiles are individual line segments constituting specific transportation routes. These line segments are also supported by databases containing further attribute data used to calculate factors of cost. The shapefiles for maritime routes and roadways were sourced from the National Transportation Atlas Database's (NTAD) 2011 spatial data collection.

The research conducted by Winebrake et al. on the GIFT model reveals the use of a *hub-and-spoke* approach whereby segments of a transportation network are connected via artificially manufactured spokes to hubs that digitally represent transfer facilities such (2008, 6). An important component of a spokes is its ability to take on certain attributes. In real world operations, transferring cargo from one modality to the next incurs both a time and cost penalty. The estimated penalties of transferring plastic from trucks to a barge can be applied to the spokes and factor into the calculations for the optimal routes. Figure 4.1 visually depicts the *hub-and-spoke* approach. Ports and shredding facilities constitute the transfer facilities in our network even though a shredding facility may maintain the same transportation mode for inbound and outbound flows. In order to digitally construct the port facilities required to service the barge route, the same procedure for constructing candidate shredding facilities was followed. Using Google Earth ™ to determine the coordinates of the ports, shapefiles were manually created as points on the network.

Industry experts were instrumental in approximating the weightings of each potential transportation route. G. McNeil, General Manager of CV Logistics and T. Paterson, Assistant Manager of Marketing and Business Development at McKeil Marine offered advice on how to approximate truck and barge rates respectively. The calculations for the modal rates are presented in section 3.2. The final stage of establishing a functioning network on ArcGIS is to integrate the various thematic layers in order for them to operate simultaneously. This is a basic function of the Network Analyst tool.

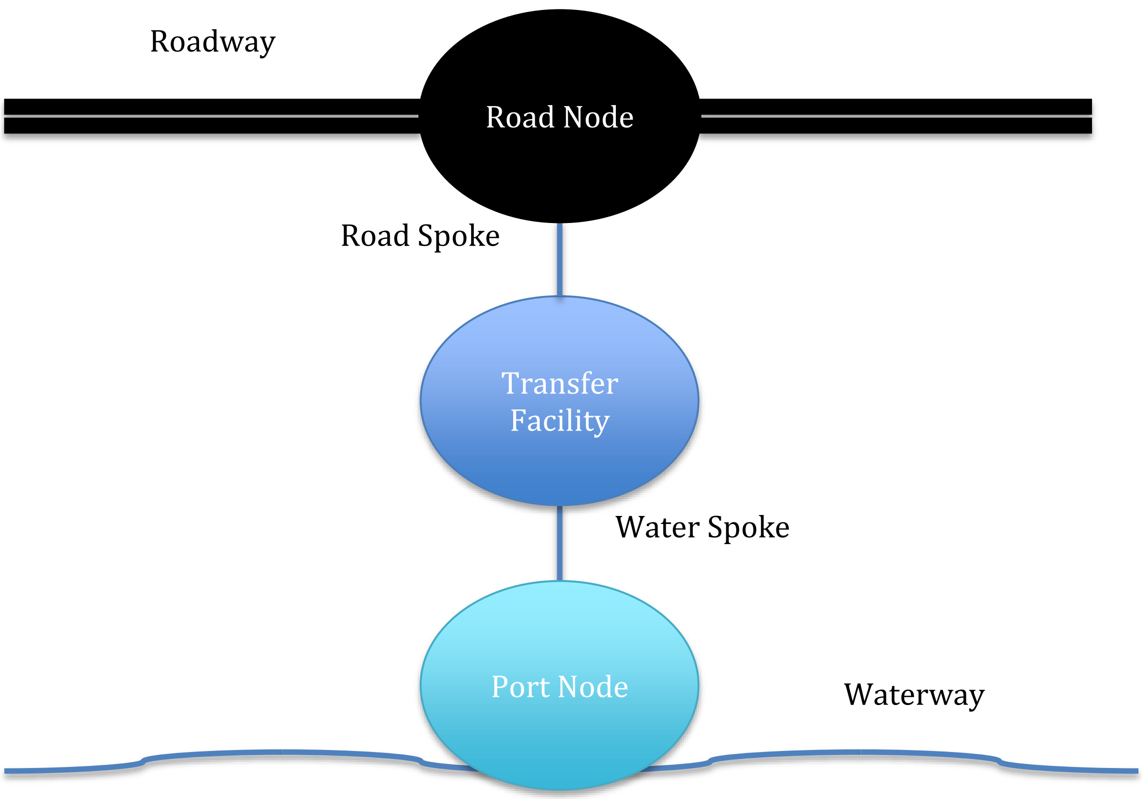

Figure 4.1: An illustration of the hub-and-spoke method (Author, 2012).

4.2 Selecting Candidate Sites for Transhipment Facilities

While researching for this thesis, a variation of a facility location model known as a *covering-based model* was discovered. The *covering-based model* assists in the placement of facilities by determining the optimal number of facilities and the optimal location of the facilities required to service a given area. While this seems ideally suited for determining the location of the shredding facilities, the objectives of this thesis would not be met if this model were employed. The four candidate sites available to the network were purposely selected because they each embody a specific attribute that is important to test in this supply chain. Candidate site one is located in Oshawa, Ontario and is the origin node for any freight moving on water. Oshawa was decided on because it has access to Lake Ontario, is far enough away from Hamilton to allow for the quotation of freight rates that are competitive with truck rates and it is within close proximity to five MRFs. Candidate site two is located in Whitby, Ontario and was selected because it is located at a focal point on the road portion of the network. It is either in close proximity or on a route used by seven MRFs. If moving freight over the water is deemed infeasible because of external costs not relating directly to transportation i.e. facility requirements and loading and unloading times, candidate site two has the potential to determine if the reduction of the tonne kilometre rate that results from shredding will have an impact on the outcome of the experiment. Candidate site three is located in Hamilton, Ontario and is connected to the gasification facility. The facility was strategically placed to determine if the reduction of transportation costs resulting from the decoupling of shredding from the gasification plant are unjustified. Candidate site four, located in London, Ontario was situated to determine if the model is functioning properly. The site is not located near any of the 13 MRFs nor is it on or near a path linking any of the MRFs with the gasification facility.

Furthermore, members of the Operations Department at McKeil Marine determined that each candidate facility must be a minimum of 6,000 square feet with at least 3,000 square feet of the facility reserved for warehouse space. The size requirements are instituted in order to accommodate the inflows of plastic, storage of the plastic and the outflows. The required height of each facility's interior ceiling is 20 feet to accommodate the forklifts and Front-End-Loaders needed to handle the plastic. In order to find available properties meeting the criteria, *espace Listings* (http://www.espacelistings.com/) was used to locate industrial zoned properties in each of the locations described above. The cost of leasing each facility for a one-year period is based on the price per square foot a year and is presented in Table 3 in section 4.5.

4.3 Stowage Factor

Before rates can be determined for the barge and truck routes, the stowage factor of plastic needs to be calculated. The stowage factor indicates how many cubic meters one metric tonne occupies or conversely, how many metric tonnes can fit into one cubic meter of space. This is a difficult task for this particular network because the plastic being shipped from the MRF consists of seven different resins, each having a unique stowage factor. To discover the average stowage factor of plastic, Jake Westerhof, Vice President of Operations at Canada Fibre Ltd. was interviewed.

Westerhof revealed that the industry minimum for shipping plastic from Canada to foreign markets is 40,000 pounds in a 40-foot sea container. By measuring the interior dimensions of a 40-foot International Standards Organization (ISO) shipping container, it was determined that the container has a volume of 67.7 cubic metres. 40,000 pounds of plastic is equal to 18.1437 metric tonnes. The stowage factor is determined by dividing the cubic meters by metric tonnes:

$$= 67.00 \text{ m}^3 \div 18.1437 \text{ mt} \tag{5.1}$$

$$= 3.7313 \text{ m}^3 / \text{mt} \tag{5.2}$$

According to McKeil's Vessel Manager G. Seymour, "this is a very bad number for transporting a product if you are quoting on a per tonne basis because the plastic requires 3.7313 cubic metres of space for every metric tonne moved. The cargo will eat up capacity very quickly" (2012). T. Paterson has had experience with moving shredded material. "Based on my experience with wood chips and industry information pertaining to plastic granules, it is my understanding that granules can have a stowage factor of around 3.0 cubic meters per metric tonne" (2012). While this is still high, it is significantly lower than the stowage factor of plastic bails.

$$= 3.0 \text{ m}^3 / \text{mt} \tag{5.3}$$

To determine the cost of each of the potential routes, we will use the stowage factor of 3.7313 cubic metres per metric tonne for all routes that occur prior to the shredding of the plastic cargo. Any route that accommodates vehicles carrying the shredded plastic cargo will use the stowage factor of 3.0 cubic metres per metric tonne.

4.4 Determining the Weightings for Each Arc on the Network

The first step for establishing the tonne kilometre value associated with each arc is to determine the quickest path from each of the origin nodes to each of the transhipment nodes. In the first step, trucks carry out all of the transportation. ArcGIS will determine the shortest route by taking into account the speed differences attributed to the different road classes i.e. the average speed on a highway vs. the average speed on a city road etc. The second step determines the shortest route between transhipment nodes and the destination node. Once again, all road routes are weighted by their average speeds. As there is only one path for the barge to travel along – it is already an established shipping lane – ArcGIS will not be required to determine the water route. In step three, G. McNeil, General Manager of CV Logistics was contacted in order to advise on the method for establishing trucking rates along all of the routes in the network. According to McNeil:

> Determining rates for your network is a difficult task because of the potential transhipment points, the close proximity of all of the facilities in the network and requirement of a tonne kilometre value. To formulate rates for a truck, the company or trucker needs to know how long it will take to load the cargo, how long it will take to transport the cargo and how long it will take to

> unload the cargo. Obviously, in a network like the one you are describing, you would have a dedicated fleet of trucks. A dedicated fleet would alter the freight rates substantially. In general, the close proximity of all of your facilities means that the routes will be quoted as hourly rates. The optimal type of truck for the cargo on your network is a 40-foot dump truck The hourly rate for that particular truck is C$80.00 per hour with a four hour minimum. Due to the fact that you have so many multiple runs, you do not need to factor in the minimum time requirement in establishing a tonne kilometre rate. Even though most, if not all of the trucking routes are less than the four-hour minimum, a vehicle will make multiple trips in a single day. (McNeil, 2012)

It is not possible to establish a standard tonne kilometre rate for the routes on the network. Instead, we are required to establish one for each arc. A tonne kilometre is a function of distance and the total tonnage of cargo that can be moved in one full vehicle load. In our case, we need to determine the distance in kilometres between each origin node and each transhipment node and then determine the distance from each transhipment node to the destination node. Once those distances are compiled, we need to determine which type of vehicle will travel on each arc, either a truck or a barge and how many tonnes a fully loaded vehicle can transport on a single trip. Based on McNeil's insights, rates for trucks will be quoted on a per hour basis. To illustrate the process, we will undertake an example for determining the freight rate of one arc. The origin node will be MRF one, which is located in Kingston and the destination node will be transhipment facility three, which is located in Hamilton. The distance calculated between the two nodes is 330 kilometres. The stowage factor for bailed plastic is 3.7 cubic metres per metric tonne and the capacity of one 40-foot trailer is equal to the interior length x width x height. It is assumed that the combined loading and unloading time will be less than an hour but all times need to be rounded up to the nearest hour unless the time over one full hour is less than 10 minutes because that is how billing occurs. The cubic capacity of one 40-foot truck is:

$$= 12.03 \text{ m x } 2.35 \text{ m x } 2.37 \text{ m} \tag{6.1}$$

$$= 67 \text{ m}^3 \tag{6.2}$$

The capacity of the truck is then divided by the applicable stowage factor to determine the number of tonnes one full trailer load can transport. The total tonnage carried by one truck:

$$= 67 \text{ m}^3 \div 3.7 \text{ m}^3/\text{ mt} \tag{6.3}$$

$$= 18 \text{ mt} \tag{6.4}$$

Step four requires that the total number of rounded hours be computed in order to determine the cost of transporting the goods. In the case of Kingston to Hamilton, the trip will take approximately 3 hours and 44 minutes plus 1 hour of loading and unloading time. This number is rounded up to 5 hours. Based on G. McNeil's rate of C$80.00 per hour, the trip will cost C$400.00. Step five determines the tonne kilometre rate by combining all of the necessary variables. The tonne kilometre value of the route is:

$$= 18 \text{ mt x } 330 \text{ km} \tag{7.1}$$

$$= 5940 \text{ mtkm} \tag{7.2}$$

The rate per tonne kilometre is equal to:

$$= \text{C\$}400.00 \div 5940 \text{ mtkm} \tag{7.3}$$

$$= \text{C\$}0.06734 \tag{7.4}$$

Table 3 exhibits the total yearly output of plastic from each of the 13 MRFs. The values were determined in a two-step process. Step one involved discovering which MRF each of the municipalities' blue box materials are delivered to (Entec Consulting Ltd., 2007, 8-10). The OBBP facilitates the recycling of materials other than plastic. To determine the plastic totals generated by each municipality, the municipal datacall titled, *Plastic Tonnes Marketed by Municipal Group,* was consulted (Waste Diversion Ontario, 2010). To find the total cost of moving the entire supply of plastic from the MRF in Kingston to the shredding facility in Hamilton, the tonne kilometre rate is divided by the total tonnage of plastic multiplied by the distance between the two facilities. For example:

$$= 1120 \text{ mt x } 330 \text{ km} \tag{8.1}$$

$$= 369{,}600 \text{ mtkm} \tag{8.2}$$

$$= 369{,}600 \text{ mtkm x C\$}0.06734 \tag{8.3}$$

$$= \text{C\$}24{,}888.84 \tag{8.4}$$

In the example above, there are no further transportation costs because the shredding facility in Hamilton is within the gasification complex. If any of the three remaining transhipment facilities are utilized, the cost of transportation between the transhipment facility and the gasification facility will have to be added to the total cost. Furthermore, any route from a transhipment node to the gasification facility is subject to the reduced stowage factor exhibited in equation 5.3. The amount of cargo a single truck can carry after the reduction of stowage factor is:

$$= 67 \text{ m}^3 \div 3 \text{ m}^3/ \text{ mt} \tag{9.3}$$

$$= 22.3 \text{ mt} \tag{9.4}$$

Table 3: Plastic Tonnage Marketed by Each MRF in 2010

MRF	Region Serviced	Total Plastic Tonnage	Tonnes
Kingston			
	Greater Nappanee, Township of		150
	Loyalist, Township of		71
	Stone, Mills		10
	Addignton Highlands, Township of		7
	Frontenac		107
	Central Frontenac, Township of		34
	Frontenac Islands, Township of		18
	North Frontenac, Township of		43
	Kingston, City of		680
		Total:	**1120**
Trenton			
	Mohawks of the Bay of Quinte		13
	Deseranto, Town of		12
	Tudor-Cashel, Town of		3
	Wollaston, Township of		6
	Peterborough, County of		297
	Bancroft, Town of		44
	Hastings Highlands, Municipality of		25
	Carlow Mayo, Township of		2
	Faraday		26
		Total:	**428**
Northumberland			
	Northumberland, County of		413
	Kawartha Lakes, City of		423
		Total:	**836**
Peterborough			
	Peterborough, City of		495
		Total:	**495**
Whitby			
	Durham, Regional Municipality of		3196
		Total:	**3196**
East Gwillimbury			
	York, Regional Municipality of		3520
		Total:	**3520**
Dufferin			
	Toronto, City of		5434
		Total:	**5434**
Brampton			
	Peel, Regional Municipality of		4403
		Total:	**4403**
Guelph			
	Guelph, City of		937
	Southgate, Township of		33
	Simcoe		33
	Shelburne		33
	Orangeville		196
	Mulmur, Township of		24
	Mono, Township of		43
	Melancthon, Town of		18
	Howick, Town of		10
	East Luther Grand Valley, Town of		27
	East Garafaxa		25
	Chatsworth		22
	Ashfield-Colborne-Wawanosh, Town of		18
	Amaranth, Town of		37
		Total:	**1456**

Waterloo			
	Waterloo, Regional Municipality of		3232
		Total:	**3232**
Simcoe			
	Simcoe County		1888
		Total:	**1888**
Hamilton			
	Hamilton, City of		3817
		Total:	**3817**
Niagara Falls			
	Niagara, Regional Municipality of		3866
		Total:	**3866**
		Total Combined:	**33691**

(Author, 2012)

Computationally, trucking freight rates have their loading and unloading times built in to the overall price because the price is determined from an hourly rate. The price of the barge will also be quoted as an hourly rate but there is a need for capital-intensive infrastructure to support the loading and unloading of the barge. As a result, the facility located in Oshawa will maintain additional fixed costs. To construct the rates for the barge route, the same steps undertaken to determine the truck rates will be followed. Unlike the hourly rate quoted for trucks, a job cost model will be consulted to determine the rate for the tug and barge. The hourly rate for the combined tug and barge was determined to be C$650.00 / hour.[4] Additionally, it is necessary to outfit the OC 181 with bin walls in order to allow for the transportation of shredded plastic. The cost of the bin walls are factored into the CAPEX of the OC 181 in the job cost model presented in section 4.6. An example of a bin wall is displayed in Figure 4.2. To determine the capacity of the barge, the dimensions of the bin walls need to be determined. For safety and structural reasons, the bin-walls will be recessed 2 feet from edge of the barge's length and width. The dimensions of the barge are displayed in Figure 2.6 and the height of the bin walls were set at 6.4008 metres (Seymour, 2012).

[4] In section 4.6, the hourly rate for the tug and barge are calculated.

Figure 4.2: An example of a bin wall on McKeil's deck barge Niagara Spirit (McKeil, 2012).

The Cubic Capacity of the OC 181 Spirit:

$$= 53.6448 \text{ m} \times 15.24 \text{ m} \times 6.4008 \text{ m} \quad (6.1)$$ [5]

$$= 5{,}980.518 \text{ m}^3 \quad (6.2)$$

The capacity of the barge is then divided by the stowage factor to determine the number of tonnes one full barge load can transport:

$$= 5{,}980.518 \text{ m}^3 \div 3 \text{ m}^3/\text{ mt} \quad (6.3)$$

$$= 1{,}993.506 \text{ mt} \quad (6.4)$$

Like the calculations used to determine the truck rate, the total number of working hours rounded up needs to be computed in order to determine the cost of transporting the

[5] The values for the length, width and height are converted to metres from particulars of the barge in Figure 2.6.

goods. The total distance between the two ports is 107 kilometres and the speed of the Ecosse will be 6 knots. 6 knots is equal to 11.112 kilometres per hour. The 107 kilometres will be traversed in 10 hours (rounded up) with an additional 1.5-hours for the loading and discharge. The total amount of hours the vessel is utilized will be 13. The tonne kilometre value of the route is:

$$= 1{,}993.506 \text{ mt} \times 107 \text{ km} \tag{7.1}$$

$$= 213{,}305.142 \text{ mtkm} \tag{7.2}$$

The rate per tonne kilometre is equal to:

$$= \text{C\$}650.00 \text{ X } 13 \text{ hr} \div 213{,}305.14 \text{ mtkm} \tag{7.3}$$

$$= \text{C\$ } 0.03961 \tag{7.4}$$

4.5 Constructing A Hierarchical Uncapacitated Fixed Charge Location Model

The second of the three steps in the experiment is designed to assist in the decision-making process for locating transhipment facilities on the network by minimizing the combined transportation and fixed cost of the facility or facilities used in the supply chain. The model takes into the account the annual tonnage produced by each MRF as well as the fixed and variable costs associated with the facilities and transportation. Fixed costs are those costs that are incurred regardless of how many tonnes are shipped to and from a facility. The fixed costs in this model are the cost(s) of renting an available commercial property. Variable costs incurred by the supply chain include the cost of transportation before and after the reduction of the stowage factor as a result of shredding. Transportation costs are subject to the distance each tonne of plastic is required to travel in order to reach the gasification facility, the stowage factor of the plastic before and after shredding and the capacity of the vehicle being used on each potential route. The transhipment facilities are not constrained by a capacity limit. The fixed cost of a one-year lease is known for each candidate location and in the case of the candidate facility located in Oshawa; the cost includes an automated loading system and the automated discharge system in Hamilton. The cost of the system is financed through an amortized loan that extends eight years. The transportation costs considered in the model are based on the total cost of shipping an entire year's worth of tonnage from each MRF to each Transhipment node and then onto the gasification plant. All of the information relevant to the model is presented below:

Inputs and Sets:

n = The number of candidate shredding facilities and their capacities
s = The number of supply nodes
S_j = The annual supply of origin node
K_{i} = The potential capacity of plant *i*
f_i = Annualized fixed cost of keeping factory *I* open

c_{ij} = Cost of producing and shipping one tonne of plastic from factory *i* to market *j*

Decision Variables:

y_i = 1 if facility *i* is open, 0 otherwise (8.1)

c_i = 1 if facility *i* is open, 0 otherwise (8.2)

x_{ij} = quantity shipped from plant i to market j (8.3)

The Objective Function:

$$Min \sum_{i=1}^{n} f_i y_i C_i + \sum_{i=1}^{n} \sum_{j=1}^{s} C_{ij} x_{ij} \quad (8.4)$$

Subject To:

$$\sum_{i=1}^{n} X_{ij} = S_j \quad \text{for } j = 1, \ldots, \text{s} \quad (8.5)$$

$$\sum_{j=1}^{s} X_{ij} \leq K_i y_i \quad \text{for } i = 1, \ldots, n \quad (8.6)$$

$y_i \in \{0,1\}$ for $i = 1, \ldots, n, x_{ij} \geq 0$ (8.7)

$c_i \in \{0,1\}$ for $i = 1, \ldots, n, x_{ij} \geq 0$ (8.8)

The objective function stated in equation 8.4 is designed to find the lowest sum of the combined transportation costs and fixed facility costs. Constraint 8.5 states that the gasification plant must process all of the supply originating from each origin node. Constraint 8.6 states that a transhipment node cannot accommodate more plastic than the capacity of a facility. We assume that each of the candidate facilities maintains a capacity equal to the total amount supplied by all of the origin nodes. This justifies the model's distinction of being an uncapacitated network and allows for the absolute minimized cost location(s) to be chosen because the potential location(s) will not be constrained by a restricted capacity. Constraint 8.7 states that a facility is either open (y_i = 1) or closed (y_i = 0) and constraint 8.8 states that if a facility is open it will incur transportation costs. Solving the model will determine which transhipment facility or facilities will be open as well as the amount of plastic that is allocated to the transhipment facility or facilities from the origin nodes.

The model's solution is determined by using Microsoft Excel's Solver. Tables 4 - 7 display the step-by-step process undertaken to construct the model in Excel. For simplicity, the Tables display only one of the 13 individual tests carried out simultaneously in the HFCUFLM. Table 4 displays the origin node located in Kingston and the total supply of plastic the Kingston MRF generates each year in cell *B8*. The four candidate transhipment sites, Hamilton, Oshawa, Whitby and London are presented in cells *A4-A7* along with their capacities in cells *D4-D7*. Each of the transhipment facilities has a capacity equal to the total supply of the 13 MRFs on the network. The capacity ensures that a facility can process the total amount of plastic in the case that it is the most cost effective solution. The fixed charge of each facility displayed in cells *C4-C7* is based on a one-year lease and in the case of Oshawa; a yearly payment for the automated loading and unloading systems required service the barge. The cost of transportation between the origin node and each of the transhipment nodes is displayed in cells *B4-B7*.

Table 4: The Preliminary Inputs to Determine the Optimal Transhipment Facility for Kingston

	A	B	C	D
1	**Inputs**			
2		**Supply Location**		
3	**Transhipment**	**Kingston**	**Fixed Charge**	**Capacity**
4	**Hamilton** 208 Hillyard St. ON L8L 6B6	$24,888.84	$28,500.00	1120
5	**Oshawa** 1050 Farewell St, ON L1A 3A1	$19680.74	$130,000.00	1120
6	**Whitby** 5 Carlow Ct. ON L1N 9T7	$31,964.92	$31,500.00	1120
7	**London** 522 Newbold St. ON N6E 1K6	$41,920.48	$34,969.50	1120
8	**Supply**	1120		

(Author, 2012).

Table 5 displays the *decision variable* segment of the model. The cells *B12-B15* link to the decision variable X_{ij} and will display how much of the origin node's supply an open shredding facility or facilities will process. The cells *C12-C15* link to the binary decision variable y_i; 1 indicates that the facility will be open and a 0 indicates a facility will be closed. The cells *C12-C15* link to the binary decision variable c_i. If a facility is open, than a 1 will indicate that the facility's associated inbound and outbound transportation costs will be incorporated into the minimized objective function.

Table 5: The Decision Variable Segment of the Model

	A	B	C	D
9	**Decision Variables**			
10				
11	**Transhipment**	**Kingston**	**Facility (1=Open)**	**Transportation Costs**
12	**Hamilton** 208 Hillyard St. ON L8L 6B6	0	0	0
13	**Oshawa** 1050 Farewell St, ON L1A 3A1	0	0	0
14	**Whitby** 5 Carlow Ct. ON L1N 9T7	0	0	0
15	**London** 522 Newbold St. ON N6E 1K6	0	0	0

(Author, 2012).

Table 6 displays the *constraints* segment of the model. Cells *B19-B22* maintain the capacity constraint stated in equation 8.6. When all 13 tests are considered simultaneously, the capacity of each potential shredding facility is 33,691. Any excess capacity that results from more than one facility being open will be displayed in the cells *B19-B22*. Cell *B23* maintains the constraint stated in 8.5. The value of the cell must be zero because the constraint requires that all of the supply be processed.

Table 6: The Constraint Segment of the Model

	A	B	C	D
16	**Decision Variables**			
17				
18	**Transhipment**			
19	**Hamilton** 208 Hillyard St. ON L8L 6B6	0		
20	**Oshawa** 1050 Farewell St, ON L1A 3A1	0		
21	**Whitby** 5 Carlow Ct. ON L1N 9T7	0		
22	**London** 522 Newbold St. ON N6E 1K6	0		
23	**Unmet Supply**	0		

(Author, 2012).

Table 7 displays the *objective function* segment of the model. Cell *B24* is programmed to determine the minimized sum of the combined transportation and fixed facility cost(s) and is defined mathematically by equation 8.4.

Table 7: The Objective Function Segment of the Model

	A	B	C	D
16	**Objective Function**			

(Author, 2012).

In addition to the visual explanations presented in Tables 4-7, a complete list of the cell formulations are presented in Table 8 and the Solver Parameters used for the model are presented in Figure 4.10.

Table 8: The Equations Used in Excel and the Corresponding Cells

Cell	Cell Formula	Equation	Copied To
B23	=B8-SUM(B12:B15)	8.5	-
B19	=C12*D4-B12	8.6	B19:B22
D12	=C12	8.8	D12:D15
B24	=SUMPRODUCT(D12:D15,B4:B7)+SUMPRODUCT(C12:C15,C4:C7)	8.4	-

(Author, 2012).

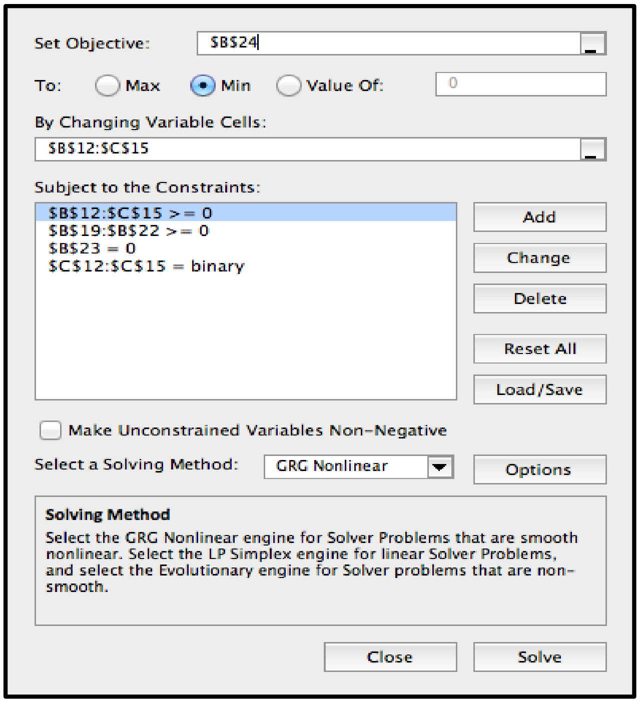

Figure 4.3: A screenshot of the solver parameters created for the HFCUFLM (Author, 2012).

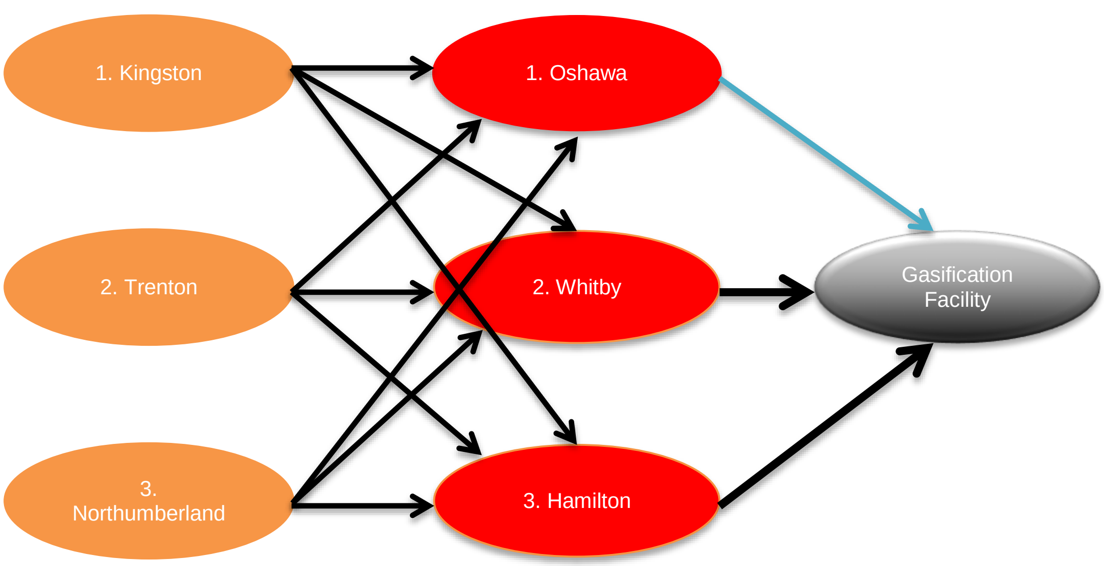

Figure 4.4: A visual depiction of a portion of the entire untested network (Author, 2012).

4.6 Constructing a Job Cost Model for McKeil Marine

The financial information required to present an accurate model is confidential. However, approximate data was made available. To construct an accurate model without exposing sensitive information, the capital expenditures (CAPEX) and operational expenditures (OPEX) for the tug and barge were combined. Combining the yearly capital payments for each vessel and then dividing that value by 365 produced the combined daily CAPEX. The cost of the barge's bin walls will be accounted for in the CAPEX. Regardless of the number of hours the units work in a day, the CAPEX will remain the same. The OPEX were more difficult to approximate because there are fixed daily operational costs and variable operational costs. McKeil models OPEX by averaging out the all of the weekly costs incurred by a vessel from the previous sailing season. An additional 2.5% is added to the OPEX every year to account for escalating costs resulting from ageing equipment. The fixed OPEXs were entered into the model unchanged, approximations for the variable OPEXs for both the Ecosse and OC 181 had to be calculated. To approximate the values of the variable OPEX, the daily averages, based on a 24-hour period, were divided by 24 and then multiplied by the amount of time the units were used. For example, the Ecosse records 10 sailing hours on the route considered by the network. The known value of the Ecosse's daily burn rate while sailing is divided by 24 and multiplied by 10. The process is repeated with the values for the standby burn rate. The sailing and standby fuel costs are combined to determine the total cost of fuel for the 13 hour trip. Table 9 displays the job cost model used in this thesis. The daily breakeven is the sum of the daily CAPEX and OPEX. It is the value that must be made in revenue in order for McKeil to not lose money. The daily revenue is a value created by McKeil Marine, which targets a 20% margin on daily breakeven rate. This is also the value that the hourly rate was determined by. The daily revenue is divided by 13 hours, which is the total time the units are being used:

$$\text{C\$8,400.00} \div 13\ \text{hr} \tag{9.1}$$

$$= \$650.00 \tag{9.2}$$

Table 9: The Job Cost Model Used for McKeil Marine

	Combined Ecosse and OC 181
Daily CAPEX	$500.00
Daily OPEX	$6,500.00
Daily Break Even	$7,000.00
Daily Revenue on a 13 hour charter	$8,400.00
Daily Profit	$1,400.00
Vessel Value	$1,283,000.00
85% Finance	$1,090,550.00
Interest	Undisclosed
Economic Life	25
Depreciation	$51,320.00

(Author, 2012)

Chapter 5 Results of Experiment

The results of each step of the experiment will be explained in three distinct sections. The first section will address the outcomes of the various routes determined through the use of ArcGIS. The second section will explain the outcomes of the HFCUFLM. The third and final section will address the job cost model in relation to the two previous sections and divulge the known costs and revenue of the gasification system in an attempt to make an informed decision on opening the plant.

5.1 The ArcGIS routes

Table 10 exhibits all of the variables used to determine the cost of each of the 96 routes considered by the network. The *distances* column contains all of the distances discovered by ArcGIS from each point of origin to each point of destination. The *tonne* column displays the amount of cargo that is carried by an individual vehicle on each of the routes. The tonnage capacity of trucks increases from 18 tonnes to 22.3 tonnes after shredding occurs. The *rate* column displays the hourly rate for the vehicles used on the network. A truck requires $80.00 per hour and a barge requires $650.00 per hour. The *hours* column displays the total number of hours a vehicle will be required to operate on each specific route. This includes transit time as well as loading and unloading times. Based on G. McNeil's advice, the hours are rounded up unless the amount of time exceeding 1 hour is less than 10 minutes. The *total tonnage* column reveals the total amount of plastic being moved from the origin node over each route. The *tonne kilometre* column displays the total amount of kilometres each tonne of plastic is carried in one full vehicle. The value is determined by multiplying the value in the *distance* column with the value in the *tonne* column. The *rate* column displays the cost of moving one full vehicle load of plastic along an individual route. The value is determined by multiplying the value in the *rate* column by the value in the *hours* column and then dividing that sum by the value in the *tonne kilometre* column. The *total rate* column displays the total cost of moving the entire volume over each individual route on the network.

Table 10: The Variables for Determining the Cost of Each Route

	To Hamilton								
	Route ID	Distance	Tonne	Rate	Hours	Total Tonnage	Tonne Kil	Rate	Total Rate
Kingston	1	330	18	80	5	1120	5940	0.06734007	$24,888.89
Trenton	2	240	18	80	4	428	4320	0.07407407	$7,608.89
Northumberland	3	200	18	80	4	836	3600	0.08888889	$14,862.22
Peterborough	4	206	18	80	4	495	3708	0.08629989	$8,800.00
Whitby	5	140	18	80	3	3196	2520	0.0952381	$42,613.33
East Gwillimbury	6	127	18	80	3	3520	2286	0.10498688	$46,933.33
Dufferin	7	81	18	80	2	5434	1458	0.10973937	$48,302.22
Brampton	8	73	18	80	2	4403	1314	0.1217656	$39,137.78
Guelph	9	53	18	80	2	1456	954	0.16771488	$12,942.22
Waterloo	10	79	18	80	3	3232	1422	0.16877637	$43,093.33
Simcoe	11	88	18	80	3	1888	1584	0.15151515	$25,173.33
Hamilton	12	4	18	80	1	3817	72	1.11111111	$16,964.44
Niagara Falls	13	67	18	80	2	3866	1206	0.13266998	$34,364.44

	To Oshawa								
	Route ID	Distance	Tonne	Rate	Hours	Total Tonnage	Tonne Kil	Rate	Total Rate
Kingston	14	200	18	80	3	1120	3600	0.06666667	$14,933.33
Trenton	15	111	18	80	2	428	1998	0.08008008	$8,804.44
Northumberland	16	70	18	80	2	836	1260	0.12698413	$7,431.11
Peterborough	17	77	18	80	2	495	1386	0.11544012	$4,400.00
Whitby	18	25	18	80	1	3196	450	0.17777778	$14,204.44
East Gwillimbury	19	84	18	80	2	3520	1512	0.10582011	$31,288.89
Dufferin	20	61	18	80	2	5434	1098	0.14571949	$48,302.22
Brampton	21	78	18	80	2	4403	1404	0.11396011	$39,137.78
Guelph	22	137	18	80	3	1456	2466	0.0973236	$19,413.33
Waterloo	23	164	18	80	3	3232	2952	0.08130081	$43,093.33
Simcoe	24	208	18	80	4	1888	3744	0.08547009	$33,564.44
Hamilton	25	129	18	80	3	3817	2322	0.10335917	$50,893.33
Niagara Falls	26	185	18	80	3	3866	3330	0.07207207	$51,546.67

	To Whitby								
	Route ID	Distance	Tonne	Rate	Hours	Total Tonnage	Tonne Kil	Rate	Total Rate
Kingston	27	267	18	80	4	1120	4806	0.06658344	$19,911.11
Trenton	28	117	18	80	3	428	2106	0.11396011	$5,706.67
Northumberland	29	77	18	80	2	836	1386	0.11544012	$7,431.11
Peterborough	30	83	18	80	2	495	1494	0.10709505	$4,400.00
Whitby	31	17	18	80	1	3196	306	0.26143791	$14,204.44
East Gwillimbury	32	76	18	80	2	3520	1368	0.11695906	$31,288.89
Dufferin	33	53	18	80	2	5434	954	0.16771488	$48,302.22
Brampton	34	71	18	80	2	4403	1278	0.12519562	$39,137.78
Guelph	35	129	18	80	3	1456	2322	0.10335917	$19,413.33
Waterloo	36	157	18	80	3	3232	2826	0.08492569	$43,093.33
Simcoe	37	201	18	80	4	1888	3618	0.08844666	$33,564.44
Hamilton	38	122	18	80	3	3817	2196	0.10928962	$50,893.33
Niagara Falls	39	178	18	80	3	3866	3204	0.07490637	$51,546.67

	To London								
	Route ID	Distance	Tonne	Rate	Hours	Total Tonnage	Tonne Kil	Rate	Total Rate
Kingston	40	432	18	80	6	1120	7776	0.0617284	$29,866.67
Trenton	41	343	18	80	5	428	6174	0.06478782	$9,511.11
Northumberland	42	303	18	80	5	836	5454	0.07334067	$18,577.78
Peterborough	43	309	18	80	4	495	5562	0.05753326	$8,800.00
Whitby	44	235	18	80	4	3196	4230	0.07565012	$56,817.78
East Gwillimbury	45	223	18	80	4	3520	4014	0.07972098	$62,577.78
Dufferin	46	184	18	80	3	5434	3312	0.07246377	$72,453.33
Brampton	47	165	18	80	3	4403	2970	0.08080808	$58,706.67
Guelph	48	120	18	80	3	1456	2160	0.11111111	$19,413.33
Waterloo	49	102	18	80	3	3232	1836	0.13071895	$43,093.33
Simcoe	50	92	18	80	3	1888	1656	0.14492754	$25,173.33
Hamilton	51	130	18	80	3	3817	2340	0.1025641	$50,893.33
Niagara Falls	52	193	18	80	3	3866	3474	0.06908463	$51,546.67

	From Oshawa to Hamilton								
	Route ID	Distance	Tonne	Rate	Hours	Total Tonnage	Tonne Kil	Rate	Total Rate
Kingston	53	107	1,993.51	650	13	1120	213305.142	0.03961461	$4,747.41
Trenton	54	107	1,993.51	650	13	428	213305.142	0.03961461	$1,814.19
Northumberland	55	107	1,993.51	650	13	836	213305.142	0.03961461	$3,543.61
Peterborough	56	107	1,993.51	650	13	495	213305.142	0.03961461	$2,098.19
Whitby	57	107	1,993.51	650	13	3196	213305.142	0.03961461	$13,547.09
East Gwillimbury	58	107	1,993.51	650	13	3520	213305.142	0.03961461	$14,920.45
Dufferin	59	107	1,993.51	650	13	5434	213305.142	0.03961461	$23,033.44
Brampton	60	107	1,993.51	650	13	4403	213305.142	0.03961461	$18,663.27
Guelph	61	107	1,993.51	650	13	1456	213305.142	0.03961461	$6,171.64
Waterloo	62	107	1,993.51	650	13	3232	213305.142	0.03961461	$13,699.68
Simcoe	63	107	1,993.51	650	13	1888	213305.142	0.03961461	$8,002.79
Hamilton	64	107	1,993.51	650	13	3817	213305.142	0.03961461	$16,179.36
Niagara Falls	65	107	1,993.51	650	13	3866	213305.142	0.03961461	$16,387.06

	From Whitby to Hamilton								
	Route ID	Distance	Tonne	Rate	Hours	Total Tonnage	Tonne Kil	Rate	Total Rate
Kingston	66	125	22.3	80	3	1120	2787.5	0.08609865	$12,053.81
Trenton	67	125	22.3	80	3	428	2787.5	0.08609865	$4,606.28
Northumberland	68	125	22.3	80	3	836	2787.5	0.08609865	$8,997.31
Peterborough	69	125	22.3	80	3	495	2787.5	0.08609865	$5,327.35
Whitby	70	125	22.3	80	3	3196	2787.5	0.08609865	$34,396.41
East Gwillimbury	71	125	22.3	80	3	3520	2787.5	0.08609865	$37,883.41
Dufferin	72	125	22.3	80	3	5434	2787.5	0.08609865	$58,482.51
Brampton	73	125	22.3	80	3	4403	2787.5	0.08609865	$47,386.55
Guelph	74	125	22.3	80	3	1456	2787.5	0.08609865	$15,669.96
Waterloo	75	125	22.3	80	3	3232	2787.5	0.08609865	$34,783.86
Simcoe	76	125	22.3	80	3	1888	2787.5	0.08609865	$20,319.28
Hamilton	77	125	22.3	80	3	3817	2787.5	0.08609865	$41,079.82
Niagara Falls	78	125	22.3	80	3	3866	2787.5	0.08609865	$41,607.17

	From London to Hamilton								
	Route ID	Distance	Tonne	Rate	Hours	Total Tonnage	Tonne Kil	Rate	Total Rate
Kingston	79	126	22.3	80	3	1120	2809.8	0.08541533	$12,053.81
Trenton	80	126	22.3	80	3	428	2809.8	0.08541533	$4,606.28
Northumberland	81	126	22.3	80	3	836	2809.8	0.08541533	$8,997.31
Peterborough	82	126	22.3	80	3	495	2809.8	0.08541533	$5,327.35
Whitby	83	126	22.3	80	3	3196	2809.8	0.08541533	$34,396.41
East Gwillimbury	84	126	22.3	80	3	3520	2809.8	0.08541533	$37,883.41
Dufferin	85	126	22.3	80	3	5434	2809.8	0.08541533	$58,482.51
Brampton	86	126	22.3	80	3	4403	2809.8	0.08541533	$47,386.55
Guelph	87	126	22.3	80	3	1456	2809.8	0.08541533	$15,669.96
Waterloo	88	126	22.3	80	3	3232	2809.8	0.08541533	$34,783.86
Simcoe	89	126	22.3	80	3	1888	2809.8	0.08541533	$20,319.28
Hamilton	90	126	22.3	80	3	3817	2809.8	0.08541533	$41,079.82
Niagara Falls	91	126	22.3	80	3	3866	2809.8	0.08541533	$41,607.17

(Author, 2012)

Table 11 displays the total cost of each complete route (from origin node to transhipment node to destination node) on the network. In order to determine the values, the total cost of moving an origin node's yearly supply of plastic to a transhipment node was combined with the total cost of moving the total tonnage from the transhipment node to the destination node. For example, the total cost of moving Whitby's 3,196 tonnes of plastic to the transhipment facility in Oshawa is $14,204.44. The cost of moving the total volume of shredded plastic from Oshawa to Hamilton is $13,547.09. Therefore, the total cost of moving plastic from Whitby through the transhipment facility in Oshawa is $27,751.53.

Table 11: The Total Cost of Transportation

	The Transhipment Facilities and the Cost to Transport an Entire Year's Supply of Plastic from an MRF			
MRFs	**Hamilton**	**Oshawa**	**Whitby**	**London**
Kingston	$24,888.89	$19,680.75	$31,964.92	$41,920.48
Trenton	$7,608.89	$5,618.64	$10,312.94	$14,117.39
Northumberland	$14,862.22	$10,974.72	$16,428.42	$27,575.09
Peterborough	$8,800.00	$6,498.19	$9,727.35	$14,127.35
Whitby	$42,613.33	$27,751.53	$48,600.86	$91,214.19
East Gwillimbury	$46,933.33	$46,209.34	$69,172.30	$100,461.19
Dufferin	$48,302.22	$96,604.44	$106,784.73	$130,935.84
Brampton	$39,137.78	$57,801.05	$86,524.32	$58,706.67
Guelph	$12,942.22	$25,584.97	$35,083.29	$35,083.29
Waterloo	$43,093.33	$56,793.02	$77,877.19	$77,877.19
Simcoe	$25,173.33	$41,567.23	$53,883.73	$45,492.62
Hamilton	$16,964.44	$67,072.69	$91,973.15	$91,973.15
Niagara Falls	$34,364.44	$67,933.73	$93,153.84	$93,153.84

(Author, 2012)

Table 11 validates the predictions made in section 3.1. Moving cargo through the transhipment facility located in London is, in all but one scenario, the most costly facility to transport cargo through. The transhipment facility in Hamilton maintains the lowest transportation cost for cargo moving from the three large MRFs in East Gwillimbury, Dufferin and Brampton. The transportation costs through the transhipment facility in Whitby are neither the least nor the most expensive transportation costs for any of the 13 MRFs. The transhipment facility in Oshawa – the entry point for moving cargo over water – is the most cost effective transhipment facility with respect to transportation for the MRFs in Kingston, Trenton, Northumberland and Peterborough.

5.2 The Outcomes of the Hierarchical Uncapacitated Fixed Charge Location Model

Table 12: The Results of the HFCUFLM for the MRF Located in Kingston

	A	B	C	D
1	**Inputs**			
2		**Supply Location**		
3	**Transhipment**	**Kingston**	**Fixed Charge**	**Capacity**
4	**Hamilton**	$24,888.89	$28,500.00	1120
5	**Oshawa**	$19,680.75	$130,000.00	1120
6	**Whitby**	$31,964.92	$31,500.00	1120
7	**London**	$41,920.48	$34,969.50	1120
8	**Supply**	1120		
9	**Decision Variables**			
11	**Transhipment**	**Kingston**	**Facility (1=Open)**	**Transportation Costs**
12	**Hamilton**	1120	1	1
13	**Oshawa**	0	0	0
14	**Whitby**	0	0	0
15	**London**	0	0	0
16	**Constraints**			
18	**Transhipment**			
19	**Hamilton**	0		
20	**Oshawa**	0		
21	**Whitby**	0		
22	**London**	0		
23	**Unmet Supply**	0		
24	**Objective Function**	$ 53,388.89		

(Author, 2012).

Table 12 displays the result of an individual experiment conducted on the HFCUFLM. The model has determined that cargo originating from the MRF in Kingston is to pass the through transhipment facility located in Hamilton. The objective function determines that the combined cost of transportation and the facility cost for the transhipment facility in Hamilton is $53,388.89 – the lowest cost out of all of the possibilities offered by the network. When the entire model is run simultaneously, the fixed charge for an open facility is only considered once.

Table 13 displays which transhipment facility the model has determined will lead to lowest combined transportation and facility cost for each of the MRFs. The Hamilton transhipment facility, located in the same complex as the gasification system, was the optimal transhipment point for the flows of cargo coming out of each of the 13 MRFs.

The total minimized cost for each MRF is presented in the *Minimized Transportation and Fixed Facility Cost* column. The total cost of the network is the combined transportation costs and the yearly fixed charge for the facility which is equal to $394,184.44.

Table 13: The Results of the HFCUFLM

Location of Material Recovery Facility (Origin Node)	Location of Shredding Facility (Transhipment Node)	Minimized Transportation and Fixed Facility Cost
Kingston	Hamilton	$24,888.89
Trenton	Hamilton	$7,608.89
Northumberland	Hamilton	$14,862.22
Peterborough	Hamilton	$8,800.00
Whitby	Hamilton	$42,613.33
East Gwillimbury	Hamilton	$46,933.33
Dufferin	Hamilton	$48,302.22
Brampton	Hamilton	$39,137.78
Guelph	Hamilton	$12,942.22
Simcoe	Hamilton	$43,093.33
Niagara Falls	Hamilton	$25,173.33
	Total:	**= $365,684.44 + 28,500 = $394,184.44**

(Author, 2012)

5.3 The Outcome of the Job Cost Model

The job cost model created for McKeil Marine in section 4.6 determined the hourly rate of the tug and barge. The value determined by the model, $650.00, was a deterministic variable in the HFCUFLM. As expected, the barge route did offer the lowest tonne kilometre rate for cargo originating from five of the MRFs. However, the model determined that transporting cargo over water would not lead to a minimized cost for any of the MRFs and as a result no further calculations can be made for McKeil Marine because the company not have the opportunity to move any volume of cargo with the Ecosse and OC 181.

There are a number of unknown variables for determining the overall economic feasibility of the gasification plant. While the cost of transporting plastic to the plant along with the fixed facility costs are known, the OPEX of the transhipment facilities are unknown. Furthermore, Agilyx was unwilling to provide the cost for constructing a gasification plant that can process 98 tonnes per day. However, estimates of the potential revenue generated by the plant are presented in Table 13. The table consists of three different scenarios of operating efficiency. According to L. Feucht, Director of Business Development at Agilyx, an Agilyx system has the potential of operating at 100% efficiency for 365 days per year if the optimal plastic resins are fed into the system (2012). From the information obtained from the OBBP, it is known that the plastic feedstock originating from the MRF contains a variety of resins that will lead to suboptimal outputs. As a result, three scenarios were reviewed in order to determine a number of possible outcomes given an output efficiency of 50%, 60% and 70%. Furthermore, It is assumed that the facility will have a 98% utilization rate over the course of the year rather than 100%. The price of oil was also determined to be a variable subject to change. Three benchmark prices for Brent crude oil were used to determine revenue for each of the three efficiency scenarios.

Table 14: Revenue Scenarios of Agilyx Gasification Plant

Number of Barrels Produced at 100% Efficiency	Number of Barrels Produced at 50% Efficiency	Production Days	Estimated Price of Brent Crude	Total Revenue Generated Yearly
553	276.5	358	$100.00	$9,898,700.00
553	276.5	358	$120.00	$11,878,440.00
553	276.5	358	$140.00	$13,858,180.00
Number of Barrels Produced at 100% Efficiency	**Number of Barrels Produced at 60% Efficiency**	**Production Days**	**Estimated Price of Brent Crude**	**Total Revenue Generated Yearly**
553	331.8	365	$100.00	$11,878,440.00
553	331.8	365	$120.00	$14,254,128.00
553	331.8	365	$140.00	$16,629,816.00
Number of Barrels Produced at 100% Efficiency	**Number of Barrels Produced at 70% Efficiency**	**Production Days**	**Estimated Price of Brent Crude**	**Total Revenue Generated Yearly**
553	387.1	365	$100.00	$13,858,180.00
553	387.1	365	$120.00	$16,629,816.00
553	387.1	365	$140.00	$19,401,452.00

Chapter 6 Analysis of Results

6.1 Arc GIS Routes

The routes generated by ArcGIS were consistent with several of the predictions made in the hypotheses. The transhipment facility in London was the most expensive facility to transport plastic through for all but three MRFs and it was never the most cost effective. The London facility had the exact same transportation costs as the transhipment facility in Whitby for plastic originating from the MRFs in Guelph and Waterloo. This is a result of a similar total distance between the MRFs and gasification facility when the plastic was routed through the two transhipment nodes. Furthermore, the transhipment nodes have similar tonne kilometres rates because of the similar distances, volumes of plastic and hours required for transportation. The transhipment facility in Whitby generated a higher transportation cost than the facility in London for plastic flowing from the MRF in Simcoe. This is a result of the Simcoe MRF being located closer to London than Whitby.

The transhipment facility in Whitby did not generate the most expensive transportation costs for any of the MRFs nor did it ever generate the least expensive cost. One important observation of the facility in Whitby is that the reduced tonne kilometre rate resulting from shredding the plastic in the Whitby did not make the facility more cost effective. Instead, the additional time required to reload the cargo onto trucks in Whitby and unload the cargo in Hamilton caused an increase in cost that overwhelmed any savings borne of the reduced tonne kilometre rate. For example, trucks traveling directly from the MRF in Whitby to the transhipment facility in the gasification plant require three hours to complete one full load. This costs $240.00. If the MRF in Whitby were to transport plastic through the transhipment facility in Whitby, a single truckload would take four hours and cost $320.00. That is a 25% increase in cost that is not made up by the reduced tonne kilometre rate.

The transhipment facility in Oshawa produced the lowest transportation costs for six (Kingston, Trenton, Northumberland, Peterborough, Whitby and East Gwillimbury) of the 13 MRFs. By examining Figures 1.3 and 1.4, it becomes apparent that the geographic positions of the six MRFs share similarities relative to the remaining seven origin nodes. If the distance, from an MRF to the transhipment facility in Oshawa is less than the total distance to the transhipment facility located within the gasification plant, then the lower tonne kilometre rate offered by the barge will generate a lower total cost of transportation. For example, the distance from the MRF in Whitby to the transhipment facility in Oshawa is 25 kilometres and the barge route from Oshawa to the gasification plant is 107 kilometres. The total distance of the route through Oshawa is 132 kilometres compared to the 140 kilometres of the direct route to Hamilton. Without taking facility costs into account, Oshawa is the obvious choice for transhipment because the distance less and the the tonne kilometre rate is 35% lower for 81% of the journey. In contrast, the direct route from the MRF in Dufferin to the gasification plant is 81 kilometres compared to the 168 kilometres if the plastic is routed through the facility in Oshawa. The direct route is more cost effective.

The transhipment facility in Hamilton is the most cost effective facility for transporting cargo for seven of the MRFs. The low transportation costs are a result of the minimized cargo handling times described earlier as well as the facility’s relative location to the seven MRFs. The Oshawa facility is the only facility that can compete with the Hamilton facility for providing the lowest transportation costs and this only occurs when an MRF is advantageously located in a closer proximity to he Oshawa facility.

6.2 A Hierarchical Uncapacitated Fixed Charge Location Model

It was predicted in the hypotheses that the Hamilton transhipment facility would be the only facility opened by the model. The outcome of the model validated the hypotheses and determined that the Hamilton transhipment facility will service the entire network. Even though the barge route maintains a lower transportation cost for five of the MRFs, the additional costs of the automated cargo handling systems required to service the barge made the facility in Oshawa uncompetitive with the facility in Hamilton. It is important to note that the automated systems were an initial requirement of McKeil Marine. This is before the research uncovered the minimal volume of plastic moving through the network. If the gasification facility where able to process greater volumes of plastic per year and there was a greater supply of plastic available to the network, then perhaps an automated system would be a justified requirement because the systems and the barge would realize a higher utilization rate. Further research must be conducted to establish if the Oshawa facility would be opened if the automated systems were not a requirement. However, the results of the model are not predicted to change because the cost of transporting goods via barge would increase due to the stevedoring costs and the expected increase in cargo handling times. At the same time, the Oshawa facility only offered the lowest transportation rates for six MRFs with a total supply of 9,595 tonnes of plastic divided over a one-year period. Paying a facility's fixed cost an entire year to service only 28% of the network's supply does not seem economically sensible.

6.3 The Cost Models

The job cost model constructed for McKeil Marine determined the hourly rate for the tug and barge. The rate covered all of McKeil's expenditures and was competitive enough to make the barge route attractive for six of the MRFs. However, the HFCUFLM determined that the facility in Oshawa would not be opened and therefore none of the plastic supplied would move over the barge route.

The model constructed to determine the overall feasibility of the gasification plant could not be completed because not enough information was available. In the worst-case scenario, the plant will generate $9,898,700.00 in revenue. In the best-case scenario, the plant will generate $19,401,452.00. The HFCUFLM determined that the total minimized cost of the network would be $394,184.44. However, the value only accounts for the transportation of plastic and the fixed cost of a transhipment facility. What the model doesn't account for are the OPEX associated with transhipment facility and gasification plant as well as the fixed cost of the gasification plant. There may also be a cost for the plastic feedstock. In an interview with L. Feucht, it was revealed that the Agilyx system in Oregon sources most of its plastic for free from businesses that do not want to pay for its disposal. However, this is becoming increasingly difficult, as a viable market have developed for recycled plastic.

Chapter 7 Conclusions

The objective of this paper was to construct a supply chain network for a gasification facility in Southern Ontario in order to determine if any of the plastic feedstock required by the facility could be delivered via barge. The experiment determined that delivering plastic via barge was not economically feasible given the lower alternative costs available by transporting the plastic via truck. The outcome of the experiment was subject to the nature of the cargo, volume of the supply and the close proximity of the facilities within the network. Nevertheless, a viable method for constructing an intermodal supply chain was created for McKeil Marine. In the future, the company hopes to create and test supply chains, similar to the network created in this thesis, in order to pre-emptively target potential customers.

Furthermore, McKeil's existing customers may benefit from the methodology used in this thesis. By working with its customers to locate facilities, McKeil has the ability to adapt from its singular role as a carrier into a logistical provider that is advantageously positioned to extol the virtues of barge transportation. Within the last decade, McKeil has begun to develop relationships with two trucking companies. Hunts Transportation Ltd. and CV Logistics have both established partnerships with McKeil to fulfil the needs of certain customers. The integration of transportation modalities is mutually beneficial for all of the parties involved. The methodology for creating an intermodal network in this thesis can be adapted to facilitate further integration between McKeil and various carriers throughout McKeil's service region.

There is a tremendous potential for growth on the East Coast of Canada and in the Arctic. Both areas are relatively underdeveloped. The construction of infrastructure for major oil, gas and mining projects are in the conception stages. At the time of publishing, McKeil was involved in bidding business for three major projects developing in Labrador and the Arctic. The formulation of transportation networks coupled with a method for determining the optimal location of facilities within the networks may prove to be an important asset for McKeil as it continues to grow and prosper.

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