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Agent-Based Approach of Sustainability Assessment of Resource Sharing in Freight Transportation

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Abstract. This article presents the sustainability assessment of resource sharing of a freight transportation network. In this analysis, we consider the road transportation of semi-trailers (referred to as containers in this paper) through a network of hubs, in which containers wait for their next route segment. Resource sharing takes two forms. On the one hand, trucks can haul two containers (i.e., road trains). On the other hand, each container is hauled to destination using several trucks through the network of hubs inspired by the Physical Internet model. Sustainability is assessed in terms of logistic performance (i.e., delay, fill rate, unit cost), drivers working condition (i.e., percentage of night spent at home), and environmental impact (i.e., GHG emission). In order to assess these indicators, we developed an agent-based simulation model with Netlogo to implement and simulate various levels of resource sharing. The simulation model considers 10% of the entire volume of full truckload transportation in eastern Canada and the north east of the USA. A total of 18 scenarios of transportation with different levels of resource sharing, plus 3 scenarios of transportation without resource sharing were simulated 100 times each, for a total of 2100 simulation runs. Both models were compared and analyzed. The results indicate that resource sharing significantly improves all performance, social and environmental indicators, compared to the traditional model.

Keywords: Sustainability assessment, resource sharing, agents-based simulation, logistics, freight transportation, Physical Internet.

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1 Introduction

In the global economy, optimizing the flow of materials and products requires all supply chain partners involvement from producers, distributers, to consumers, as well as road users. Freight transport and third-party logistics companies must provide different services for a variety of products at minimum costs, while seeking ways to become more sustainable.

Sustainability in road freight transport is a key issue for industrialized societies. Although this industry is slowly recovering from the 2009 crisis (OECD/ITF, 2012), road freight transport is a key driver of the economy and a major contributor of CO_2 emission (van Essen, 2008). Transport, of both freight and passengers, has several impacts on natural ecosystems and human societies. Van Essen (2008) mentions different impacts of transport from GHG and pollutant emission, to noise, landscape degradation, waste and accidents. It is consequently necessary for our society to better understand how this fundamental need to move goods and people impact the environment and our health and way of life in order to design and implement transportation systems that are both low-impact and competitive.

The concept of Physical Internet (PI, π) was initiated in order to achieve these objectives (Montreuil (2011)). The PI is an innovative, ground-breaking transportation philosophy. Its principles are based on the assumption that current logistics networks are unsustainable. Therefore, one of the basic principles of a PI network is the sharing of infrastructures, including transportation hubs, warehouse, hauling capacity and containers among its participating members. In this context, the deployment of a PI network inevitably leads to a deep reorganization of logistics processes, transportation networks, as well as their resources. In addition, according to Montreuil (2011), the PI may also have a huge impact on how goods are purchased by consumers around the world, how they are designed, produced and distributed to cities and families. The PI is based on 13 general principles, which can be divided into operational principles (i.e., tools, accountability, systems, openness and universality) and organizational principles (i.e., interconnection, consistency, accessibility to the network, singularity, encapsulation, agents, hiring and certification) (Ballot 2010). Besides the sharing of physical resources and information, Montreuil (2010) also highlights the fundamental need to design and use:

- modular containers of various sizes;
- hubs and facilities (e.g., for cross-docking, sorting, inter-modal handling);
- vehicles carrying or handling the loads.

Based on these general characteristics of the Physical Internet, this paper proposes to analyze the sustainability of a collaborative transportation system. In this context, collaborative logistics refers to the practice of two or more organizations committed to some form of resources sharing in order to increase their performance, while maintaining a certain balance of power. For instance, collaborative transportation in the wood industry in Norway shows that backhauling reduces empty transport distance by 15 percent, and transportation cost by 6 and 7 percent (Frisk *et al.*, 2010). Similarly, collaborative production planning can also reduce energy used in transportation by coordinating transportation process with manufacturing operations (Meller 2012, van Weele 1999).

The collaborative transportation system studied in this paper is based on resource and asset sharing, such as containers, trucks and drivers, and the use of a network of hubs in order to support flexible and dynamic truck-to-container allocation. In other words, we consider road freight transport by articulated heavy goods vehicles through a network of hubs, in which container progress to their destination through segments between hubs that are dynamically assigned to different trucks. In this system, resource sharing takes two forms. On the one hand, trucks can haul two containers (i.e., road trains), which final destination is not necessary the same. On the other hand, each container is hauled to their destination using several trucks, which range of operation is limited to a few hundreds km around their hub. In this study, sustainability is assessed in terms of logistic performance (i.e., delay, fill rate, unit cost), drivers working condition (i.e., percentage of night spent at home), and environmental impact (i.e., CO_2 emission). More specifically, this paper proposes to assess several criteria of sustainability using an agent-based simulation model, which is used to compare the impacts of different scenarios of resources sharing (i.e., trucks) and different transportation systems (i.e., door-to-door, hub-and-spoke).

The paper is organized as follow. Section 2 presents an overview of the relevant literature. Next, Section 3 presents the agent-based transportation simulation models. Next, Section 4 presents the methodology of the experiments, as well as the different performance indicators. Finally, Section 5 presents and analyse the results, while Section 6 concludes and present future work.

2 Literature Review

This literature that is reviewed in this paper covers two main domains. The first domain deals with sustainable transport, its advantages and its impacts on society. The second domain concerns collaborative transportation and resource sharing.

2.1 Sustainable transportation

The growth and development of societies worldwide leads to economic growth and increasing demand for transport services. Transport is a key component of supply chain activities. Transportation cost is a significant part of the price paid by customers, who continuously expect faster delivery and high fulfillment rate (Stank 2000, Xu and Beamon 2006, Groothedde 2005, Rivera, Sheffi, and Welsch 2014, Bhattacharya et al. 2014). High service level includes quick delivery, punctuality, and availability. Average delivery time and delivery time reliability is often listed as the most important factor of transportation (Ballou 2004). The value of quick delivery is also function of the type of freight to transport. For example, perishable goods are time sensitive.

Transportation cost account for about one third of total logistics cost. Consequently, freight transportation requires effective and cost efficient mechanisms to coordinate the various operations from order processing, to handling and loading, freight transport across complex networks of manufacturing and distribution activities to customers. The determinants of transport cost has been studied by several authors, with a focus on issues such as quality and communication infrastructures (Limão and Venables 2001, US-DOT 2010, Meixell and Gargeya 2005), economies of scale (Hummels 2002, Caplice 1996) and transport operations (Lambert and Cooper 2000, Morash and Clinton 1997). In particular, freight rates competition is central to this study. The full truck-load (i.e., FTL) industry is easy to enter because it requires only a driver, rolling freight to haul, and a broker (Forkenbrock 1999). Because of low fixed cost and sensitivity to the location of available resources, relocating empty resources such as trucks and containers is a major source of cost for FTL carriers. FTL carriers tend to have slight diseconomies of scale and exhibit significant economies of scope.

Road transportation mode is suitable for transport over short distances, 500 km on average, with loads of small volume and high value added. Furthermore, it is flexible, capable of door-to-door transport, and is complementary to other transportation modes. It is generally the best option to transport finished or semi-finished products, which often require high availability and speed (Ballou 2004, Furtado 2010, Bowersox 2012).

Because of its numerous advantages, the majority of the freight transport in Europe, and a large portion in North America, is undertaken by road (van Essen (2008)). Road transport has increased significantly over the past few decades in distribution channels. This rapid growth has led to massive utilization of road networks without significant improvement in existing infrastructures.

This resulted in various externalities like traffic congestion, increased energy consumption, and negative environmental impact, noise, accidents and social impact to truck drivers' life. In the last decade in the US, truck driver death rate represented 11.6% of all deaths in the transportation industry (Savage 2013, Noland 2013).

The characteristics of transportation networks have a key role in the design of sustainable logistics networks (Dekker, Bloemhof, and Mallidis 2012, Elhedhli and Merrick 2012). As mentioned in the introduction, transportation has a wide range of environmental and social impacts including resource consumption, land use, acidification, noise, pollutants and Greenhouse Gas (GHG) emissions (Mohammadi, Torabi, and Tavakkoli-Moghaddam 2014). Transport, in general, contributes to 33% of US CO_2 emissions and to large portions of several air pollutants (e.g., 58% of NO_X, 36% of volatile organic compounds, 77% of CO). Along this line, truck drivers can be on the road 2 to 3 weeks at a time and thus, they are often away from their home and family.

Consequently, the assessment of the various environmental and social impacts of transportation is a key issues to designing sustainable transportation systems. There is an on-going effort to improve the methods use quantify these impacts. For instance, Kim and Van Wee (2014) present a methodology to assess CO_2 emission of intermodal and truck-only freight systems, and discover that intermodal systems are not always the lowest impact system. McKinnon and Piecyk (2009) present a review of different methods used in the UK to assess CO_2 emissions of road freight transport in different contexts (e.g., rigid and articulated heavy goods vehicles, light vehicles).

Along this line, the practices of green logistics and green supply chain management are gaining importance (US-EPA 2004, Sheu, Chou, and Hu 2005, Nealer et al. 2011). For instance, Nasiri et al., (2009) propose a decision support model that aims at planning transport operations (i.e., allocation of products to deliver to various modes of transportation), while considering both economic and environmental indicators. Similarly, asset sustainability is becoming a growing interest for companies and their operations (Pagell and Wu 2009). For companies, sustainability can be marketed to consumers who are environmentally conscious. However, successful adoption of sustainable practices as a result of external pressure requires the integration of sustainability at the strategic level. For instance, (De Rosa et al. 2013, Frota Neto et al. 2008, Lee, Dong, and Bian 2010, Wang, Lai, and Shi 2011, Chaabane, Ramudhin, and Paquet 2012) consider sustainability as a factor of the design of logistics networks. Frota Neto, Bloemhof-Ruwaard et al. 2008 develop a framework for the design and evaluation of sustainable logistic networks, in which profitability and environmental impacts are balanced; Lee, Dong et al. 2010 proposes a stochastic programming approach to take into account sustainability for the design of logistics network under uncertainty; Wang, Lai et al. 2011 proposes a multi-objective optimization model that captures the trade-off between the total supply chain cost and cost of environmental initiatives; Chaabane, Ramudhin et al. 2012 introduces a mixed-integer linear programming framework for sustainable supply chain design, and the evaluation of the trade-offs between economic and environmental objectives under various cost and operating strategies in the aluminum industry. In this paper, we consider the configuration of a freight transportation network. However, we not only consider both economic and environmental factors, but also take the social impact of the configurations into account.

2.2 Resource Sharing

For some experts, collaborative relationships take the form of alliances (Rinehart et al. 2004, Golicic and Mentzer 2006), which are perceived as more durable. In this type of relationship, organisations develop new structures to work closely, with shared missions and visions, and higher levels of trust (Ferrer 2010). Such relationships require comprehensive planning, seamless linkages (Krause and Ellram 1997), and well-structured communication channels operating at all levels. Information exchange plays an important role in improving supply chain collaboration

(Lambert and Cooper 2000). Risk sharing is greater in inter-firm collaborative relationships because participants commit their resources and are willing to share rewards and penalties (Spekman and Carraway 2006).

The literature distinguishes between three types of collaborations (Danloup, Allaoui, and Goncalves 2013, Cruijssen, Dullaert, and Fleuren 2007, Mason 2007, Barratt 2004, Bahinipati and Deshmukh 2012, Bahinipati, Kanda, and Deshmukh 2009): vertical collaboration, horizontal collaboration, and lateral collaboration. Vertical collaboration occurs when two or more organizations at different level such as the manufacturer, the distributor, the carrier and the retailer share their responsibilities, resources, and performance information to serve relatively similar end customer (Schmoltzi and Wallenburg 2011). Horizontal collaboration is defined as a business agreement between two or more companies at the same level in the supply chain or network in order to allow greater ease of work and cooperation towards achieving a common objective. Finally, Danloup, Allaoui, and Goncalves (2013) defines lateral collaboration as a form of relationship which aims to gain more flexibility by combining and sharing capabilities in both vertical and horizontal manners.

In this paper, we consider a horizontal form of collaboration. Danloup, Allaoui et al., (2013) distingish between two forms of horizontal collaboration in the transport industry. On the one hand, carrier collaboration aims at reducing costs, increasing productivity, improving service levels, and strengthening market position by sharing truck capacities and operations (Cruijssen, Cools, and Dullaert 2007). On the other hand, shipper collaboration aims at reducing empty travel by maximizing backhauling opportunities. This paper considers both forms of collaboration and resource sharing. These forms of collaboration, and resource sharing in particular, are becoming one of the most prominent forms of coordination mechanism in supply chains (Varamaki and Vesalainen 2003, Xu and Beamon 2006, Bratton et al. 2000). Lambert and Cooper (2000) claim that in a competitive business, such as freight transport, success depends on the ability to manage and share resources such as information and assets, as well as cost and risk. Indeed, organizations that adopt collaboration to share risks and rewards, and the costs of coordination and resources (Ferrer 2010, Gulati and Singh 1998, Dyer and Chu 2003).

The next section presents the models of both traditional and collaborative transportation systems studied in this paper, as well as the general agent-based simulation approach.

3 Simulation Models

In order to achieve the objectives of this study, this paper proposes to develop a model of the different transportation systems to assess, and implement these models using agent-based simulation. Agent-based simulation is a type of application of multi-agent technology. This technology is used in very different applicative contexts, to develop intelligent software systems composed of interacting, and often simple, entities referred to as software agents (Frayret 2012).

Among other applications, multi-agent technology is useful to simulate complex systems related to the economic, social and natural sciences, as well as engineering. It is particularly useful where the structure of a system can be modeled as a network (Conte (1997), although it is not limited to it. With agent-based simulation, it is possible to implement and simulate systems within their environment in order to explore future scenarios and potential alternative decisions, and determine probable outcome and trends (Axelrod 1997). It is also possible to model the actors of a system using simple reactive behaviour with predefined responses to stimuli, or proactive and more complex goal-oriented behaviours. Agent-based simulation is relevant when the system size is large and modular in nature, when its environment is dynamic, and when its actors do not have necessarily simple and reactive behaviours. Consequently, it is appropriate for modeling supply chains and logistic networks (Ahn and Lee 2004).

This section presents a general overview of the both traditional and collaborative transportation models. Next, it introduces the architecture of the simulation platform and the agents' models.

3.1 General Overview and common elements

Basically, in the both models, client companies must send the content of a full container to a specific destination. In order to do so, they express their need to the nearest hub, referred to as the origin hub or the origin, which is responsible to find a truck willing to transport their container. Transportation needs contain a specific number of containers (e.g., 1 or 2 containers) to transport to a destination, referred to as the destination hub, as well as a delivery date.

In the proposed models, the hubs' locations correspond to the major cities in Quebec, Ontario and New England. The models consider also the major road network between these cities, and for simplification purpose, the length of the arcs of this network is determined using the cities' location (i.e., latitude and longitude).

As every city has only one hub, the generation of the destinations of the transportation needs is proportional to the population of each city. Here, we assume that cities with higher population have more deliveries. However, the origin is random (i.e., uniform distribution). Similarly, truck availability at each hub is also based on the population size. Here we assume that the larger the city, the bigger fleet.

In this simulation, each container has a capacity of 40 tonnes. We also only consider Full Truck Load (FTL) transportation. The truck will be a road train, and they travel at a speed of 100km/h, which is used to calculate travel time. Along this line, truck drivers have 8-hour shifts distributed randomly within the day, according to a normal distribution. Most truck drivers have day shifts, although the transportation network operates 24 hours.

Transport costs include a fixed cost and variable costs. The variable cost is a function of the number of kilometers traveled ($/km.container). This is a simplification of reality, as costs in North America are calculated according to complex tables, and are also function of the origin and destination states. In this model, the notion of priority is only associated with the delivery date. In other words, containers in hubs are processed in sequence according to their delivery date (i.e., earliest due date).

3.2 Resource Sharing Transportation Model

This section presents the general hypothesis used to develop the resource sharing transportation model. First, concerning the hub deployment, each arc has a distance of no more than 3 hours of transportation in order to allow drivers to make a round-trip in 8 hours. Therefore, if travel time between major cities were higher than 3 hours, we added hubs at specific locations, within smaller cities. Second, some trucks can haul 1 or 2 containers, to form a road train.

Next, concerning the general functions and operations of this model, routes are planned both in a centralized and decentralized manner. In other words, when a container arrives at a hub, this hub calculates the fastest routes toward the final hubs (i.e., the final destination) using Dijkstra algorithm (e.g., shortest path) based on the total transportation time. To do so, it considers all possible routes through the entire network, the travel time between hubs and the current processing time for handling containers in the hubs in order to take into account their actual congestion. However, only the road segment to the next hub is actually planned and implemented. When the container arrives at the next hub, the route is similarly planned again, and so on and so forth until the container reaches the final hub. The processing time for handling containers is dynamically estimated by each hub taking into account the handling capacity of the hub and the number of container to process. Each hub updates its current waiting time and sends it to the others in order to compute the containers' fastest routes.

Next, when trucks arrive at a hub and their container is detached, instead of returning empty to their origin hub, trucks have the possibility to wait for an opportunity to haul another container on their way back. More specifically, truck drivers have two levels of willingness to wait for another container for backhauling. At the first level, trucks have no willingness to wait. Therefore, they return as soon as the initial container is delivered. If there is a container to haul back, they return hauling a container. Otherwise, they return empty. At the second level, trucks wait for another container to haul up to 1 hour, thereby increasing the probability of returning to their origin hauling a container.

Finally, when containers arrive at their destination, if there is enough time left in the work shift of the truck driver, trucks can be assigned to another trip to transport another container to their origin hub. In other words, when a container is delivered, its final delivery beyond its final hub is not tackled in this model. This aspect will eventually be adjusted in a future model in order to take into account a more detailed description of the last miles delivery.

The general business model proposed in this model includes some form of revenue sharing. Specifically, the origin hub, to which demand is expressed, is paid by the client. In turn the origin hub pays a portion of this revenue to the intermediate hubs used to transport the container, and the truck drivers. The payment to the intermediate hub is based on fixed transit costs (e.g., cost of processing the container). This transit cost is calculated as an average cost per container, which includes the cost of handling and storing containers, and an administrative cost. Truck drivers are paid according to their hauling distance travelled, the amount of containers hauled as well as the load hauled.

3.3 Traditional Transportation model

In the traditional model, containers are hauled from origin to destination by a single container. Therefore, trucks do not stop at intermediate hubs in order to go back to their origin with another container. Furthermore, as for the model with resource sharing, some trucks may backhaul another container to avoid return empty. Along this line, in this model, route planning is fully centralized. In other words, the original hub plans the entire trip to its destination (i.e., the final hub).

Another difference between the two models is the generation of trucks. Hence, the number of trucks per hub is only a function of the size of the city and its position in the network. However, the total number of trucks is the same.

Furthermore, unlike the resource-sharing model, trucks are not assigned to a single hub. They are assigned to a zone that contains several hubs (i.e., truck origin zone in Figure 1). Figure 1 presents an example of route with backhauling. After the container is delivered at the destination hub, the driver search for a container to transport back within its origin zone. To do so, he first searches at the destination hub, and then he extends his search within a set of eligible hubs, close to its original destination. If there is a container, than he hauls it back. If there is no container, he starts his journey back empty. Then, if there is a container to haul back on his route, than he hauls it. In this backhauling process, we assume that trucks cannot be consolidated, and the size of the truck origin zone and the zone of hubs that are eligible for pick up are the same.

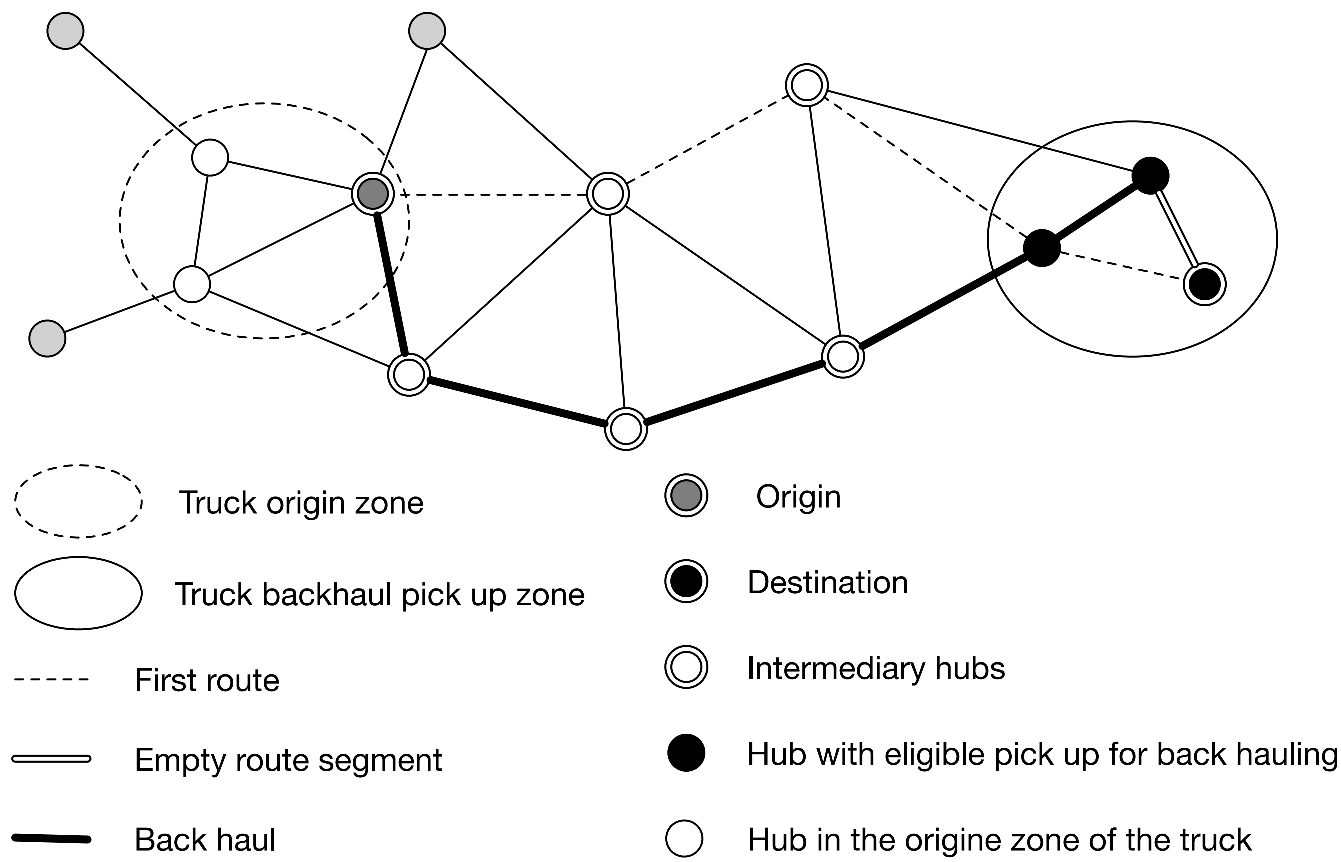


Figure 1: Back haul zone and route illustration

3.4 Systems general architecture

In the proposed agent-based model, the two transport network models are implemented similarly. Trucks and hubs are implemented as agents with specific behaviours, while routes, route segments and containers are simple objects with no behaviour. Agents and objects communicate with each other through shared global data and variables.

This model simulates the interaction between components (e.g., agents and objects). Components have various levels of autonomy (e.g., control over its own actions) and different perception (e.g., ability to perceive certain information) of the environment. Agents are divided into external agents (e.g., customers) and internal agents (e.g., cooperative, hubs, trucks/truck drivers). Unlike agents, objects do not make decisions. They are created dynamically as needed, and provide information to agents.

The general control architecture of this agent-based simulation is a dynamic quasi-heterarchy. In other words, hub agents (e.g. hub) dynamically propose road segments to sub-set of truck driver agents (e.g., trucks that are dynamically available at the hub), who can accept or refuse the job. Because trucks move from one hub to the other, they are under the dynamic quasi-supervision of different hubs according to the jobs they accept to do. Furthermore, as mentioned in Section 3.2, hubs exchange information about their dynamic processing time in order to balance the load of containers throughout the network. In this architecture, each type of agents has a specific function/role, and limited information, as specified by their individual functions and behaviours describe below.

3.4.1 Customers

In the general model, customer represents container transportation demands. When a customer contacts a hub asking for a transportation service, he sends the number of container to transport, the pickup and delivery points, as well as the delivery time of each container. In this paper, customers are not simulated. Containers are created in hubs according to probability distribution as outlined in Section 3. Once arrived at their destination hubs they are simply discarded. This represents a limit of the model, in which empty containers are not managed.

3.4.2 Hub Agents

In both models, hubs are the backbone of the transportation system. They have many roles, such as managing local transportation operations, including local pick-ups and deliveries on site. However, because demands are generated as origin-destination transport requirements within the hub network, the simulation model does not take local pick-up and delivery into account.

Therefore, the main function of hub agents is to manage the flow of containers through the network. In order to do this, they first plan the next hub (i.e., next hub to destination) of each container waiting for a truck. Using the travel time between hubs and the current waiting time of each hub, hub agents also assign an available truck to each container ordered by due date (i.e., earliest first). This is done using procedures PLANROUTES() and FINDTRUCK() described below.

Procedure PLANROUTES(allContainersWaitingForTransport, allTrucksAvailable)

```
containers ← allContainersWaitingForTransport
truckAvailable ← allTrucksAvailable
destinations ← ø
While containers ≠ ø do
  container ← SELECTCONTAINER(containers)
  If destination(container) ∉ destinations Then
    destinations ← destinations ∪ destination(container)
  End if
  containers ← containers - container
Next
While destinations ≠ ø do
  SELECTDESTINATION(destinations)
  route ← MINIMUMPATH(currentHub, destination, hubs)
  nextHub ← NEXTHUB(route)
  containers ← allContainersWaitingForTransport
  While containers ≠ ø do
    container ← SELECTCONTAINER(containers)
    If destination(container) = destination Then
      truckAssigned(container) ← FINDTRUCK(container, nextHub, trucksAvailable)
      If #CONTAINER(truckAssigned(container)) = MaxContainer(truckAssigned(container))
       then
        trucksAvailable ← trucksAvailable - truckAssigned(container)
      End if
    End if
    containers ← containers -container
  End
End
Return truckAssigned(container) with container ∈ allContainersWaitingForTransport
```

With:

destination(container) is the final destination of container;

truckAssigned(container) is the truck assigned to container;

currentHub is the planning hub;

#CONTAINER(truck) returns the number of containers assigned to the truck;

MaxContainer(truck) returns the maximum number of container that can be assigned to truck (i.e., 1 if no consolidation, 2 if consolidation);

MINIMUMPATH(currentHub, destination, hubs) returns the shortest path from currentHub to destination through hubs;

SELECTCONTAINER(containers) return the container from containers with the earliest due date.

PROCEDURE FINDTRUCK(container, nextHub, trucksAvailable)

```
trucks ← trucksAvailable
containerAssigned ← false
While containerAssigned = false and trucks ≠ ø do
    truck ← SELECTTRUCK(trucks)
    trucks ← trucks - truck
    If COMMIT(truck, container, nextHub) = true then
        containerAssigned = true
    End if
End
Return truck
```

With:

SELECTTRUCK(trucks) returns a truck from trucks;

Basically, PLANROUTES() first computes the shortest route of all the possible destinations of the containers waiting for their next haul. Next for these containers, the procedure tries to find a truck for each container using procedure FINDTRUCK(). This procedure may not return a truck for some containers, depending on the available trucks at the hub. Furthermore, it invokes another procedure (i.e., COMMIT()) used by truck agents (see below) in order to determine whether the truck is willing to commit for a specific haul. At this point, procedure PLANROUTES() also manages consolidation by assigning as many containers as possible to each truck (up to MaxContainer).

Finally, hub agents update the transportation information on the blackboard (e.g., next hubs). Once new containers arrive at a hub, the hub agents also update their current waiting time on the blackboard.

3.4.3 Truck Agents

In order to simulate the behaviour of trucks, we developed an agent, which main roles are to manage the state of the truck and to decide whether to commit to haul a specific container to a hub. Truck agents can be in three distinct states (Figure 2): *driving*, *resting* or *waiting* at a hub for another container to haul. The transitions between *driving* and *resting* are associated with the beginning and the end of the truck driver's work shift. In the all tested scenario, truck drivers have 8-hour shifts that can start any time of the day. Next, the transitions between *driving* and *waiting* are associated with the location of the truck (i.e., it must be at a hub to wait), the arrival time of the truck at the hub, the maximum time the truck driver is willing to wait (i.e., 0 or up to 2 hours), new container assignments, the time required to drive back to its origin hub. This transition is implemented using procedure COMMIT(). In other words, if a truck is waiting at a hub and has enough time to haul another container and be back before the end of its work shift, then it commits to haul the container. Finally, the transitions between *resting* and *waiting* are associated with the truck assignment before it became *resting* (i.e., if the truck agent started a rest period at home or in the hub without an assignment).

Procedure COMMIT(truck, container, nextHub)

```
commit ← false
If currentHub = origin(truck) then
   If Time + 2 x timeTo(nextHub) ≤ endShift(truck)
      commit ← true
   End if
Else
   If nextHub = origin(truck) and Time + timeTo(nextHub) ≤ endShift(truck) then
      commit ← true
   End if
End if
Return commit
```

With

origin(truck) is the hub with which truck is associated;

Time is the current simulated time;

timeTo(nextHub) is the travel time to go to nextHub;

endShift(truck) is the time of the end of the shift of truck.

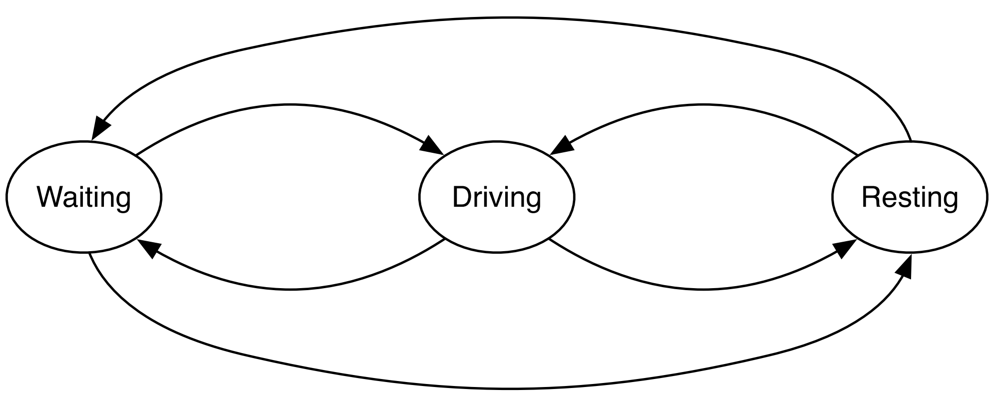


Figure 2: Truck agent states

3.4.4 Simulation principle

In this simulation, time advances incrementally. At each time increment, truck agents update their state according to their environment (i.e., current time, new container assignment) and their attributes (i.e., work shift start and end time). Trucks in the *driving* state move forward according to the speed of the traffic on their road segment. Trucks in the other states (i.e., *waiting* and *resting*) do nothing. Similarly, at each time increment, hub agents update the state of the hub adding newly arrived containers, available trucks, and new demand for transportation, and removing newly assigned containers and trucks. Then, hub agents compute new assignments, until the end of the simulation. Hubs are always active and do not rest like trucks.

4 Methodology and Experiments

This section first discusses the implementation of the simulation models. Next, the parameters of both models are defined, as well as the key performance indicators used to analyse the results. Finally, the general designs of experiment are presented.

4.1 Model Implementation

Several agent-based simulation platforms are available to implement the simulated models (Frayret 2012). These platforms can be classified according to two characteristics: required programming expertise and modeling flexibility. In the proposed models, all agent interactions and behaviours are simple. *Netlogo* was selected for its intuitive interface and simple yet powerful programming language.

4.2 Parameters definition

In order to analyze the feasibility and the performance of the proposed transportation models, two simulation models were implemented. More specifically, we designed a virtual network based on general shipping data between the Canadian provinces of Quebec and Ontario, and the U.S. states of Rhode Island, Massachusetts, New Hampshire, Pennsylvania, Vermont, Maine, and New York. According to RITA (2012), these states and provinces accounted for 16.13% of the value of the trade between the two countries in 2010. Similarly, Canada (2012c) presents that the Canadians highways transported 82.7 million tonnes in exports and imports in 2009, which represents 82% of the 2010 road's trade between the two countries. Therefore, we estimated that 82% x 82.700.000 x 16.13% = 10.94 million tonnes of goods are moved by truck in this region. Considering that a container has a capacity of 40 tonnes, this region moved almost 28 million containers. Therefore, based on the hypothesis presented earlier, which states that demand for container transportation is based on population, we extrapolate the average demand for each city/hub, by splitting the 28 million containers proportionally. Therefore, larger cities generate higher demand for transportation.

After demand was estimated for each hub, we similarly estimated the fleet size and the hubs' capacity to process containers. In order to follow the same logic, the number of trucks at a hub is directly proportional to the population size. As the trips in traditional transport are door-to-door (i.e., no stop at the intermediate hubs), the hubs' fleet size is only considered for the transportation model with resource-sharing. Concerning the hubs' capacity to process container, the problem is different. Indeed, if there is not enough capacity to process containers, performance will be artificially low. Therefore, in order to make sure that each hub possesses enough, although reasonable, container processing capacity, a different approach was used. Because of the characteristics of the resource-sharing network, the number of containers/container passing through any hub depends on both the size of global demand and the centrality of its position in the network. In order to take this into account, we estimated the centrality of each hub using the number of roads passing through then. Therefore, both capacities were chosen in order to represent a realistic transportation network with a capacity that is in a state of equilibrium with demand. The capacity is fixed during each simulation runs. The next section presents the various scenarios that were simulated, and discusses the general results obtained.

4.3 Key performance indicators

This section describes the different measures and performance indicators used to analyze the scenarios. These variables were directly programmed in Netlogo and accumulated during the entire simulation horizon. Several authors (Pels and Rietveld (2000); Novaes (2007); Bowersox, Closs, and Cooper (2008)) consider that cost comparison constitutes a way to understand and determine transport efficiency. However, according to Alvarenga and Novaes (2000), it is also necessary to compare service times, damaged good rate, as well as delivery errors. Still, Ballot and Fontane (2008) affirms that performance should also considerer the cost of downtime caused by a rupture of stock. This paper presents also three other performance indicators.

First, total cost is calculated as the sum of the fixed transportation cost, the variable transportation cost and the processing cost in hubs. The fixed cost is allocated to each transport demands (Equation 1). The variable cost is calculated as a rate $/km traveled per container, including fuel costs per km and the remuneration of truck drivers (Equations 2, 3 and 4). Finally, the transit cost is calculated as an average cost per container, including the cost of maintenance and storage of container and administrative costs (Equation 5).

$$Fixed_{cost} = Fleet\ x\ (tire\ cost\ +\ maintenance\ cost\ +\ fixed\ charges\ +\ depreciation) \quad (1)$$

$$Variablecost\ =\ \$gas\ +\ \left(total\ distance\ traveled\ empty\ and\ loaded\ x\ \frac{\$}{truck}\ driver\right) \quad (2)$$

For the cost of gas ($gas), we distinguish between without and with consolidation (Equation 3 and 4).

$$\big((total\ distance\ traveled\ loaded\ x\ consumption\ per\ km\ without\ consolidation) + (total\ distance\ traveled\ empty\ x\ consumption\ par\ km\ empty)\big) x\ gas\ price \qquad (3)$$

$$\big((total\ distance\ traveled\ loaded\ x\ consumption\ per\ km\ with\ consolidation) + (total\ distance\ traveled\ empty\ x\ consumption\ par\ km\ empty)\big) x\ gas\ price \qquad (4)$$

$$number\ of\ container\ in\ transit\ x\ storage\ and\ handling\ cost \qquad (5)$$

Beyond the total cost indicator, the other indicators include logistic performance indicators, social indicators, as well as environmental indicator. Logistic performance indicators include:

- Number of containers in transit (e.g., containers in *driving* and *waiting* states at any given time);
- Number of empty and loaded trucks (whether or not containers are consolidated);
- Total distance traveled empty and loaded (km);
- On-time delivery (Fill rate);
- Fleet efficiency (ratio of the number of loaded trips vs. the number of trips);
- Average delay (hours).

The social performance indicator is mainly represented by the percentage of time spent at home per truck driver, which the ratio between the amount of hours at home and the amount of hours in 1 week (192 hours).

Finally, the environmental performance indicator is represented by the amount of greenhouse gas (GHG) emissions. It is calculated according to Equation (6) as a quantity of CO_2 per useful traveled distance in km.container equivalent (i.e., a hauling of one container over one km). It was calculated according to statistics corresponding that an average road train emission, which is 2.7 KgCO_2 GHG per liter (Canada 2012a). Furthermore, a truck hauling two containers uses 17% more gas than an empty truck, and 14% more than a truck hauling one container (Canada 2012a, Canada 2011, 2012b).

$$kg\ CO_2\ per\ km.container = \frac{CO_2(empty)+CO_2(non_{consolidated})+CO_2(consolidated)}{\left((1-\%consolidated)+2*\%consolidated\right)*Distance(loaded)} \tag{6}$$

4.4 Design of Experiment

One of the objectives of this research is to verify if transportation with resource sharing has a better social, environmental and economic performance than its traditional counterpart. To do so, we studied the performance of various configurations of both transportation models. For comparison purpose, demand level and fleet size are always the same for both models. Demand level is fixed at 10% of the total demand (from literature) and fleet size is fixed at 100% of the total fleet (estimated to meet 10% of total demand).

4.4.1 Resource-sharing transportation model

The first parameter of the resource-sharing model concerns the notion of consolidation. As mentioned previously, if a truck can consolidate, it can haul two containers per trip. Otherwise, it can only haul one container. Hence, we defined three levels of consolidations: low, medium and high. The medium level is based on (Meller 2012), and it represents 57% of the fleet that can haul two containers. The low and high levels represent respectively 49% and 65% of the fleet (i.e., +/-15% of medium level). In all scenarios, trucks capacity to consolidate is generated randomly based on these parameters.

The second parameter studies the impact of the truck driver's willingness to wait for a new container at a hub before he comes back. We defined two levels of willingness to wait: no willingness to wait (NW) and willingness to wait up to 2 hours (W). The maximum limit is 2 hours, because a truck driver can make a round trip and wait 2 hours at the intermediate hub in 8 hours (i.e., work shift).

4.4.2 Traditional Transportation Model

The traditional transportation model has only one specific parameter linked to the size of the area truck drivers are willing to search for backhauling opportunities (the backhauling zone). We defined 3 levels for this parameters, 100km, 150km, and 200km.

4.4.3 Scenarios and experiments

The plan of experiments is based on the factors described in the previous section. They lead to 18 scenarios for the resource sharing model and 3 scenarios for the traditional model, as shown in Tables 1 and 2. Each of these scenarios was simulated 100 times (i.e., 100 repetitions) for a total of 2100 simulation runs. Each simulation represents eight days of transportation (i.e., simulation horizon), which includes one day as warm-up. Time in each simulation is discretized as 384 periods of 30 minutes.

Table 1: Resource Sharing Scenarios

	Fleet size	*10%*		*50%*		*100%*	
Consolidation	*Willingness to wait* / *Demand*	*NW*	*W*	*NW*	*W*	*NW*	*W*
Low	*1%*	*1*	*2*	*x*	*x*	*x*	*x*
	5%	*x*	*x*	*3*	*4*	*x*	*x*
	10%	*x*	*x*	*x*	*x*	*5*	*6*
Medium	*1%*	*7*	*8*	*x*	*x*	*x*	*x*
	5%	*x*	*x*	*9*	*10*	*x*	*x*
	10%	*x*	*x*	*x*	*x*	*11*	*12*
High	*1%*	*13*	*14*	*x*	*x*	*x*	*x*
	5%	*x*	*x*	*15*	*16*	*x*	*x*
	10%	*x*	*x*	*x*	*x*	*17*	*18*

Table 2: Traditional Transport Scenarios

Fleet size	*100%*		
backhauling zone size	*100km*	*150km*	*200km*
Demand			
10%	*1*	*2*	*3*

4.4.4 Model Validation

In this study, only the traditional model can be validated, as results from the simulation of the resource-sharing model cannot be compared to any actual equivalent. Thus, in order to validate the traditional model, we compared the percentage of empty trip per km and per path from the simulation results of the traditional model to information from (Meller 2012). This study claims that in practice, 20% to 30% of all trips are empty. The results for the scenarios with a demand of 10%, a fleet size of 100%, and backhauling zones of 100km, 150km and 200km are presented in Table 3. For these scenarios, results are between 20% and 30%, therefore, we can assume the validity of the traditional model.

Table 3: Processing capacity and fleet size of each Hub

KPI/Scenario	*100km*	*150km*	*200km*
% Empty Trip (per km)	*26.62%*	*29.45%*	*29.47%*
% Empty Trip (per path)	*29.75%*	*28.98%*	*28.39%*

5 Results and discussion

First, in order to assess the relative value of the proposed transportation model with resource sharing over the traditional approach, we compared and analyzed the results from both models. Next, we analyze other specific aspects of the resource-sharing model in order to assess the impacts of various parameters.

5.1 General comparison of transportation models

Figures 3 to 6 present respectively the economic, logistics, social and environmental indicators for both models for the high demand scenario, and a normal fleet size. For the traditional model, scenarios with different backhauling zone sizes are presented. Concerning the resource-sharing model, we used a medium consolidation level. Scenarios with and without willingness to wait are also presented.

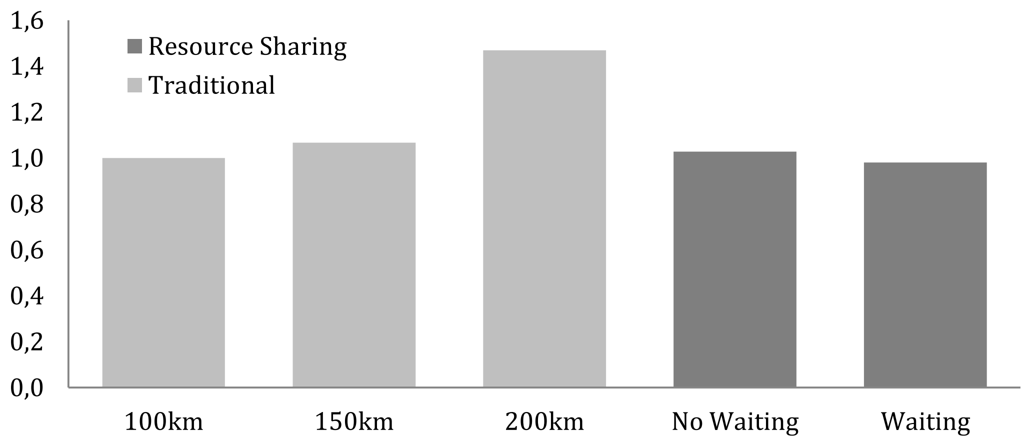
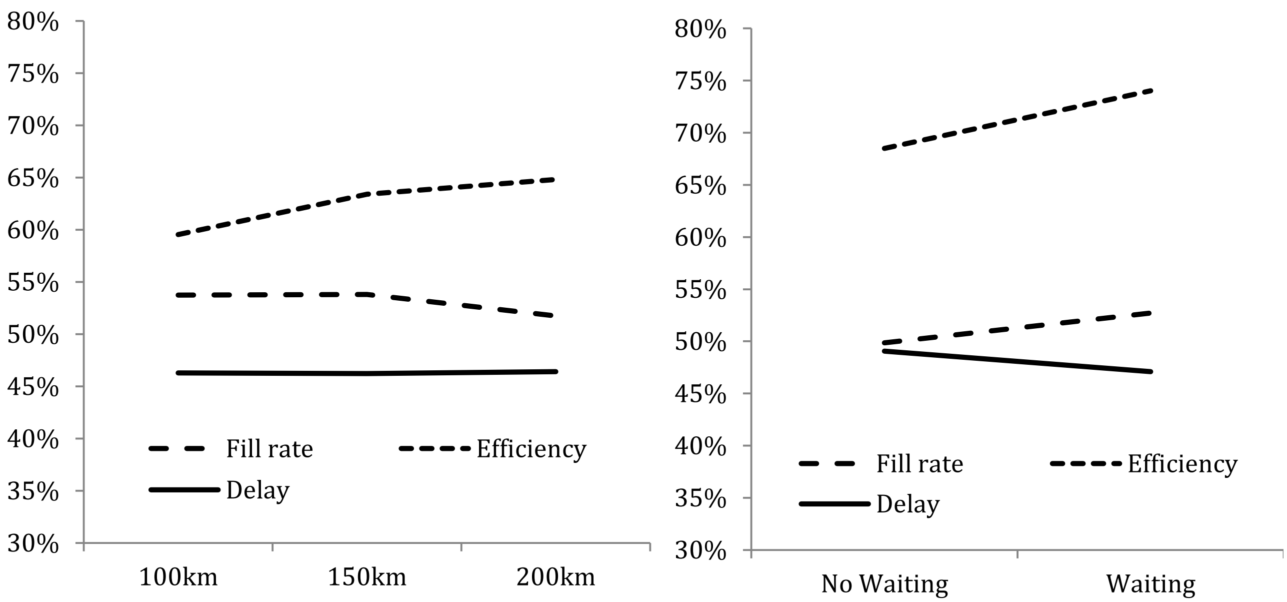


Figure 3: Normalized unit operation Cost

In Figure 3, we used the cost of the traditional model for a backhauling zone size of 100km as a reference. First, the graph shows that unit cost increases for the traditional model as the backhauling zone size increases. This is normal because the increased distance to pick-up a container for backhauling impacts directly the unit cost. Next, the unit cost of the resource-sharing scenario without waiting time is higher by 3%. However this cost is lower by 2% when truck drivers are willing to wait, which increases backhauling opportunity. Furthermore, the average cost of resource-sharing scenarios represents respectively 94% and 68% of the cost of the traditional scenarios with a backhauling zone respectively 150km and 200km. The main economic benefit of resource-sharing occurs because in the traditional model, the total distance traveled is on average 23% higher for an equivalent number of containers.

Figure 4 (a and b), we present the logistic indicator for the same scenarios. Concerning delay, both models have equivalent results, although, on average, resource-sharing scenarios have 4% more delayed trips. However, the average delay (hours) is three times higher for the traditional model. In other words, delays are respectively less than eight hours for resource-sharing scenarios, and more than 24 hours for traditional scenarios.



(a) Traditional transportation model (b) Resource-sharing transportation model

Figure 4: Delay, Fill rate and Efficiency as a function of backhauling zone size and willingness to wait.

Concerning the fill rate, the average for the traditional transportation model is slightly better (53%) than the average for the resource-sharing transportation (51%), although it is not really significant. This is consistent with the previous results. This result can be attributed to the container processing time and the wait at intermediate hubs, which slightly increase the total travel time. These extra operations do not exist in the traditional model.

Finally, concerning efficiency, which is a quality performance indicator connected to truck utilization, resource-sharing have, as expected, better results than the traditional transportation model. Scenarios when drivers are willing to wait have an even better efficiency (>70%), because it significantly increases backhauling opportunity. Again, the traditional transportation model with a larger backhauling zone size has better results (65%) for the same reason. However, increasing the backhauling size does not increase efficiency linearly. The further the truck must go to pick-up a container, the less efficient the route is.

As far as the social indicator is concerned (Figure 5), the percentage of time spent at home per truck driver is significantly higher (25%) with the resource-sharing model. Because truck drivers make shorter trips in the resource-sharing model, this latter is more socially friendly than the traditional transport.

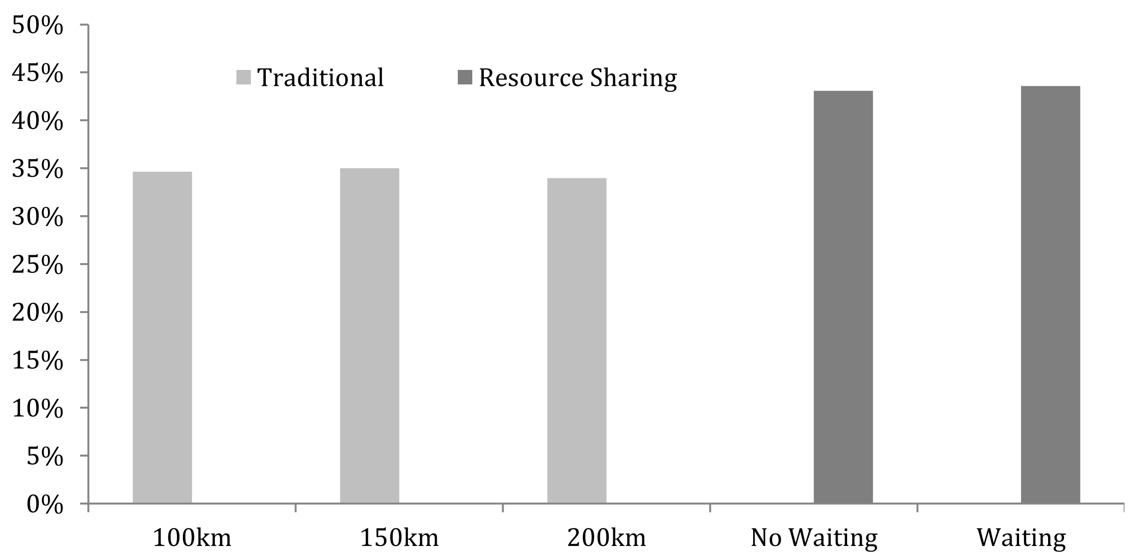


Figure 5: Time spent at home as a function of backhauling zone size and willingness to wait.

Finally, the environmental indicator (Figure 6), the resource-sharing models generate significantly less GHG per km.container than the traditional model with an average of 33% reduction. GHG emission calculation is based on gas consumption and the total distance traveled (empty and loaded). On average, the distance traveled in the resource-sharing model is 21% lower. Therefore, increased efficiency and consolidation leads to significantly lower GHG emissions.

Consequently, for an equivalent logistic performance and cost, the proposed resource-sharing transportation model has significantly better results with respect to environmental and social performance than the traditional transportation model. The next section analyzes the specific impact of various parameters of resource-sharing on performance.

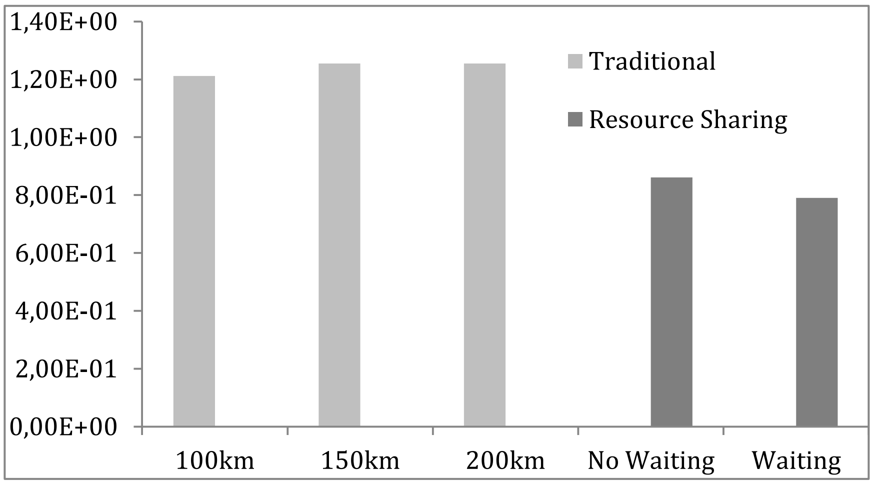


Figure 6: GHG Emission (kgCo2 per km.container) as a function of backhauling zone size and willingness to wait.

5.2 Resource-sharing transportation model analysis

In order to assess the impact of different parameters, we compared the average values of different indicators of specific scenarios.

5.2.1 Combined impact of consolidation and demand level

First, we analysed the combined impact of consolidation and demand levels on all performance indicators. Results show that as demand increases, the gap between the maximum capacity of consolidation and consolidation utilisation decreases. For demands of 1%, 5% and 10%, the average the gap is respectively 29%, 10% and 4.7%. In other words, when demand increases, there are more consolidation opportunities, which lead to significantly higher performance as shown in Figures 7 to 10.

Concerning total unit operation cost per km.container, Figure 6 shows that increasing demand significantly reduces unit operation cost. A demand increase from 1% to 5% and from 5% to 10% reduces respectively unit cost by 83% and 50%. However, the level of consolidation does not seem to have any significant impact on unit operation cost.

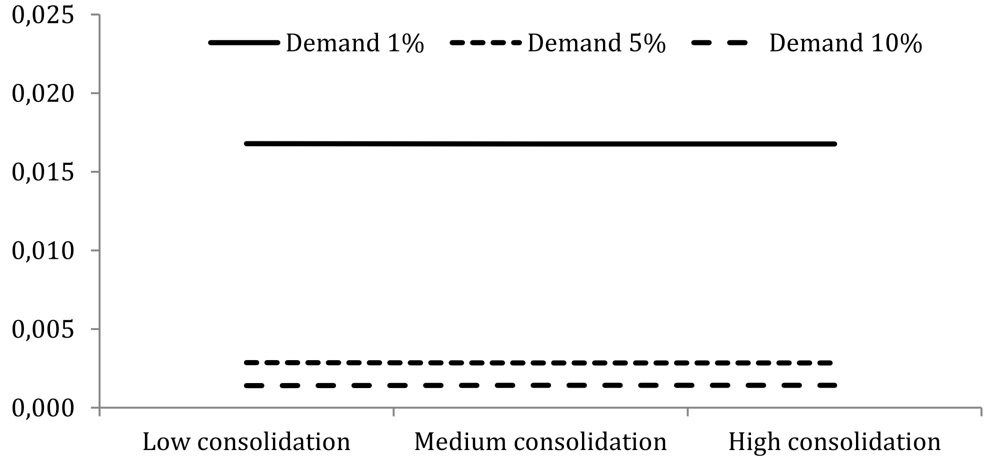


Figure 7: Unit cost per km.container ($) as a function consolidation and demand levels.

Concerning logistic indicators (Figure 8 (a) and (b)), Delay slightly decreases as demand increases, whatever the level of consolidation (i.e., consolidation only seems to have a slight impact, if any). Inversely, fill rate increases at the same rate. Similarly, efficiency slightly increases when demand increases, which is consistent with the impacts of demand on unit cost (Figure 7).

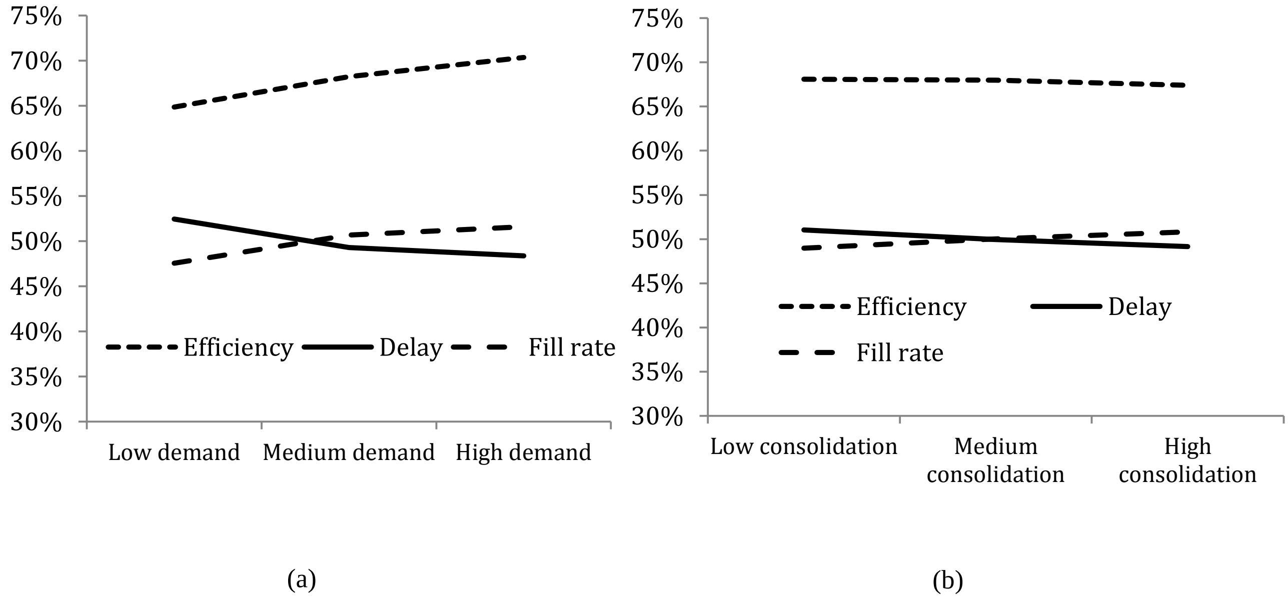


Figure 8: Delay, Fill rate and Efficiency as a function of demand levels (a) and consolidation (b).

Figure 9 shows the impact of demand and consolidation on the time truck drivers spend at home. First, consolidation has only a small impact (i.e., from low to high consolidation, the variation of the time spend at home is only 0.4%, 0.6% and 1% for demand level of 1%, 5% and 10% respectively), which is, again, consistent with the impact on logistic indicators. However, higher demand impacts more significantly the time spent at home, especially when demand reaches 10%. This can be explained by the fact that when demand increases, the number of backhauling opportunities also increases, which leads to less time spent in a hub waiting for a backhaul.

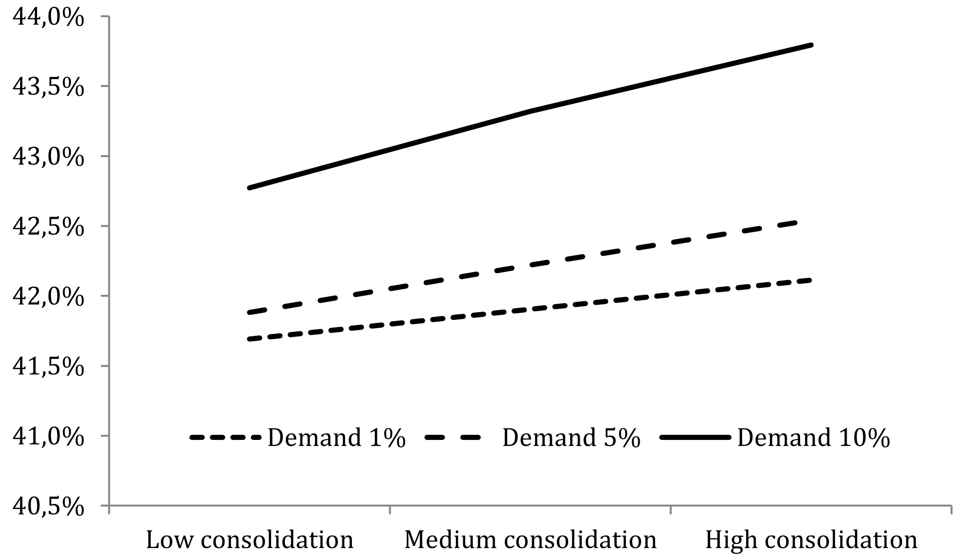


Figure 9: Time Spent at Home as a function consolidation and demand levels.

Concerning the GHG emission, Figure 10 shows that demand has, as expected, a positive impact on GHG emission per km.container, as previously discussed, with a decrease of 18%-19% of CO_2 emission between 1% and 10% demands. Again, this can be explained by the fact that when demand increases, the number of backhauling opportunities also increases. However, consolidation has a slight negative impact on GHG emission. It happens because consolidated truck consumes more gas than an empty or a non-consolidated truck.

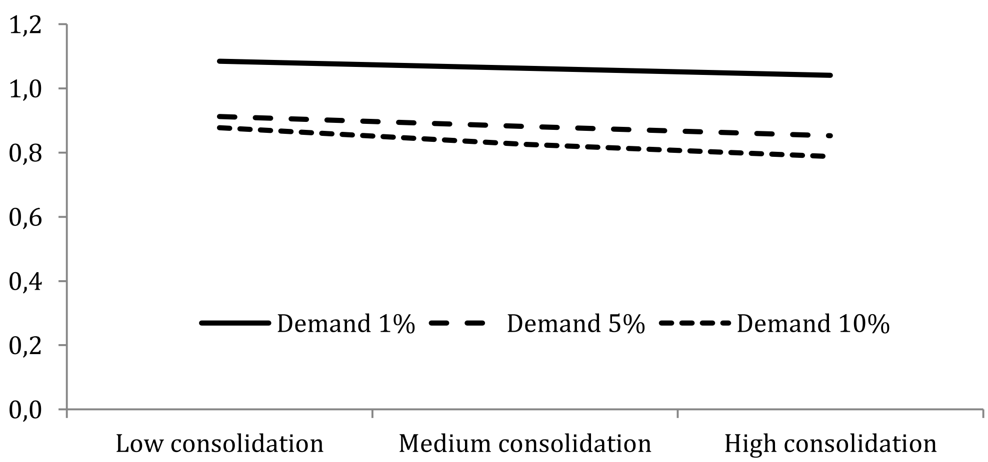


Figure 10: GHG Emission (kgCo2 per km.container) as a function of consolidation.

5.2.2 *Combined impact of willingness to wait and consolidation*

Figures 11 present the results of a similar analysis concerning the combined impact of consolidation level and the willingness to wait for a backhauling opportunity. As shown in Figure 11, consolidation has a very small positive impact on unit cost per km.container. Inversely, willingness to wait has a small negative impact on unit cost. This can be simply explained by the fact that a truck wait for a backhaul at a hub, the truck does not travel (either loaded or empty), which in turn increases unit cost. On average, the willingness to wait only increases unit cost by 1%, which is not really significant.

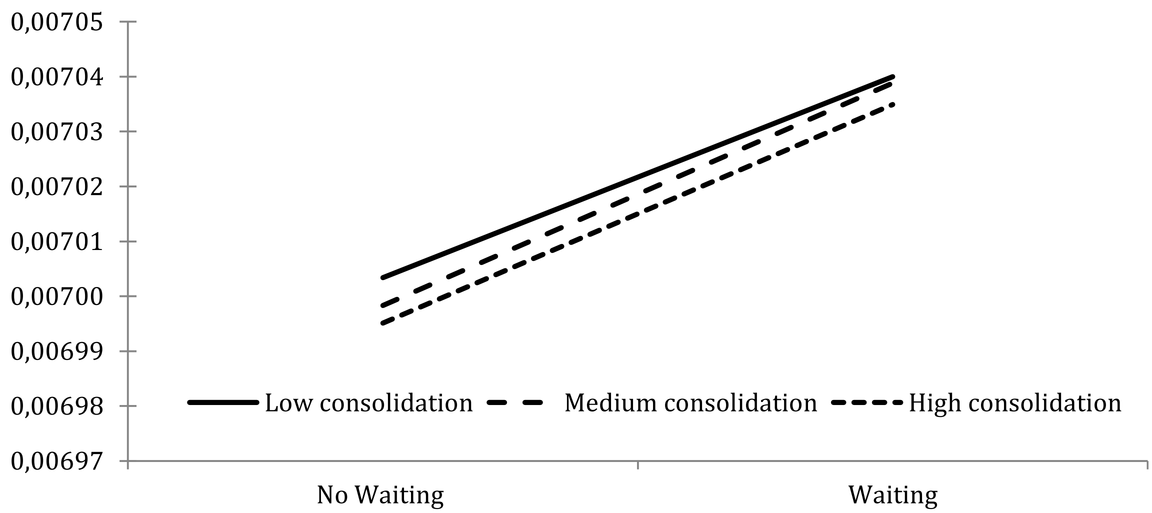


Figure 11: unit cost per km.container ($) as a function consolidation level and willingness to wait.

Concerning logistic performance (Figure 12), the willingness to wait for a backhauling opportunity has a positive impact on all performance indicators, which is to be expected. On average, fill rate increases by 3%, delay is reduced by 3%, and efficiency increases by 6%.

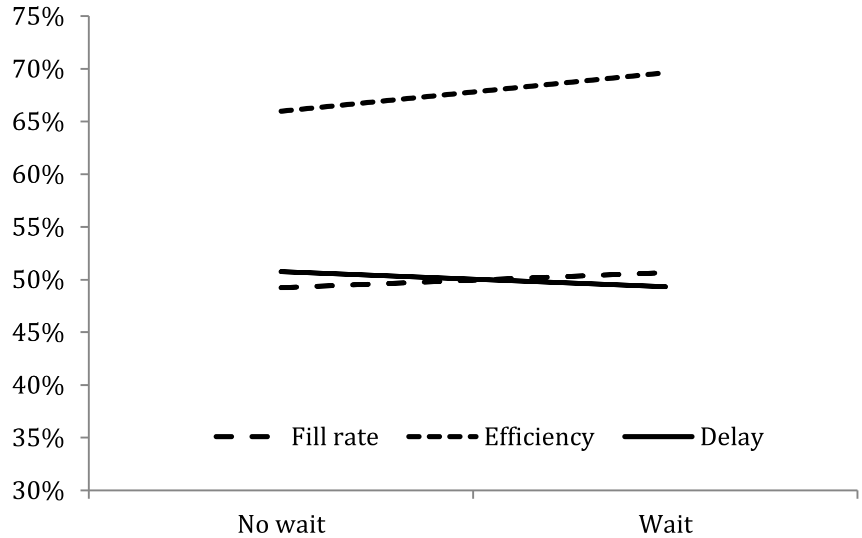


Figure 12: Delay, Fill rate and Efficiency as a function of willingness to wait.

Concerning the social indicator, Figure 13 confirms that the willingness to wait for a backhauling opportunity reduces slightly, as expected, the time the truck drivers spent at home. Indeed, if a truck driver decides to wait at an intermediated hub, his work shift is generally longer than if he decides to comeback immediately. However, results also show that this slight negative impact is largely outweighed by the improvement of all other indicators.

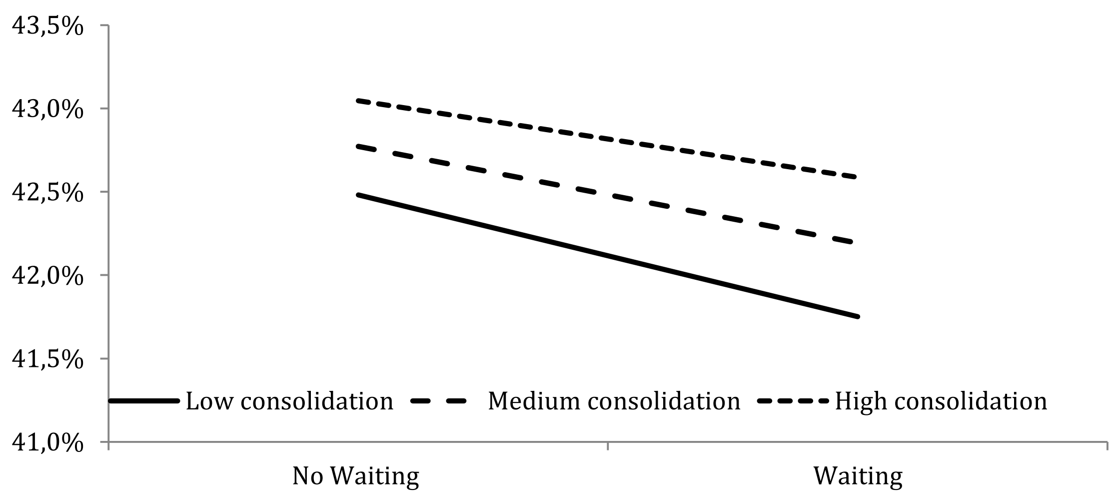


Figure 13: Time Spent at Home as a function of consolidation level and willingness to wait.

Finally, concerning GHG emission, the impacts of both willingness to wait and consolidation have a smaller impact then demand, although they remain significant with a decrease of, respectively, 5% and 7 % of CO_2 emission (Figure 14). This result is expected because both willingness to wait and consolidation increase the opportunity of sharing resources in the form of container consolidation.

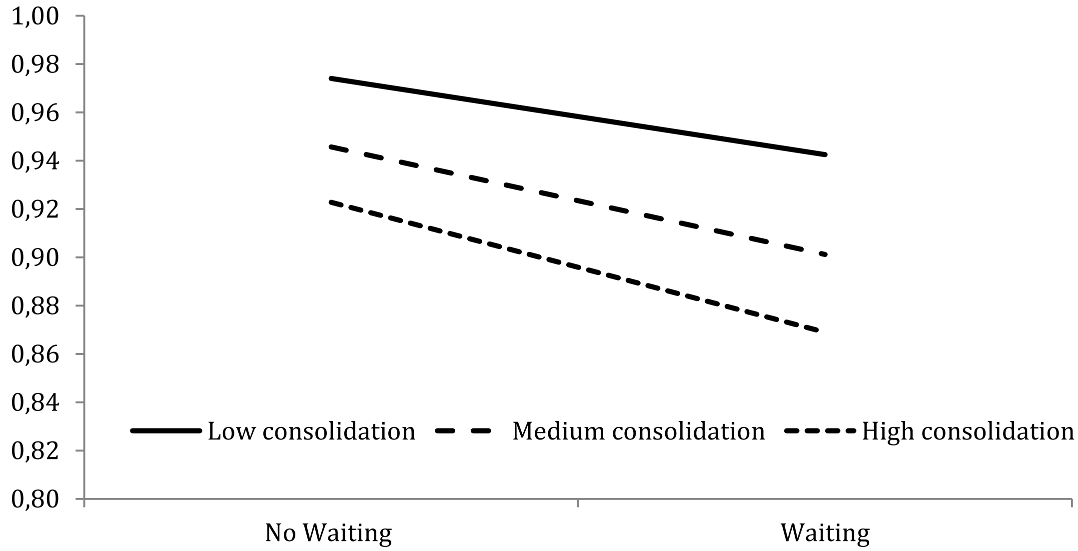


Figure 14: GHG Emission (kgCo2 per km.container) as a function of consolidation level and willingness to wait.

6 Conclusion and future development

The study presented in this paper provides an analysis of various performance indicators of a simple implementation of the PI philosophy. To do so, this article presents a freight transportation model based on the resource sharing methodology. This model was compared to a traditional approach, which was modeled as a door-to-door container transportation model, for which planning is fully centralized by the original hub.

In order to compare the two models, we created five scenarios (three for the traditional, and two for the resource-sharing). Each scenario was simulated 100 times. The traditional model was validated by comparing the proportion of empty trip per distance and per paths with the study in (Meller 2012).

After validation, we simulated 100 times each scenario for both model. General results indicate that resource-sharing transportation has a better economic, logistic, social and environmental performance than the traditional model.

More specifically, results show that both consolidation and the demand have a positive impact on unit cost per km.container, as well as on the fill rate, delay, efficiency, and the time spent at home. However, only demand has as a significant positive impact of GHG emission per km.container. Both willingness to wait and consolidation have a very small negative impact at the GHG emission, which may be attributed to a limit of the resource-sharing model.

The resource sharing results show that both demand and willingness to wait improve the probability of an opportunity of backhauling and have a positive impact on the percentages of fill rate, the efficiency, and the delay. However, they have a negative impact on the unit cost per km.container, the percentage of time spent at home. The unit cost is higher with willingness to wait, because of the reduction of the amount of km travelled. The social performance is also lower, because willingness to wait leads to longer work shift than with no willingness to wait. Finally, GHG emission per km.container is lower because of both demand and willingness to wait increase the opportunity of truck pooling, and therefore, a lower emission of CO_2 per transported container.

Finally, this paper also presents some research direction to improve the model to further implementation of the PI philosophy. Several aspects of these simulations models will be improved. First, the simulations were designed in a way that containers disappear from the simulation when they are delivered in the destination hub. Therefore, the first aspect to be changed is to improve containers delivery as well as the management of containers after delivery in order to return them to the origin hub.

Container management is important because once delivered at destination, containers have an existence that affects the use of the transportation capacity. They also play a role during the last mile delivery and the temporary storage of goods at their destination. Along the same line, containers are owned, rent and maintained. They are an integral part of the transportation service for which the owners receive contributions.

Other scheduling rules will be tested in a future version of this model. Similarly, different classes of priority (e.g., 24h delivery, 48h delivery) will also be implemented.

Therefore, the management of empty container will have to take into account the transport of empty container to hubs with high demands. The most typical example of unbalanced container traffic in a macro scale proportion is the one happening between the U.S.A. and China.

Along the same line, we will implement an intermodal network (train and maritime transportation) and compare each modal and intermodal checking the system sustainability.

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