A multimodal network flow problem with product quality preservation, transshipment, and asset management

Citation for published version (APA):
Steadie Seifi, M., Dellaert, N. P., & Woensel, van, T. (2014). *A multimodal network flow problem with product quality preservation, transshipment, and asset management*. (BETA publicatie : working papers; Vol. 442). Technische Universiteit Eindhoven.

Document status and date:
Published: 01/01/2014

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 17. Nov. 2023

A multimodal network flow problem with product quality preservation, transshipment, and asset management

Maryam SteadieSeifi, Nico Dellaert, Tom Van Woensel

Beta Working Paper series 442

BETA publicatie	WP 442 (working paper)
ISBN	
ISSN	
NUR	804
Eindhoven	January 2014

A multimodal network flow problem with product quality preservation, transshipment, and asset management

Maryam SteadieSeifi*, Nico Dellaert, Tom Van Woensel
School of Industrial Engineering and Innovation Sciences,
Technical University of Eindhoven, P.O.Box 513, 5600 MB, Eindhoven, Netherlands
*Email: `m.steadie.seifi@tue.nl`

Edition January 6, 2014

Abstract

In this paper, we present an optimization model for a transportation planning problem with multiple transportation modes, highly perishable products, demand and supply dynamics, and management of the reusable transport units (RTIs). Such a problem arises in the European horticultural chain, for example. As a result of geographic dispersion of production and market, a reliable transportation solutions ensures long-term success in the European market. The model is an extension to the network flow problem. We integrate dynamic allocation, flow, and repositioning of the RTIs in order to find the trade-off between quality requirements and operational considerations and costs. We also present detailed computational results and analysis.

Keywords: Multimodal transportation, Mixed-Integer Program, reusable transport unit, Perishability

1 Introduction

Perishable supply chains around Europe are continent-wide businesses. An example is the horticultural sector of the Netherlands which is the largest exporter of fresh products in Europe. Everyday hundreds of perishable product types (fruit, dairy, flower, etc.) with their own characteristics and preservation requirements are transported throughout Europe. These products have short shelf-lives, and they travel for long and in different climates. The temperature fluctuation and long handling time have direct influence in their deterioration. It is difficult to manage timely transportation that not only ensures the freshness of products, but also offers a competitive price. Minimizing transportation costs is one of the key drivers of global success in such highly price-sensitive industries.

In a transportation system as described above, a smooth and synchronized flow with minimum waiting and handling is needed. This is highly dependent on the availability of Reusable Transport Items (RTI). A RTI is an empty transport loading unit which can have different sizes ranging from a small box to a large 45-feet container (Figure 1). In the horticultural chain for instance, flowers and bouquets are loaded in the small RTIs (e.g. boxes and buckets) and then medium RTIs (e.g. cages and trolleys) at the origin locations, and are unloaded at the destination locations. For the long haul part of the transportation, these filled RTIs are further loaded in the big ones (e.g. a cooled 45-feet container), in order to use the opportunities that multimodal transportation offers. By the next decade, it is expected that truck transport will decrease in favour of deep sea and short sea ships, barge and train transportation. However, the number of all RTIs is limited. Returning or repositioning these units is costly for carriers and does not bring any direct profit to them. As a

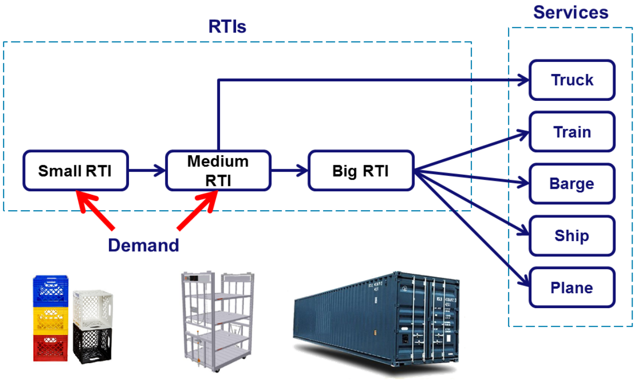


Figure 1: Resource allocation structure in a long-haul transportation system

result, solutions integrating the forward flow of filled RTIs with the backward flow of empty ones are needed to minimize the system-wide costs while preserving the quality of products.

In this research, we study this integrated flow planning, present a model and analyze the behavior of the solutions against changing the parameters. The outline of this paper is as follows. Section 2 gives an overview on the literature of perishability and asset management issues in multimodal transportation planning. Sections 3 and 4 respectively describe the designed model and the proposed formulation. In Section 5, the mathematical formulation is tested and the results are analyzed, and finally, in Section 6, we give some concluding remarks and future works.

2 Literature Review

Transportation of perishable products demands quality preservation conditions which should be respected in the planning. Figure 2 provides an overview on perishability in different planning problems in the literature. We can group the problems into three main groups: long-haul transportation, last-mile transportation, and other problems. Transportation considerations in the body of supply chain design and production-distribution planning problems have been fairly studied. However, the number of research studying multimodal systems is few. The examples are Ahumada and Villalobos [2011], and Yu and Nagurney [2013]. Ahumada and Villalobos [2011] model the production-distribution of perishable products and consider the perishability both as a loss function in the objective function, and as a constraint on product storage. Yu and Nagurney [2013] propose a model for competitive supply chain design problem including multiple transportation modes. They introduce arc multipliers to incorporate food deterioration and add costs of spoiled food to their objective function.

Last-mile distribution of products is modeled as Vehicle Routing Problems with Time Windows (VRPTW) and the goal is to find the optimal load, delivery routes, and departure times of the fleet of vehicles. Doerner et al. [2008] study the pickup and delivery problem of blood products where the pickup plan is inter-related to the dispatching policy. There are strict time windows and after a certain time, the product is completely spoiled. They model this problem and design three heuristics to solve it. Hsu et al. [2007] model a food distribution planning problem with stochastic and time-dependent travel times, and time-varying temperature. They also account for the penalty of violating time windows in the objective function. In order to solve this problem, they modified and applied the time-oriented nearest-neighbor heuristic in the literature. Osvald and Stirn [2008] address distribution of fresh vegetables with time-dependent travel times, and propose a Tabu Search algorithm to solve it. They add a loss of quality term to their objective function which is a linear function of quality degradation based on time. Tarantilis and Kiranoudis [2001] develop an adaptive threshold accepting algorithm for the distribution of fresh milk with a heterogeneous fixed fleet, and Tarantilis and Kiranoudis [2002] develop a list-based threshold accepting algorithm for the distribution of fresh

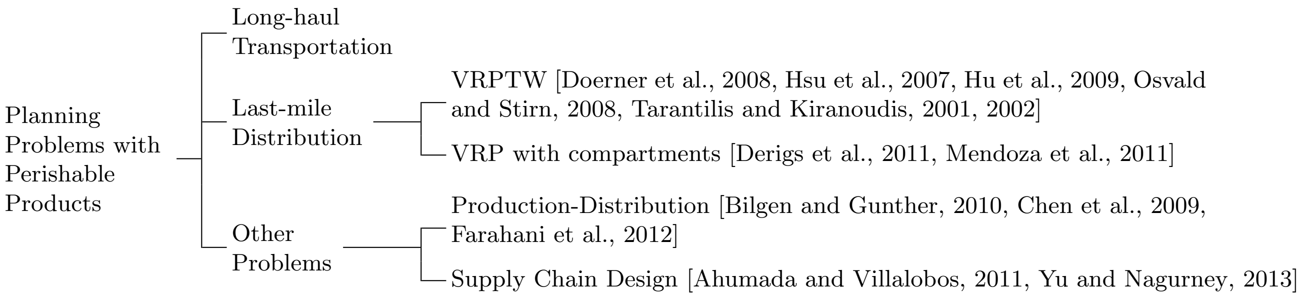


Figure 2: OR literature on different planning problems with perishable products

meat in a multi-depot network. However, neither of them exclusively contemplate the perishability of products.

In addition to the perishability, in some distribution systems, the products are incompatible and they cannot be loaded in the same truck or unit. Planning for such products separated, and allocating separate trucks, while customers order them simultaneously, result in excessive transportation costs. One solution is to divide the truck space into compartments and load each compartment with a unique product type. The examples in the literature are Derigs et al. [2011] and Mendoza et al. [2011]. Derigs et al. [2011] study such a distribution planning problem for food and petrol. They model it as a VRP with flexible compartments and propose a Large Neighborhood Search (LNS) algorithm to solve this problem. Mendoza et al. [2011] study another VRP with compartment and stochastic demand, and design three heuristics based on stochastic programming.

We could not find any research on long-haul transportation of perishable products, while international perishable supply chains might need tailored policies and solutions which the literature does not offer.

An optimal transportation planning is equivalent to the optimal utilization of the assets. *Assets* can be RTIs, vehicles, crews, power units, engines, etc [SteadieSeifi et al., 2014]. Positioning, balancing, allocating, repositioning, and rotation of assets are the subject of asset management. An optimal asset management ensures a smooth transportation which is critical in perishable product supply chains. Figure 3 gives an overview on the different approaches in the literature, studying asset management in multimodal transportation problems. We can divide them into tactical and operational planning problems. Tactical and operational planning deal with optimally utilizing a given infrastructure and the available assets by choosing services and associated transportation modes, allocating their capacities to orders, allocating other resources to the orders, and planning the itineraries and frequency. The only difference is that in operational planning we need to answer to the real-time requirements of all multimodal operators, carriers and shippers [SteadieSeifi et al., 2014]. Overall, on both planning levels, repositioning of vehicles has been mostly investigated, and the number of papers managing RTI

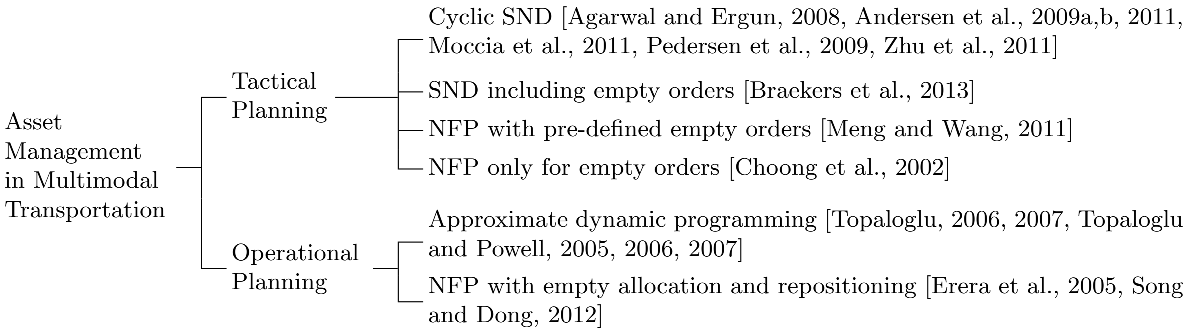


Figure 3: OR literature of asset management in multimodal transportation

fleets is few. Since the operational planning is out of our scope, we refer the interested reader to the references.

On tactical level of multimodal transportation planning, *Network Flow Planning* (NFP) problems relate to the flow planning decisions addressing the movement of orders (commodities) throughout the network. *Service Network Design* (SND) problems in comparison involve the service planning decisions including all decisions on choosing the transportation services and modes to move those commodities.

SND problems with cyclic service design account for returning of empty vehicles to their service starting location. Agarwal and Ergun [2008] study a liner shipping network design with transshipment at the hubs, and present three heuristics, namely a greedy, a column generation based, and a Benders' decomposition heuristic algorithm. Pedersen et al. [2009], Andersen et al. [2009a], Andersen et al. [2009b], and Andersen et al. [2011] present comprehensive study on formulating SND problems with vehicle repositioning and their computational differences. Moccia et al. [2011] propose a column generation heuristic for a rail and road transportation system with both consolidated and dedicated services. They transform the physical network such that for each shipment (O/D pair) they have a virtual digraph where nodes represent time windows of using transportation modes. Pedersen et al. [2009] solve their SND problem by means of a Tabu search algorithm, and show the power of the Tabu search compared to a MIP solver.

Braekers et al. [2013] and Meng and Wang [2011] are the two examples we found where empty container repositioning is included into liner shipping service design. Braekers et al. [2013] show that shipping lines may reduce costs by simultaneously planning barge services and empty container repositioning movements instead of planning empty container repositioning movements in a post-optimization phase. Meng and Wang [2011] also compare the solutions with and without simultaneous empty repositioning planning, and see cost reductions up to 15%. However, in both papers, the repositioning orders are given and pre-defined, and can be treated as additional orders besides the usual product orders. Choong et al. [2002] model the flow of owned and leased empty containers on barges, investigate 15-day and 30-day planning horizons, and conclude that a longer planning horizon is more desirable in their case. Longer planning horizon also result in utilization of cheaper transportation modes. Choong et al. [2002] however do not study the integration of empty repositioning and forward flow of products.

Zhu et al. [2011] is the only example we found on simultaneous planning of multiple type of assets in SND problems. They study a rail system with car classification, car blocking, and train makeup, and model it as a three-layered network (for service, block, and car). They solve this problem by means of a hybrid metaheuristic algorithm combining slope scaling, enhanced by long-term memory-based perturbation strategies and ellipsoidal search method.

This paper is the first to study the long-haul transportation of perishable products by carriers. In this regard, we include a quality preservation measure and integrate the forward flow of filled RTIs with the backward flow of empty ones. We assume to have one product type and we only focus on a single-RTI (e.g. cages) transportation system. Therefore, we leave the flow of smaller or bigger RTIs and the last-mile distribution of products out of scope. The reason is the high complexity of such transportation system which makes it difficult and intractable to be modeled at once. Moreover, detailed planning of the operations inside the locations is also out of our scope. We address them only as aggregated time, costs, etc.

To summarize, we build upon the literature, and model this problem as a multimodal network flow problem with quality preservation, transshipment, and asset management. Moreover, the objective of this problem is to minimize total system costs. This research adds to the literature of NFP problems by studying the trade-off between the critical delivery requirements of this industry and its operational costs. Figure 4 illustrates the conceptual model for tactical planning of this transportation system. In the rest of this paper, we describe and formulate this tactical planning problem in Sections 3 and 4.

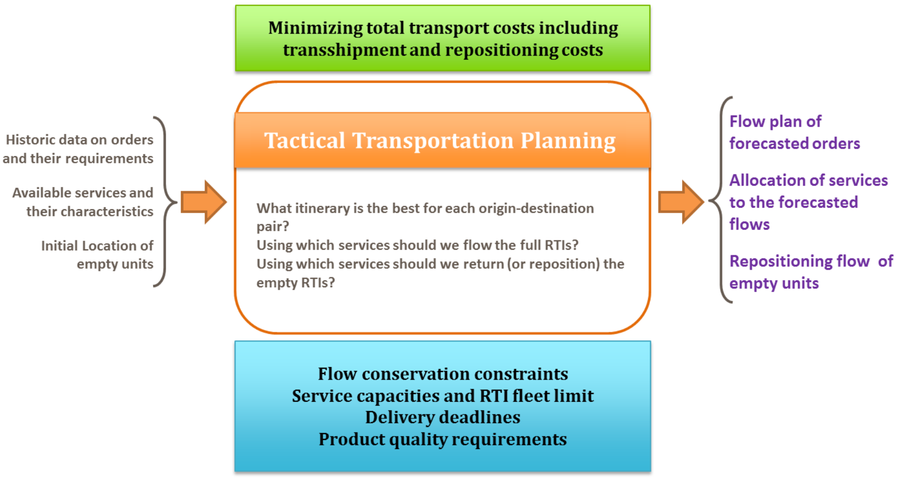


Figure 4: The tactical planning model for a perishable transportation system

3 Problem Definition and Modeling Approach

In this section, we provide definitions and assumptions which will be later used for mathematical formulation. Table 8 in the Appendix provides a summary of all notations used. Note that the usage of *Prime* signs might look strange at the beginning, but we use them in the way to avoid a messy and confusing mathematical formulation.

The physical transportation network is characterized by nodes i' representing the $\mathcal{N}$ locations, and the arcs (i', i'') representing different routes connecting these locations. Between each location pair, at least one service m' can operate. A service is the transportation job operated by the related transportation modes, characterized by its origin, destination, its route, and price. Services also have departure and arrival schedules (which represent their frequency during a particular time horizon). A mode is characterized by its capacity, speed, and temperature regime. Truck, train, barge, deep-sea and short-sea ship, and airplane are the main modes.

We have a fleet of $\mathcal{M}$ services. Each of these services has its own capacity $cap^{m'}$, travel time $r_{it}^{m'}$ and temperature $l_{it}^{m'}$, variable transportation cost $C_{full}^{m'}$ per full RTI per time period, and variable repositioning cost $C_{empty}^{m'}$ per empty RTI per time period. In addition, we assume a maximum number of vehicles for each service type as $|F^m|$.

Demand is defined by the arrival of orders for RTIs at the origin terminals in different time period. An order p is characterized by the number w_p of RTIs requested at an origin terminal $O(p)$ to be transported to a destination terminal $D(p)$. This order can be picked up at earliest at time $PT(p)$ and should be delivered to the destination, while preserving the requested Time Temperature Sum (TTS) of $\mathcal{L}_p$ and respecting the deadline $DT(p)$. TTS is a measure in some fresh produce industries representing the total time that products can be transported in different temperature regimes. For instance, if a filled RTI is moved on a train for 3 days, and the temperature inside the train is 10 degree celcius, the TTS of this travel is 30, and for each order the summation of these TTS's should be less than $\mathcal{L}_p$ (say 200 $Days \times Degree$).

In order to include all dynamics such as transshipment, we transform the physical network into a *mode-space-time representation*. First, we divide the time horizon T (e.g. a season) into smaller time periods t' (e.g. days), and map the physical network in both time and space. Each node in this network represents a location at a time period. Then, the space-time mapping is furthermore multiplied by $\mathcal{M}$. Figure 5 gives an illustration of a simple mode-space-time network with 3 terminal locations, 15 time periods, and 2 modes. In this example, a feasible flow itinerary for an order from location 1 to location 3 with PT of 4 and DT of 11 is shown. All empty RTIs are kept at location 2,

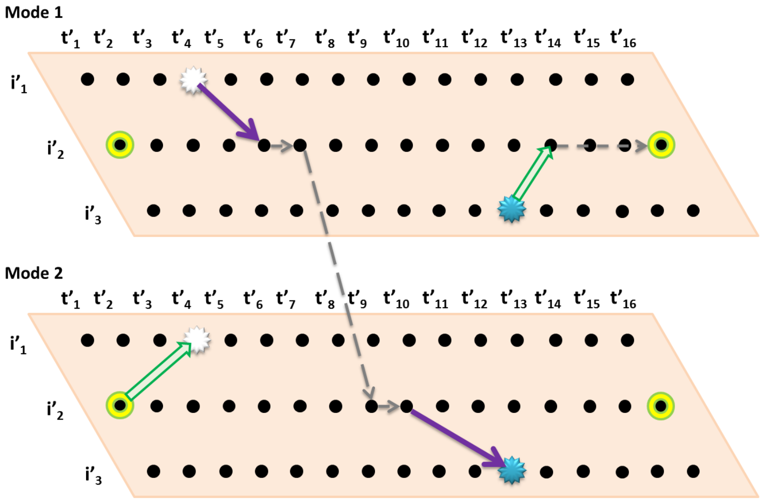
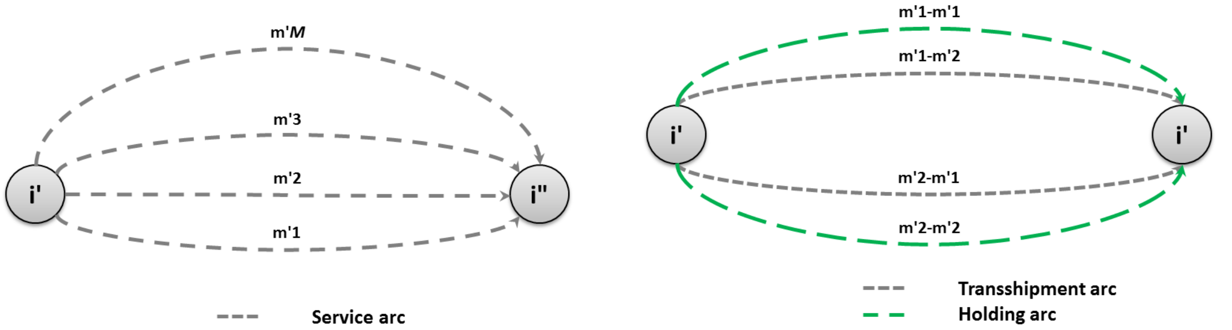


Figure 5: An example of the mode-space-time representation of a flow network problem

and at the end of planning horizon, these empty RTIs should be returned to this location. For this order, the number of needed empty RTIs is moved from location 2 by service type 2. Then the full RTIs are loaded at location 1 and moved to location 2 on service type 1. Then after waiting for one period at location 2, the full RTIs are transshipped to service type 2 which also takes one period. After waiting for another period, the full RTIs are delivered and unloaded at location 3 by the time 11. In the end, the emptied RTIs are returned to location 2 by service type 1.

In this mode-space-time network, an arc (i, t, g) can represent three types of operations: (i) a *service arc* for the travel between locations (i', i''), leaving at time t' and arriving at time t'', by service type m' (Figure 6a), (ii) a *transshipment arc* for the transshipment of orders at location i' between services m' and m'' starting at time t' and finishing at time t'', and (iii) a *waiting/holding arc* for the stop of service m' (e.g. for switching rail tracks at borders, or custom clearance) at i' at time t', or holding empty RTIs. Since the last two operations occur at locations, the arcs representing them are called location arcs (Figure 6b).

The waiting/holding arcs have the length of one period, while the other two types of arcs depending on the location and service can take more than one period. The terminal operations can have different natures such as waiting of a service, consolidation, transshipment, loading and unloading, and holding. We believe that the transshipment and waiting arcs (Figure 6b) cover all these terminal operations in our scope. As an example, in some transportation systems, the loading and unloading jobs are a part of the service contract, therefore, we assume that the time and costs of these jobs have already been



(a) Service arcs connecting different nodes

(b) Location arcs representing terminal operations

Figure 6: An illustration of different arcs in the model

included in the service time and cost parameters.

The location arcs all have their own operation time $r_{i't}$, temperature $l_{i't}$, and cost $C_{i'}^T$ per location for transshipment. We assume that locations are uncapacitated regarding the number of operations they can do, the number of RTIs they can hold, or the number of vehicles they can accommodate.

Note that not all services are feasible for each location pair, therefore, the locations cannot accommodate all kinds of services. Moreover, not all locations have a storage facility available. As a result, the network is not a complete or even a dense graph.

In this problem, x_{itp}^g, $\bar{x}_{it}^g$, and y_{it}^g are the decision variables representing the flow of full RTIs per order p, flow of empty RTIs, and the number of vehicles engaged on an arc respectively. In order to capture the need for empty RTIs, two extra variables $U_{i't'p}$ and $\bar{U}_{i't'p}$ are added to the model to track the in-flow and out-flow of full and empty RTIs at origins, destinations, and intermediate nodes. These variables are used to calculate the flow of empty RTIs throughout the network. The auxiliary binary variables b_{itp}^g are also added to help calculating TTS.

We assume that the location and the number of RTIs per location is fixed at the beginning of the planning horizon. Therefore, for each location, $S_{i'}$ number of RTIs are available at the beginning of the time horizon. Since this is a single-horizon model, meaning that we only plan for one planning horizon (e.g. one season), we assume that the RTIs should return to their initial locations, so the number of available RTIs at each location at the end of horizon should equal to $S_{i'}$.

4 Mathematical Model

In this section, we present the mathematical formulation for our single-RTI, single-product, multimodal network flow problem with quality preservation and transshipment. Table 8 in the Appendix gives a summary of all notations used. The objective function (1) is in the form of minimizing total system costs. The first term represent total flow costs of the full and empty RTIs, the second term is the total transshipment costs, and the third term contemplates all administrative costs and taxes of using the services.

$$\begin{aligned}\min \sum_{g\in\mathcal{G}} \sum_{t=1}^{T\times T} \sum_{i\in A(\mathcal{V}\times\mathcal{V})-A(i',i')} r_{it}^{m'} \Big[\sum_{p=1}^{\mathcal{P}} (C_{full}^{m'} \times x_{itp}^g) + (C_{empty}^{m'} \times \bar{x}_{it}^g)\Big] \\ + \sum_{g\in\mathcal{G}_T} \sum_{t=1}^{T\times T} \sum_{i\in A(i',i')} C_{i'}^T \times r_{i't}\Big(\sum_{p=1}^{\mathcal{P}} x_{itp}^g + \bar{x}_{it}^g\Big) + \sum_{g\in\mathcal{G}} \sum_{t=1}^{T\times T} \sum_{i\in A(\mathcal{V}\times\mathcal{V})-A(i',i')} C^{m'} y_{it}^g \qquad (1)\end{aligned}$$

Constraints (2)-(5) are flow conservation constraints. Constraint (2) defines U as the flow of full RTIs (for each order) at each location and time period.

$$U_{i't'p} = \sum_{g\in\mathcal{G}-\mathcal{G}_T} \sum_{t\in\mathcal{N}^+(t')} \sum_{i\in\mathcal{N}^+(i')} x_{itp}^g - \sum_{g\in\mathcal{G}-\mathcal{G}_T} \sum_{t\in\mathcal{N}^-(t')} \sum_{i\in\mathcal{N}^-(i')} x_{itp}^g \qquad \begin{array}{l}\forall i' \in \mathcal{V},\\ t' = 1,\dots,T\\ p = 1,\dots\mathcal{P}\end{array} \qquad (2)$$

Constraint (3) enforces the flow of full RTIs (orders) between the origin and destination locations.

$$U_{i't'p} = \begin{cases} w_p & i = O(p), t = PT(p) \\ -w_p & i = D(p), t = DT(p) \\ 0 & o.w. \end{cases} \qquad \begin{array}{l}\forall i' \in \mathcal{V},\\ t' = 1,\dots,T\\ p = 1,\dots\mathcal{P}\end{array} \qquad (3)$$

Constraint (4) and (5) determines the number of RTIs that should be repositioned in order to be able to respond to future demands. Constraint (5) emphasizes that the outbound flows of empty RTIs at the beginning of planning horizon, and the inbound flows of empty RTIs at the end of the horizon should be equal to their available number $S_{i'}$ that is given to this model. For the rest of network, there is a balance constraint ensuring the flow of empty RTIs are related to the flow of orders.

$$\bar{U}_{i't'} = \sum_{g \in \mathcal{G}-\mathcal{G}_T} \sum_{t \in \mathcal{N}^+(t')} \sum_{i \in \mathcal{N}^+(i')} \bar{x}^g_{it} - \sum_{g \in \mathcal{G}-\mathcal{G}_T} \sum_{t \in \mathcal{N}^-(t')} \sum_{i \in \mathcal{N}^-(i')} \bar{x}^g_{it} \qquad \begin{array}{l} \forall i' \in \mathcal{V}, \\ t' = 1, \ldots, T \end{array} \tag{4}$$

$$\bar{U}_{i't'} = \begin{cases} S_{i'} - \sum_{p=1}^{\mathcal{P}} U_{i't'p} & t' = 1 \\ -\sum_{p=1}^{\mathcal{P}} U_{i't'p} & 1 < t' < T \\ -S_{i'} - \sum_{p=1}^{\mathcal{P}} U_{i't'p} & t' = T \end{cases} \qquad \begin{array}{l} \forall i' \in \mathcal{V}, \\ t' = 1, \ldots, T \end{array} \tag{5}$$

Constraints (6) and (7) are logical constraints used to calculate the TTS of orders.

$$x^g_{itp} \geq b^g_{itp} \qquad \forall i \in A(\mathcal{V} \times \mathcal{V}), \qquad t \in A(T \times T), \qquad p = 1, \ldots \mathcal{P}, \qquad g \in \mathcal{G} \tag{6}$$

$$x^g_{itp} \leq M b^g_{itp} \qquad \forall i \in A(\mathcal{V} \times \mathcal{V}), \qquad t \in A(T \times T), \qquad p = 1, \ldots \mathcal{P}, \qquad g \in \mathcal{G} \tag{7}$$

Based on the Constraints (6) and (7), Constraint (8) states that for each order, the total *days* × *temperature* of moving and handling that order must be less than the total desired TTS of the order.

$$\sum_{g \in \mathcal{G}} \sum_{t=1}^{T \times T} \sum_{i \in A(\mathcal{V} \times \mathcal{V}) - A(i',i')} l^{m'}_{it} \times r^g_{it} \times b^g_{itp} + \sum_{g \in \mathcal{G}} \sum_{t=1}^{T \times T} \sum_{i \in A(i',i')} l_{i't} \times r_{i't} \times b^g_{itp} \leq \mathcal{L}_p \qquad \forall p = 1, \ldots \mathcal{P} \tag{8}$$

Constraint (9) forces the capacity of a chosen service on the total number of RTIs (empty or full) that is moved by that service.

$$\sum_{p=1}^{\mathcal{P}} x^g_{itp} + \bar{x}^g_{it} \leq y^g_{it} \times cap^{m'} \qquad \forall i \in A(\mathcal{V} \times \mathcal{V}), \qquad t \in A(T \times T), \qquad g \in \mathcal{G} \tag{9}$$

Constraint (10) states that the total number of services in operation and services engaged in handling jobs in each time period is limited.

$$\sum_{g \in \mathcal{G}_{m'}} \sum_{t \in A(\tilde{t} \leq t', \hat{t} \geq t')} \sum_{i=1}^{\mathcal{V} \times \mathcal{V}} y^g_{it} \leq |F^{m'}| \qquad \forall t' = 1, \ldots, T, \qquad m' = 1, \ldots, \mathcal{M} \tag{10}$$

And finally, Constraints (11) and (12) define the nature of the model variables.

$$x^g_{itp} \geq 0, \; b^g_{itp} \in \{0, 1\} \qquad \forall i \in A(\mathcal{V} \times \mathcal{V}), \qquad t \in A(T \times T), \qquad p = 1, \ldots \mathcal{P}, \qquad g \in \mathcal{G} \tag{11}$$

$$\bar{x}^g_{it} \geq 0, \; y^g_{it} \in \mathbb{N} \qquad \forall i \in A(\mathcal{V} \times \mathcal{V}), \qquad t \in A(T \times T), \qquad g \in \mathcal{G} \tag{12}$$

In the next section, we test this formulation on a number of instances and analyze its sensitivity to its parameter settings.

5 Numerical Experiments

In this section, we verify the proposed formulation presented in Section 4 on different instances. We explain the tactics used to strengthen and speed up the computation, and give some practical insight. We solve all instances with Gurobi solver 5.5.0 on a Core2Duo CPU 2.93 GHz with 4.00 GB RAM.

Table 1: Service inputs

	$F^{m'}$	$cap^{m'}$	$l_{i't}$	$freq^{m'}$	$Speed^{m'}$	$C^{m'}_{full}$	$C^{m'}_{empty}$
Truck services	100	2	12	1	56	50.78	22.58
Train services	25	91	12	3	32	290.41	129.16
Barge services	25	500	12	4	14	64.5	28.68

5.1 Instance Sets

We could not find any instances in the literature for this type of problems. Therefore, we generated a set of instances with $8, 10, 11$, and 13 locations, 2 and 3 transportation services (truck and train, or truck, train and barge) with their own feasible service routes, $50, 75$, and 90 time periods, and $10, 20, 30, 40, 50$ orders. The instance sets are generated in such a way that they are structurally similar to a real chain. The instances are named as "nAmBtCoD" where value of A shows the number of locations, value of B is the number of service types, value of C is the planning horizon, and value of D stands for the number of orders.

In base case, the parameter settings given in Tables 1 are used for services. These numbers have been inspired by the horticultural supply chain, but they were adjusted to the structure of the network in our instances.

Locations in our instances can be supply nodes (origins), demand nodes (destinations), and intermodal terminals (hubs). We assume a temperature $l_{i't}$ of 3 for hub locations and a temperature of 12 for other locations. Moreover, not all hubs have an RTI inventory $S_{i'}$, so we assume in all instances a total number of 500 RTIs. We equally distribute this number among the two hubs closest to the supply nodes.

We assume that if feasible, a truck-train or a truck-barge transshipment takes 1 time period, and a train-barge transshipment takes 2 time periods. Transshipment costs are in this order 37.86, 40.17, and 54.62 respectively. Moreover, we assume that between a hub locations and a non-hub location, only truck service is available, and the other service types are available on the interhub part of the network. For the interhub part, we test a few forms including a complete network of all service types and a directed shuttle service network (e.g. Figure 7). In the base case, the interhub is a complete network of all assigned services.

Finally, in order to generate the set of orders, we designed an algorithm that first randomly picks an origin, a destination, and the order volume. Then, it randomly chooses the pickup and delivery time of the order by looking at the distances, travel times of different services available, the TTS, and the time that it takes to procure the needed empty RTIs and transport them to the origin, and

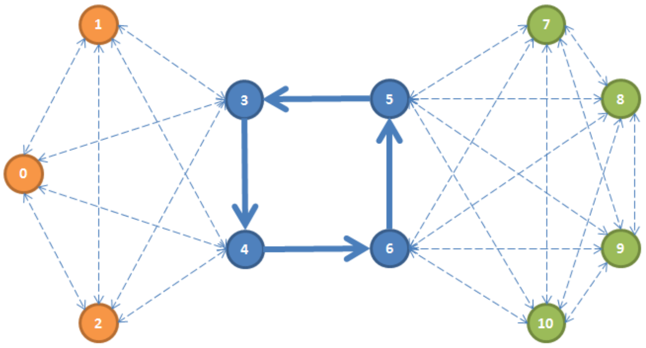


Figure 7: An example of a shuttle service on the inter-hub network among locations 3,4,5, and 6 in a 11-location instance

the time needed to reposition them. In the following sections, we give the computational results and provide some sensitivity analysis.

5.2 Computational Strengthening

The model presented in this paper can be reduced to the multi-commodity capacitated Service Network Design (SND) problems. SND problem is NP-hard [Magnanti and Wong, 1986], therefore, our model is at least as hard as an SND, and the number of variable and constraints can be more than one million in small instances. Keeping all the matrices can cost a huge amount of memory, therefore, we follow a couple of extra steps to decrease the memory consumption and speed up Gurobi.

For the first step, in the mode-space-network, we only generate the edges that are feasible based on the availability and the frequency of a service. In practice, not all services are available between pairs of locations and if they are, they do not operate every time period. Hence, we ignore all the other edges that never come in a solution.

Still, we deal with huge matrices of the parameters and variables which are extremely sparse. So, we use the so-called "colt"[1] library to replace the standard matrix format with a sparse one. After these modifications, we are able to solve relatively large instances.

5.3 Base Results

Tables 2, 3, and 4 shows the results for the base case. The columns of the tables present the total system costs (objective function), the optimality gap after one hour time limit, total number of edges used to transport full RTIs, total number of edges used for empty RTIs, number of used services (trucks, trains, barges) and computational time respectively.

Modifying the data structure, it is clear that the algorithm is fast. In 53% of all instance, we were able to find the optimal solution in less than 15 minutes and closed the optimality gap to less than 0.1% in an equal time. Despite replacing sparse matrices with the ordinary ones, in 10 instances out of 105, we ran out of memory. In smaller instance, we were able to solve instances with up to 70 orders, but in bigger instances, especially the ones with 3 service types, we cannot solve instances with 40 or 50 orders. Overall, the computational time depends not only on the number of orders, but also on the structure of the network and its density regarding the service arcs available. In addition, increasing the planning horizon alone does not bring any extra burden in the computational time.

Despite seeing consolidation of flows into trains and barges, since the delivery deadlines are tight and lateness is not allowed, trucks seem to be the most favorable means of transport. Even though the other service types are much cheaper, the solutions tend to deploy faster options.

Figure 8 shows that on average 58% of the time truck are used and their utilization is on average 97%. In contrast, trains and barges are used 29% and 25% of the time. However, their utilization is on average 35% and 5% respectively.

5.4 Practical Analysis

In this section, we test the sensitivity of the model to the change in parameters. In this regard, we manipulate the most important parameters like speed of services, costs of transshipment, and temperature of services. We also investigate the difference between a network with a shuttle interhub network and a complete interhub network. In order to keep the length of this section reasonable, we only implement the analysis on a sample of instances. These samples are n11m2t50oX, n11m3t50oX, n13m2t50oX, and n13m3t50oX. The reason is that their networks are big, but their interhub networks have different structures. Hence, we can examine how much assigned services change and whether the network structure influences this change or not.

---

[1] http://acs.lbl.gov/software/colt/

Table 2: Results for small-sized instance with truck and train service types

				Obj. Func.	**Gap** (%)	**Total full flow**	**Total empty flow**	**No. of Trucks**	**No. of Trains**	**Comp. Time (seconds)**
n8	m2	t50	o10	9765.831	0.01	211	10	56	5	one hour
n8	m2	t50	o20	21021.58	-	425	17	128	8	436.73
n8	m2	t50	o30	35138.21	-	692	15	209	9	93.05
n8	m2	t50	o40	43245.79	-	892	16	267	10	144.24
n8	m2	t50	o50	54039.10	-	1079	16	335	10	331.46
n8	m2	t75	o10	11439.74	-	211	12	64	10	176.44
n8	m2	t75	o20	24937.97	0.01	457	13	140	13	one hour
n8	m2	t75	o30	39562.33	-	668	20	216	15	897.89
n8	m2	t75	o40	50141.72	-	846	26	272	14	293.61
n8	m2	t75	o50	62131.40	-	1138	31	339	16	486.57
n8	m2	t90	o10	11522.70	0.03	226	14	69	10	one hour
n8	m2	t90	o20	28640.08	0.02	426	21	162	13	one hour
n8	m2	t90	o30	43994.63	-	707	18	240	16	837.69
n8	m2	t90	o40	60214.48	0.01	978	22	332	17	one hour
n8	m2	t90	o50	74944.44	0.01	1279	29	413	20	one hour
n10	m2	t50	o10	9532.80	0.01	209	13	56	6	one hour
n10	m2	t50	o20	20714.09	0.01	412	16	128	9	one hour
n10	m2	t50	o30	34532.86	-	659	22	209	10	141.67
n10	m2	t50	o40	42431.53	-	889	20	267	10	297.59
n10	m2	t50	o50	52978.18	-	1139	19	335	10	256.55
n10	m2	t75	o10	11156.38	0.02	180	14	64	11	one hour
n10	m2	t75	o20	24463.13	0.02	468	18	14	14	one hour
n10	m2	t75	o30	38779.44	0.01	708	23	216	16	one hour
n10	m2	t75	o40	49198.27	-	910	35	272	15	289.20
n10	m2	t75	o50	61156.03	-	1195	32	339	17	800.11
n10	m2	t90	o10	11292.08	0.03	230	14	69	11	one hour
n10	m2	t90	o20	28303.09	0.02	460	25	162	14	one hour
n10	m2	t90	o30	43550.26	0.01	700	20	240	16	one hour
n10	m2	t90	o40	59727.60	0.01	941	22	332	17	one hour
n10	m2	t90	o50	74351.14	0.01	1281	21	413	21	one hour

Table 3: Results for medium-sized instance with truck and train service types

				Obj. Func.	**Gap** (%)	**Total full flow**	**Total empty flow**	**No. of Trucks**	**No. of Trains**	**Comp. Time (seconds)**
n11	m2	t50	o10	16880.53	0.02	217	10	112	6	one hour
n11	m2	t50	o20	38587.51	-	517	16	248	7	674.19
n11	m2	t50	o30	60372.26	-	774	18	381	10	639.54
n11	m2	t50	o40	79492.43	0.02	962	23	499	12	one hour
n11	m2	t50	o50	97735.58	0.01	1195	28	614	13	one hour
n11	m2	t75	o10	17064.17	0.02	247	14	112	8	one hour
n11	m2	t75	o20	38310.47	0.02	535	20	248	11	one hour
n11	m2	t75	o30	59446.85	0.03	675	15	384	15	one hour
n11	m2	t75	o40	77790.85	0.03	1034	20	503	17	one hour
n11	m2	t75	o50	96059.38	0.02	1292	18	613	18	one hour
n11	m2	t90	o10	16966.72	0.02	258	14	116	9	one hour
n11	m2	t90	o20	38022.08	0.03	498	15	253	13	one hour
n11	m2	t90	o30	59178.72	0.04	738	17	386	16	one hour
n11	m2	t90	o40	78060.13	0.03	1007	18	501	18	one hour
n11	m2	t90	o50	-	-	-	-	-	-	out of memory
n13	m2	t50	o10	16886.53	-	206	14	113	11	363.46
n13	m2	t50	o20	38592.51	-	512	23	248	12	548.22
n13	m2	t50	o30	60379.26	0.02	741	25	381	17	one hour
n13	m2	t50	o40	79499.43	0.01	932	33	499	20	one hour
n13	m2	t50	o50	97743.58	0.02	1059	32	615	20	one hour
n13	m2	t75	o10	17070.17	0.03	238	18	112	14	one hour
n13	m2	t75	o20	38321.44	0.03	500	15	248	20	one hour
n13	m2	t75	o30	59457.85	0.02	709	20	384	25	one hour
n13	m2	t75	o40	77810.85	0.05	975	28	503	34	one hour
n13	m2	t75	o50	-	-	-	-	-	-	out of memory
n13	m2	t90	o10	16972.72	0.02	211	14	116	15	one hour
n13	m2	t90	o20	38034.08	0.03	518	15	254	23	one hour
n13	m2	t90	o30	59198.72	0.04	714	23	388	31	one hour
n13	m2	t90	o40	-	-	-	-	-	-	out of memory
n13	m2	t90	o50	-	-	-	-	-	-	out of memory

Table 4: Results for instance with truck, train, and barge service types

				Obj. Func.	**Gap** (%)	**Total full flow**	**Total empty flow**	**No. of Trucks**	**No. of Trains**	**No. of Barges**	**Comp. Time (seconds)**
n10	m3	t50	o10	8078.36	-	180	16	56	1	7	247.15
n10	m3	t50	o20	18169.16	-	400	22	128	1	10	554.19
n10	m3	t50	o30	30972.63	-	565	32	209	2	11	180.52
n10	m3	t50	o40	38615.95	-	805	24	267	2	12	134.81
n10	m3	t50	o50	48204.14	-	1045	26	336	2	13	202.81
n10	m3	t75	o10	9357.98	-	146	14	66	0	13	685.95
n10	m3	t75	o20	20453.73	-	301	19	141	0	19	432.22
n10	m3	t75	o30	32568.07	-	483	29	218	1	21	522.72
n10	m3	t75	o40	41568.95	-	648	33	274	1	24	196.04
n10	m3	t75	o50	52485.26	-	853	41	342	1	26	403.07
n10	m3	t90	o10	9560.84	0.04	177	20	69	1	11	one hour
n10	m3	t90	o20	24470.02	-	372	25	162	1	18	777.25
n10	m3	t90	o30	37830.25	0.01	571	29	240	1	19	one hour
n10	m3	t90	o40	-	-	-	-	-	-	-	out of memory
n10	m3	t90	o50	-	-	-	-	-	-	-	out of memory
n11	m3	t50	o10	14365.55	-	150	16	114	0	7	120.04
n11	m3	t50	o20	32970.05	0.01	344	18	250	0	10	one hour
n11	m3	t50	o30	51337.18	-	480	19	382	0	12	72.34
n11	m3	t50	o40	67705.44	-	648	30	499	0	14	100.03
n11	m3	t50	o50	83361.91	-	919	38	614	1	13	129.92
n11	m3	t75	o10	14461.48	0.02	136	17	114	0	11	one hour
n11	m3	t75	o20	32389.36	-	303	19	252	1	15	303.15
n11	m3	t75	o30	50244.11	-	470	25	387	2	19	541.03
n11	m3	t75	o40	65955.44	-	641	36	507	2	22	642.98
n11	m3	t75	o50	81259.00	-	737	39	616	2	23	276.43
n11	m3	t90	o10	14422.16	0.01	145	15	118	0	11	one hour
n11	m3	t90	o20	32223.96	-	328	25	254	0	18	653.14
n11	m3	t90	o30	50140.08	-	523	22	388	1	21	685.42
n11	m3	t90	o40	66271.47	-	748	29	504	1	24	819.601
n11	m3	t90	o50	-	-	-	-	-	-	-	out of memory
n13	m3	t50	o10	15247.85	-	136	15	114	6	6	43.44
n13	m3	t50	o20	35009.04	-	328	22	250	9	10	108.81
n13	m3	t50	o30	54650.09	-	484	25	384	13	13	101
n13	m3	t50	o40	71996.07	-	652	29	502	16	15	156.37
n13	m3	t50	o50	88693.52	-	844	33	616	16	16	196.40
n13	m3	t75	o10	15334.79	0.01	159	21	114	9	11	one hour
n13	m3	t75	o20	34367.26	-	306	23	253	11	15	169.21
n13	m3	t75	o30	53502.55	-	455	33	387	18	22	314.57
n13	m3	t75	o40	70296.59	0.01	596	31	507	21	26	one hour
n13	m3	t75	o50	-	-	-	-	-	-	-	out of memory
n13	m3	t90	o10	15301.33	-	179	22	118	10	12	170.79
n13	m3	t90	o20	34249.27	-	355	23	255	14	18	275.343
n13	m3	t90	o30	53344.31	-	492	37	390	18	22	511.94
n13	m3	t90	o40	-	-	-	-	-	-	-	out of memory
n13	m3	t90	o50	-	-	-	-	-	-	-	out of memory

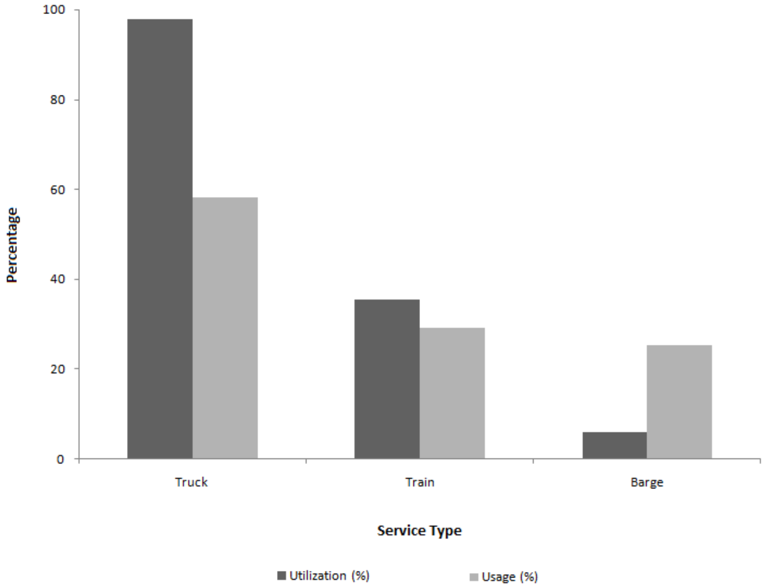


Figure 8: A comparison between the utilization of the services and the percentage of their deployment

Change of Speed of the Services

For the first sensitivity analysis, we change the speed of the services from $(56, 32, 14)$ to $(32, 32, 32)$. This means that trucks now have lower speed and barges have higher speed compared to the base case. Table 5 shows the changes in the results of this test compared to the base case.

First of all, it is clear that because of the tight deadline some of the generated orders had and the fact that no service is as fast as before, we see infeasibility happen.

The new results show around 50% increase in the costs, while the number of service vehicles have slightly decreased, even in barge services which in this test have higher speed. We can conclude that the increase cost is the result of the increase in the truck service times and the change of some routes.

Change of Transshipment Costs

There is a critical relationship between the travel costs and the transshipment costs. We changed the transshipment cost set from $(37.86, 40.17, 54.62)$ to $(67.86, 80.17, 94.62)$ to see the changes specifically in the arrangement of the fleet. Table 6 shows the results of this test.

We only see a reaction in instance n11m3t50oX. The results show about 16% increase in the costs which is due to the increase in the truck and barge services. In order to avoid transshipment, more transports occur. In addition, barges are more used because the cost of transporting by barges is still justifiable compared to transshipment costs.

The Shuttle Interhub Network

The base case has a complete network. In this section, we analyze the results on the networks with less accessibility. The new network contains a shuttle train service (Figure 9), the hub locations are no longer connected by truck services, and the non-hub locations have limited access to the other locations. The results are show in Table 7.

It is clear that the costs have increased because of lack of full access via truck services, and the increase in the travel time via train services. The number of trucks have not changed a lot since the non-hub locations can only access the hub nodes via truck services. The number of train and barge services in the three instance sets have increased, except the instances with 13 locations and 3 service

Table 5: A comparison of the results between the new speed regime and the base regime

	Change in Obj. Func. (%)	**Change in No. of Trucks**	**Change in No. of Trains**	**Change in No. of Barges**
n11 m2 t50 o10	49.06	1	0	N/A
n11 m2 t50 o20	49.64	0	0	N/A
n11 m2 t50 o30	49.35	0	1	N/A
n11 m2 t50 o40	infeasible	-	-	N/A
n11 m2 t50 o50	infeasible	-	-	N/A
n11 m3 t50 o10	56.56	-1	0	-1
n11 m3 t50 o20	57.04	-2	0	-3
n11 m3 t50 o30	56.97	0	0	-3
n11 m3 t50 o40	infeasible	-	-	-
n11 m3 t50 o50	infeasible	-	-	-
n13 m2 t50 o10	49.03	0	-1	N/A
n13 m2 t50 o20	49.63	1	0	N/A
n13 m2 t50 o30	49.35	1	0	N/A
n13 m2 t50 o40	infeasible	-	-	N/A
n13 m2 t50 o50	infeasible	-	-	N/A
n13 m3 t50 o10	53.56	-1	0	1
n13 m3 t50 o20	53.74	-2	-3	-1
n13 m3 t50 o30	53.28	0	-6	-4
n13 m3 t50 o40	infeasible	-	-	-
n13 m3 t50 o50	infeasible	-	-	-

Table 6: A comparison of the results between the new transshipment costs and the base costs

	Change in Obj. Func. (%)	**Change in No. of Trucks**	**Change in No. of Trains**	**Change in No. of Barges**
n11 m2 t50 o10	0.00	0	0	N/A
n11 m2 t50 o20	0.00	0	0	N/A
n11 m2 t50 o30	0.00	0	0	N/A
n11 m2 t50 o40	0.00	0	0	N/A
n11 m2 t50 o50	0.00	0	0	N/A
n11 m3 t50 o10	16.53	0	0	1
n11 m3 t50 o20	15.87	1	0	2
n11 m3 t50 o30	16.15	4	0	3
n11 m3 t50 o40	15.96	4	0	4
n11 m3 t50 o50	15.86	2	0	5
n13 m2 t50 o10	0.00	0	0	N/A
n13 m2 t50 o20	0.00	0	0	N/A
n13 m2 t50 o30	0.00	0	0	N/A
n13 m2 t50 o40	0.00	0	0	N/A
n13 m2 t50 o50	out of memory	-	-	N/A
n13 m3 t50 o10	0.00	0	0	0
n13 m3 t50 o20	0.00	0	0	0
n13 m3 t50 o30	0.00	0	0	0
n13 m3 t50 o40	0.00	0	0	0
n13 m3 t50 o50	0.00	0	0	0

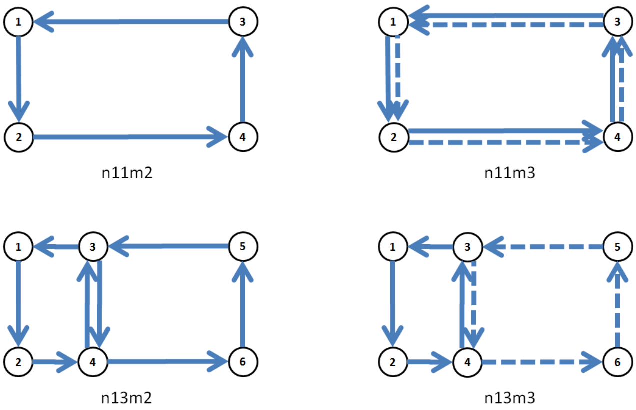


Figure 9: A comparison between the train and barge shuttle services of the four tested sets (full lines: train services, dashed lines: barge services)

Table 7: A comparison of the results between a shuttle service network with limited access to the hubs and the base case

	Change in Obj. Func. (%)	**Change in No. of Trucks**	**Change in No. of Trains**	**Change in No. of Barges**
n11 m2 t50 o10	2.89	1	2	N/A
n11 m2 t50 o20	3.41	0	2	N/A
n11 m2 t50 o30	3.14	0	1	N/A
n11 m2 t50 o40	3.03	-1	2	N/A
n11 m2 t50 o50	3.21	0	2	N/A
n11 m3 t50 o10	1.71	0	3	3
n11 m3 t50 o20	4.28	0	6	4
n11 m3 t50 o30	3.29	2	7	2
n11 m3 t50 o40	2.91	4	7	2
n11 m3 t50 o50	3.28	2	6	5
n13 m2 t50 o10	2.88	1	0	N/A
n13 m2 t50 o20	3.40	0	1	N/A
n13 m2 t50 o30	3.14	-1	0	N/A
n13 m2 t50 o40	3.03	0	0	N/A
n13 m2 t50 o50	3.21	-1	3	N/A
n13 m3 t50 o10	2.60	2	0	2
n13 m3 t50 o20	9.08	1	-1	-1
n13 m3 t50 o30	8.44	3	-4	-3
n13 m3 t50 o40	8.17	3	-5	-4
n13 m3 t50 o50	out of memory	-	-	-

types which have different train and barge shuttle services. Since the direct connections have been removed, the optimal solution contains the routes that fits the shuttle schedules of both trains and barges.

6 Conclusions

In this paper, inspired by the horticultural supply chain of the Netherlands, we developed a multimodal network flow problem for a perishable transportation system, taking quality preservation, transshipment, and asset management into account. This is the first research studying long-haul transportation of perishable products which contemplate the role of RTI allocation and repositioning in the optimal flow of products.

We tested our model on 105 different instances with different network size and structure, 2 or 3 service types and up to 50 randomly generated order sets. The computational tactics we used helped to decrease the time and memory issues with the huge matrices in the model. Despite the higher solving speed, the memory problem still exists and on a normal PC solving instances with 50 orders is almost impossible.

We also analyzed a few different scenarios to check the sensitivity of the results to the cost structure, speed and temperature of the services, and a new network structure with shuttle services. These analyses show that the solutions of such a multimodal network flow problem are notably dependent to its parameter setting.

In this paper, we assumed to have one RTI type, and we only plan for transportation of one product type. A future extension to this model is to include multiple type of RTI and their nesting relations. Another future extension is to plan for multiple product type, because some products are incompatible and need to be transported in compartments with different temperature regime. Furthermore, compared to reality with all the complexity involved, Gurobi is able to solve small to relatively medium instance sizes with simple structures. A fast and efficient heuristic is needed to solve more realistic sizes of instances with various constraints and factors. These research works are ongoing.

Acknowledgement

The study in this article has been supported by the DaVinc3i project with the reference number 2010.2.034R.

References

R. Agarwal and O. Ergun. Ship scheduling and network design for cargo routing in liner shipping. *Transportation Science*, 42(2):175–196, 2008.

O. Ahumada and J.R. Villalobos. A tactical model for planning the production and distribution of fresh produce. *Annals of Operations Research*, 190:339–358, 2011.

J. Andersen, T.G. Crainic, and M. Christiansen. Service network design with management and coordination of multiple fleets. *European Journal of Operational Research*, 193:377–389, 2009a.

J. Andersen, T.G. Crainic, and M. Christiansen. Service network design with asset management: Formulations and comparative analyses. *Transportation Research Part C*, 17:197–207, 2009b.

J. Andersen, M. Christiansen, T.G. Crainic, and R. Grønhaug. Branch and price for service network design with asset management constraints. *Transportation Science*, 45(1):33–49, 2011.

B. Bilgen and H.O. Gunther. Integrated production and distribution planning in the fast moving consumer goods industry: a block planning application. *OR Spectrum*, 32:927–955, 2010.

K. Braekers, A. Caris, and G.K. Janssens. Optimal shipping routes and vessel size for intermodal barge transport with empty container repositioning. *Computers in Industry*, 64:155–164, 2013.

H.K. Chen, C.F. Hsueh, and M.S. Chang. Production scheduling and vehicle routing with time windows for perishable food products. *Computers and Operations Research*, 36:2311–2319, 2009.

S.T. Choong, M.H. Cole, and E. Kutanoglu. Empty container management for intermodal transportation networks. *Transportation Research Part E*, 38:423–438, 2002.

U. Derigs, J. Gottlieb, J. Kalkoff, M. Piesche, F. Rothlauf, and U. Vogel. Vehicle routing with compartments: applications, modelling and heuristics. *OR Spectrum*, 35:885–914, 2011.

K.F. Doerner, M. Gronalt, R.F. Hartl, G. Kiechle, and M. Reimann. Exact and heuristic algorithms for the vehicle routing problem with multiple interdependent time windows. *Computers and Operations Research*, 35:3034–3048, 2008.

A.L. Erera, J.C. Morales, and M. Savelsbergh. Global intermodal tank container management for the chemical industry. *Transportation Research Part E*, 41(6):551–556, 2005.

P. Farahani, M. Grunow, and H.O. Gunther. Integrated production and distribution planning for perishable food products. *Flexible Services and Manufacturing Journal*, 24(1):28–51, 2012.

C.I. Hsu, S.F. Hung, and H.C. Li. Vehicle routing problem with time-windows for perishable food delivery. *Journal of Food Engineering*, 80:465–475, 2007.

X. Hu, Z. Wang, M. Huang, and A.Z. Zeng. A computer-enabled solution procedure for food wholesalers' distribution decision in cities with a circular transportation infrastructure. *Computers and Operations Research*, 36:2201–2209, 2009.

T.L. Magnanti and R.T. Wong. Network design and transportation planning: models and algorithms. *Transportation Science*, 18(1):1–55, 1986.

J.E. Mendoza, B. Castanier, C. Gueret, A.L. Madaglia, and N. Velasco. Constructive heuristics for the multicompartment vehicle routing problem with stochastic demands. *Transportation Science*, 45(3):346–363, 2011.

Q. Meng and S. Wang. Liner shipping service network design with empty container repositioning. *Transportation Research Part E*, 47:695–708, 2011.

L. Moccia, J.F. Cordeau, G. Laporte, S. Ropke, and M.P. Valentini. Modeling and solving a multimodal transportation problem with flexible time and scheduled services. *Networks*, 57(1):53–68, 2011.

A. Osvald and L.Z. Stirn. A vehicle routing algorithm for the distribution of fresh vegetables and similar perishable food. *Journal of Food Engineering*, 85:285–295, 2008.

M.B. Pedersen, T.G. Crainic, and O.B.G. Madsen. Models and tabu search metaheuristics for service network design with asset-balance requirements. *Transportation Science*, 43(2):158–177, 2009.

D.P. Song and J.X. Dong. Cargo routing and empty container repositioning in multiple shipping service routes. *Transportation Research Part B*, 46:1556–1575, 2012.

M. SteadieSeifi, N.P. Dellaert, W. Nuijten, T. Van Woensel, and R. Raoufi. Multimodal freight transportation planning: A literature review. *European Journal of Operational Research*, 233(1): 1–15, 2014.

C.D. Tarantilis and C.T. Kiranoudis. A meta-heuristic algorithm for the efficient distribution of perishable food. *Journal of Food Engineering*, 50:1–9, 2001.

C.D. Tarantilis and C.T. Kiranoudis. Distribution of fresh meat. *Journal of Food Engineering*, 51: 85–91, 2002.

H. Topaloglu. A parallelizable dynamic fleet management model with random travel times. *European Journal of Operational Research*, 175:782–805, 2006.

H. Topaloglu. A parallelizable and approximate dynamic programming-based dynamic fleet management model with random travel times and multiple vehicle types. In V. Zeimpekis, C.D. Tarantilis, G.M. Giaglis, and I. Minis, editors, *Dynamic Fleet Management*, volume 38 of *Operations Research/Computer Science Interfaces Series*, pages 65–93. 2007.

H. Topaloglu and W.B. Powell. A distributed decision-making structure for dynamic resource allocation using nonlinear functional approximations. *Operations Research*, 53(2):281–297, 2005.

H. Topaloglu and W.B. Powell. Dynamic-programming approximations for stochastic time-staged integer multicommodity-flow problems. *INFORMS Journal on Computing*, 18(1):31–42, 2006.

H. Topaloglu and W.B. Powell. Sensitivity analysis of a dynamic fleet management model using approximate dynamic programming. *Operations Research*, 55(2):319–331, 2007.

M. Yu and A. Nagurney. Competitive food supply chain networks with application to fresh produce. *European Journal of Operational Research*, 224:273–282, 2013.

E. Zhu, T.G. Crainic, and M. Gendreau. Scheduled service network design for freight rail transportation. Technical Report 38, CIRRELT, 2011.

Table 8: Summary of notations used in the first model

Indexes	
i', i''	Index for locations $1, \dots, \mathcal{N}$
$t', t'', \tilde{t}, \hat{t}$	Index for time periods $1, \dots, \mathcal{T}$
m', m''	Index for transportation service $1, \dots, \mathcal{M}$
i	Index representing the physical arc between terminal locations i' and i''
t	Index representing the time interval between t' and t''
g	Index representing the service operations (travel on one mode, if m' equals m'', and transshipment if not)
p	Index for order $1, \dots, \mathcal{P}$
Sets	
$\mathcal{V}$	Set of all locations
$\mathcal{N}^-(i')$	Set of all feasible service arcs entering location i'
$\mathcal{N}^+(i')$	Set of all feasible service arcs exiting location i'
$\mathcal{N}^-(t')$	Set of all feasible service arcs arriving at time t'
$\mathcal{N}^+(t')$	Set of all feasible service arcs leaving at time t'
$\mathcal{G}$	Set of all services, $\mathcal{G} = A(\mathcal{M} \times \mathcal{M})$
$\mathcal{G}_{m'}$	Set of all services operated by service m'
$\mathcal{G}_T$	Set of all transshipments, $\mathcal{G}_T = A_T(\mathcal{M} \times \mathcal{M})$
Model Inputs (Parameters)	
T	Total number of time periods during the planning horizon (e.g. 90 days in a season)
$\mathcal{P}$	Total number of orders
$\mathcal{M}$	Number of services
$\lvert F^{m'} \rvert$	maximum number of vehicles for each service m'
$S_{i'}$	Initial number of available empty RTIs at location i'
C^m	Fixed (administrative) cost of operating service m (per service, per hour service, or per Km service)
$C^{m'}_{full}$	Variable cost of moving full RTIs by service m' per time period
$C^{m'}_{empty}$	Variable cost of repositioning empty RTIs by service m' per time period
$C^T_{i'}$	Variable cost of transshipment between two services at location i'
$cap^{m'}$	Capacity of service m'
w_p	Demand (number of requested RTIs) for order p
$O(p)$	Origin terminal for order p
$D(p)$	Destination terminal for order p
$PT(p)$	The time that order p is available for pickup at $O(p)$
$DT(p)$	The latest delivery time for order p at terminal $D(p)$
$\mathcal{L}_p$	Vaselife of order p ($days \times temperature$)
$l^{m'}_{it}$	Temperature of service m' for traveling on physical arc i in time interval t
$l_{i't}$	Temperature inside location i' in time interval t
$s^{m'}_{it}$	Speed of service m' for traveling on physical arc i in time interval t
$dist_i$	Geographical length of arc i
$r^{m'}_{it}$	Travel time of service m' for traveling on physical arc i in time interval t
$r_{i't}$	Operation time inside location i' in time interval t
Variables	
x^g_{itp}	Nonnegative variable representing flow of full RTIs for order p, on service g on physical arc i in time interval t

$\bar{x}_{it}^{g}$	Nonnegative variable representing flow of empty RTIs on service g on physical arc i in time interval t
b_{itp}^{g}	Binary variable equal to 1, if flow of full RTIs for order p is traversed between locations i and j, by service g departing at time t, and 0, if not
$U_{i't'p}$	Real variable representing the demand (supply, if negative) of order p at location i' at time point t'
$\bar{U}_{i't'}$	Real variable representing the demand (supply, if negative) for empty RTIs at location i' at time point t'
y_{it}^{g}	Binary variable equal to 1, if physical arc i in time interval t is traversed by service g, and 0, if not

Working Papers Beta 2009 - 2014

nr.	Year	Title	Author(s)
442	2014	A multimodal network flow problem with product Quality preservation, transshipment, and asset management	Maryam SteadieSeifi, Nico Dellaert, Tom Van Woensel
441	2013	Integrating passenger and freight transportation: Model formulation and insights	Veaceslav Ghilas, Emrah Demir, Tom Van Woensel
440	2013	The Price of Payment Delay	K. van der Vliet, M.J. Reindorp, J.C. Fransoo
439	2013	On Characterization of the Core of Lane Covering Games via Dual Solutions	Behzad Hezarkhani, Marco Slikker, Tom van Woensel
438	2013	Destocking, the Bullwhip Effect, and the Credit Crisis: Empirical Modeling of Supply Chain Dynamics	Maximiliano Udenio, Jan C. Fransoo, Robert Peels
437	2013	Methodological support for business process Redesign in healthcare: a systematic literature review	Rob J.B. Vanwersch, Khurram Shahzad, Irene Vanderfeesten, Kris Vanhaecht, Paul Grefen, Liliane Pintelon, Jan Mendling, Geofridus G. Van Merode, Hajo A. Reijers
436	2013	Dynamics and equilibria under incremental Horizontal differentiation on the Salop circle	B. Vermeulen, J.A. La Poutré, A.G. de Kok
435	2013	Analyzing Conformance to Clinical Protocols Involving Advanced Synchronizations	Hui Yan, Pieter Van Gorp, Uzay Kaymak, Xudong Lu, Richard Vdovjak, Hendriks H.M. Korsten, Huilong Duan
434	2013	Models for Ambulance Planning on the Strategic and the Tactical Level	J. Theresia van Essen, Johann L. Hurink, Stefan Nickel, Melanie Reuter
433	2013	Mode Allocation and Scheduling of Inland Container Transportation: A Case-Study in the Netherlands	Stefano Fazi, Tom Van Woensel, Jan C. Fransoo
432	2013	Socially responsible transportation and lot sizing: Insights from multiobjective optimization	Yann Bouchery, Asma Ghaffari, Zied Jemai, Jan Fransoo

431	2013	Inventory routing for dynamic waste collection	Martijn Mes, Marco Schutten, Arturo Pérez Rivera
430	2013	Simulation and Logistics Optimization of an Integrated Emergency Post	N.J. Borgman, M.R.K. Mes, I.M.H. Vliegen, E.W. Hans
429	2013	Last Time Buy and Repair Decisions for Spare Parts	S. Behfard, M.C. van der Heijden, A. Al Hanbali, W.H.M. Zijm
428	2013	A Review of Recent Research on Green Road Freight Transportation	Emrah Demir, Tolga Bektas, Gilbert Laporte
427	2013	Typology of Repair Shops for Maintenance Spare Parts	M.A. Driessen, V.C.S. Wiers, G.J. van Houtum, W.D. Rustenburg
426	2013	A value network development model and Implications for innovation and production network management	B. Vermeulen, A.G. de Kok
425	2013	Single Vehicle Routing with Stochastic Demands: Approximate Dynamic Programming	C. Zhang, N.P. Dellaert, L. Zhao, T. Van Woensel, D. Sever
424	2013	Influence of Spillback Effect on Dynamic Shortest Path Problems with Travel-Time-Dependent Network Disruptions	Derya Sever, Nico Dellaert, Tom Van Woensel, Ton de Kok
423	2013	Dynamic Shortest Path Problem with Travel-Time-Dependent Stochastic Disruptions: Hybrid Approximate Dynamic Programming Algorithms with a Clustering Approach	Derya Sever, Lei Zhao, Nico Dellaert, Tom Van Woensel, Ton de Kok
422	2013	System-oriented inventory models for spare parts	R.J.I. Basten, G.J. van Houtum
421	2013	Lost Sales Inventory Models with Batch Ordering And Handling Costs	T. Van Woensel, N. Erkip, A. Curseu, J.C. Fransoo
420	2013	Response speed and the bullwhip	Maximiliano Udenio, Jan C. Fransoo, Eleni Vatamidou, Nico Dellaert

419	2013	Anticipatory Routing of Police Helicopters	Rick van Urk, Martijn R.K. Mes, Erwin W. Hans
418	2013	Supply Chain Finance: research challenges ahead	Kasper van der Vliet, Matthew J. Reindorp, Jan C. Fransoo
417	2013	Improving the Performance of Sorter Systems By Scheduling Inbound Containers	S.W.A. Haneyah, J.M.J. Schutten, K. Fikse
416	2013	Regional logistics land allocation policies: Stimulating spatial concentration of logistics firms	Frank P. van den Heuvel, Peter W. de Langen, Karel H. van Donselaar, Jan C. Fransoo
415	2013	The development of measures of process harmonization	Heidi L. Romero, Remco M. Dijkman, Paul W.P.J. Grefen, Arjan van Weele
414	2013	*BASE/X.* Business Agility through Cross-Organizational Service Engineering	Paul Grefen, Egon Lüftenegger, Eric van der Linden, Caren Weisleder
413	2013	The Time-Dependent Vehicle Routing Problem with Soft Time Windows and Stochastic Travel Times	Duygu Tas, Nico Dellaert, Tom van Woensel, Ton de Kok
412	2013	Clearing the Sky - Understanding SLA Elements in Cloud Computing	Marco Comuzzi, Guus Jacobs, Paul Grefen
411	2013	Approximations for the waiting time distribution In an *M/G/c* priority queue	A. Al Hanbali, E.M. Alvarez, M.C. van der van der Heijden
410	2013	To co-locate or not? Location decisions and logistics concentration areas	Frank P. van den Heuvel, Karel H. van Donselaar, Rob A.C.M. Broekmeulen, Jan C. Fransoo, Peter W. de Langen
409	2013	The Time-Dependent Pollution-Routing Problem	Anna Franceschetti, Dorothée Honhon,Tom van Woensel, Tolga Bektas, GilbertLaporte.
408	2013	Scheduling the scheduling task: A time Management perspective on scheduling	J.A. Larco, V. Wiers, J. Fransoo
407	2013	Clustering Clinical Departments for Wards to Achieve a Prespecified Blocking Probability	J. Theresia van Essen, Mark van Houdenhoven, Johann L. Hurink

406	2013	MyPHRMachines: Personal Health Desktops in the Cloud	Pieter Van Gorp, Marco Comuzzi
405	2013	Maximising the Value of Supply Chain Finance	Kasper van der Vliet, Matthew J. Reindorp, Jan C. Fransoo
404	2013	Reaching 50 million nanostores: retail distribution in emerging megacities	Edgar E. Blanco, Jan C. Fransoo
403	2013	A Vehicle Routing Problem with Flexible Time Windows	Duygu Tas, Ola Jabali, Tom van Woensel
402	2012	The Service Dominant Business Model: A Service Focused Conceptualization	Egon Lüftenegger, Marco Comuzzi, Paul Grefen, Caren Weisleder
401	2012	Relationship between freight accessibility and Logistics employment in US counties	Frank P. van den Heuvel, Liliana Rivera,Karel H. van Donselaar, Ad de Jong,Yossi Sheffi, Peter W. de Langen, Jan C.Fransoo
400	2012	A Condition-Based Maintenance Policy for Multi-Component Systems with a High Maintenance Setup Cost	Qiushi Zhu, Hao Peng, Geert-Jan van Houtum
399	2012	A flexible iterative improvement heuristic to Support creation of feasible shift rosters in Self-rostering	E. van der Veen, J.L. Hurink, J.M.J. Schutten, S.T. Uijland
398	2012	Scheduled Service Network Design with Synchronization and Transshipment Constraints For Intermodal Container Transportation Networks	K. Sharypova, T.G. Crainic, T. van Woensel, J.C. Fransoo
397	2012	Destocking, the bullwhip effect, and the credit Crisis: empirical modeling of supply chain Dynamics	Maximiliano Udenio, Jan C. Fransoo, Robert Peels
396	2012	Vehicle routing with restricted loading capacities	J. Gromicho, J.J. van Hoorn, A.L. Kok J.M.J. Schutten

395	2012	Service differentiation through selective lateral transshipments	E.M. Alvarez, M.C. van der Heijden, I.M.H. Vliegen, W.H.M. Zijm
394	2012	A Generalized Simulation Model of an Integrated Emergency Post	Martijn Mes, Manon Bruens
393	2012	Business Process Technology and the Cloud: Defining a Business Process Cloud Platform	Vasil Stoitsev, Paul Grefen
392	2012	Vehicle Routing with Soft Time Windows and Stochastic Travel Times: A Column Generation And Branch-and-Price Solution Approach	D. Tas, M. Gendreau, N. Dellaert, T. van Woensel, A.G. de Kok
391	2012	Improve OR-Schedule to Reduce Number of Required Beds	J.T. v. Essen, J.M. Bosch, E.W. Hans, M. v. Houdenhoven, J.L. Hurink
390	2012	How does development lead time affect performance over the ramp-up lifecycle?	Andres Pufall, Jan C. Fransoo, Ad de Jong
389	2012	Evidence from the consumer electronics industry	Andreas Pufall, Jan C. Fransoo, Ad de Jong, Ton de Kok
388	2012	The Impact of Product Complexity on Ramp-Up Performance	Frank P.v.d. Heuvel, Peter W.de Langen, Karel H. v. Donselaar, Jan C. Fransoo
387	2012	Co-location synergies: specialized versus diverse logistics concentration areas	Frank P.v.d. Heuvel, Peter W.de Langen, Karel H. v.Donselaar, Jan C. Fransoo
386	2012	Proximity matters: Synergies through co-location of logistics establishments	Frank P. v.d.Heuvel, Peter W.de Langen, Karel H.v. Donselaar, Jan C. Fransoo
385	2012	Spatial concentration and location dynamics in logistics:the case of a Dutch province	Zhiqiang Yan, Remco Dijkman, Paul Grefen
384	2012	FNet: An Index for Advanced Business Process Querying	W.R. Dalinghaus, P.M.E. Van Gorp

383	2012	Defining Various Pathway Terms	Egon Lüftenegger, Paul Grefen, Caren Weisleder
382	2012	The Service Dominant Strategy Canvas: Defining and Visualizing a Service Dominant Strategy through the Traditional Strategic Lens	Stefano Fazi, Tom van Woensel, Jan C. Fransoo
381	2012	A Stochastic Variable Size Bin Packing Problem With Time Constraints	K. Sharypova, T. van Woensel, J.C. Fransoo
380	2012	Coordination and Analysis of Barge Container Hinterland Networks	Frank P. van den Heuvel, Peter W. de Langen, Karel H. van Donselaar, Jan C. Fransoo
379	2012	Proximity matters: Synergies through co-location of logistics establishments	Heidi Romero, Remco Dijkman, Paul Grefen, Arjan van Weele
378	2012	A literature review in process harmonization: a conceptual framework	S.W.A. Haneya, J.M.J. Schutten, P.C. Schuur, W.H.M. Zijm
377	2012	A Generic Material Flow Control Model for Two Different Industries	H.G.H. Tiemessen, M. Fleischmann, G.J. van Houtum, J.A.E.E. van Nunen, E. Pratsini
375	2012	Improving the performance of sorter systems by scheduling inbound containers	Albert Douma, Martijn Mes
374	2012	Strategies for dynamic appointment making by container terminals	Pieter van Gorp, Marco Comuzzi
373	2012	MyPHRMachines: Lifelong Personal Health Records in the Cloud	E.M. Alvarez, M.C. van der Heijden, W.H.M. Zijm
372	2012	Service differentiation in spare parts supply through dedicated stocks	Frank Karsten, Rob Basten
371	2012	Spare parts inventory pooling: how to share the benefits	X.Lin, R.J.I. Basten, A.A. Kranenburg, G.J. van Houtum
370	2012	Condition based spare parts supply	Martijn Mes

369	2011	Using Simulation to Assess the Opportunities of Dynamic Waste Collection	J. Arts, S.D. Flapper, K. Vernooij
368	2011	Aggregate overhaul and supply chain planning for rotables	J.T. van Essen, J.L. Hurink, W. Hartholt, B.J. van den Akker
367	2011	Operating Room Rescheduling	Kristel M.R. Hoen, Tarkan Tan, Jan C. Fransoo, Geert-Jan van Houtum
366	2011	Switching Transport Modes to Meet Voluntary Carbon Emission Targets	Elisa Alvarez, Matthieu van der Heijden
365	2011	On two-echelon inventory systems with Poisson demand and lost sales	J.T. van Essen, E.W. Hans, J.L. Hurink, A. Oversberg
364	2011	Minimizing the Waiting Time for Emergency Surgery	Duygu Tas, Nico Dellaert, Tom van Woensel, Ton de Kok
363	2011	Vehicle Routing Problem with Stochastic Travel Times Including Soft Time Windows and Service Costs	Erhun Özkan, Geert-Jan van Houtum, Yasemin Serin
362	2011	A New Approximate Evaluation Method for Two-Echelon Inventory Systems with Emergency Shipments	Said Dabia, El-Ghazali Talbi, Tom Van Woensel, Ton de Kok
361	2011	Approximating Multi-Objective Time-Dependent Optimization Problems	Said Dabia, Stefan Röpke, Tom Van Woensel, Ton de Kok
360	2011	Branch and Cut and Price for the Time Dependent Vehicle Routing Problem with Time Window	A.G. Karaarslan, G.P. Kiesmüller, A.G. de Kok
359	2011	Analysis of an Assemble-to-Order System with Different Review Periods	Ahmad Al Hanbali, Matthieu van der Heijden
358	2011	Interval Availability Analysis of a Two-Echelon, Multi-Item System	Felipe Caro, Charles J. Corbett, Tarkan Tan, Rob Zuidwijk
357	2011	Carbon-Optimal and Carbon-Neutral Supply Chains	Sameh Haneyah, Henk Zijm, Marco Schutten, Peter Schuur
356	2011	Generic Planning and Control of Automated Material Handling Systems: Practical Requirements Versus Existing Theory	M. van der Heijden, B. Iskandar

355	2011	Last time buy decisions for products sold under warranty	Frank P. van den Heuvel, Peter W. de Langen, Karel H. van Donselaar, Jan C. Fransoo
354	2011	Spatial concentration and location dynamics in logistics: the case of a Dutch provence	Frank P. van den Heuvel, Peter W. de Langen, Karel H. van Donselaar, Jan C. Fransoo
353	2011	Identification of Employment Concentration Areas	Pieter van Gorp, Remco Dijkman
352	2011	BOMN 2.0 Execution Semantics Formalized as Graph Rewrite Rules: extended version	Frank Karsten, Marco Slikker, Geert-Jan van Houtum
351	2011	Resource pooling and cost allocation among independent service providers	E. Lüftenegger, S. Angelov, P. Grefen
350	2011	A Framework for Business Innovation Directions	Remco Dijkman, Irene Vanderfeesten, Hajo A. Reijers
349	2011	The Road to a Business Process Architecture: An Overview of Approaches and their Use	K.M.R. Hoen, T. Tan, J.C. Fransoo G.J. van Houtum
348	2011	Effect of carbon emission regulations on transport mode selection under stochastic demand	Murat Firat, Cor Hurkens
347	2011	An improved MIP-based combinatorial approach for a multi-skill workforce scheduling problem	R.J.I. Basten, M.C. van der Heijden, J.M.J. Schutten
346	2011	An approximate approach for the joint problem of level of repair analysis and spare parts stocking	R.J.I. Basten, M.C. van der Heijden, J.M.J. Schutten
345	2011	Joint optimization of level of repair analysis and spare parts stocks	Ton G. de Kok
344	2011	Inventory control with manufacturing lead time flexibility	Frank Karsten, Marco Slikker, Geert-Jan van Houtum
343	2011	Analysis of resource pooling games via a new extenstion of the Erlang loss function	Murat Firat, C.A.J. Hurkens, Gerhard J. Woeginger
342	2010	Vehicle refueling with limited resources	Bilge Atasoy, Refik Güllü, TarkanTan
341	2010	Optimal Inventory Policies with Non-stationary Supply Disruptions and Advance Supply Information	Kurtulus Baris Öner, Alan Scheller-Wolf Geert-Jan van Houtum

339	2010	Redundancy Optimization for Critical Components in High-Availability Capital Goods	Joachim Arts, Gudrun Kiesmüller
338	2010	Analysis of a two-echelon inventory system with two supply modes	Murat Firat, Gerhard J. Woeginger
335	2010	Analysis of the dial-a-ride problem of Hunsaker and Savelsbergh	Murat Firat, Cor Hurkens
334	2010	Attaining stability in multi-skill workforce scheduling	A.J.M.M. Weijters, J.T.S. Ribeiro
333	2010	Flexible Heuristics Miner (FHM)	P.T. Vanberkel, R.J. Boucherie, E.W. Hans, J.L. Hurink, W.A.M. van Lent, W.H. van Harten
332	2010	An exact approach for relating recovering surgical patient workload to the master surgical schedule	Peter T. Vanberkel, Richard J. Boucherie, Erwin W. Hans, Johann L. Hurink, Nelly Litvak
331	2010	Efficiency evaluation for pooling resources in health care	M.M. Jansen, A.G. de Kok, I.J.B.F. Adan
330	2010	The Effect of Workload Constraints in Mathematical Programming Models for Production Planning	Christian Howard, Ingrid Reijnen, Johan Marklund, Tarkan Tan
329	2010	Using pipeline information in a multi-echelon spare parts inventory system	H.G.H. Tiemessen, G.J. van Houtum
328	2010	Reducing costs of repairable spare parts supply systems via dynamic scheduling	F.P. van den Heuvel, P.W. de Langen, K.H. van Donselaar, J.C. Fransoo
327	2010	Identification of Employment Concentration and Specialization Areas: Theory and Application	Murat Firat, Cor Hurkens
326	2010	A combinatorial approach to multi-skill workforce scheduling	Murat Firat, Cor Hurkens, Alexandre Laugier
325	2010	Stability in multi-skill workforce scheduling	M.A. Driessen, J.J. Arts, G.J. v. Houtum, W.D. Rustenburg, B. Huisman
324	2010	Maintenance spare parts planning and control: A	

		framework for control and agenda for future research	R.J.I. Basten, G.J. van Houtum
323	2010	Near-optimal heuristics to set base stock levels in a two-echelon distribution network	M.C. van der Heijden, E.M. Alvarez, J.M.J. Schutten
322	2010	Inventory reduction in spare part networks by selective throughput time reduction	E.M. Alvarez, M.C. van der Heijden, W.H. Zijm
321	2010	The selective use of emergency shipments for service-contract differentiation	B. Walrave, K. v. Oorschot, A.G.L. Romme
320	2010	Heuristics for Multi-Item Two-Echelon Spare Parts Inventory Control Problem with Batch Ordering in the Central Warehouse	Nico Dellaert, Jully Jeunet.
319	2010	Preventing or escaping the suppression mechanism: intervention conditions	R. Seguel, R. Eshuis, P. Grefen.
318	2010	Hospital admission planning to optimize major resources utilization under uncertainty	Tom Van Woensel, Marshall L. Fisher, Jan C. Fransoo.
317	2010	Minimal Protocol Adaptors for Interacting Services	Lydie P.M. Smets, Geert-Jan van Houtum, Fred Langerak.
316	2010	Teaching Retail Operations in Business and Engineering Schools	
315	2010	Design for Availability: Creating Value for Manufacturers and Customers	Pieter van Gorp, Rik Eshuis.
314	2010	Transforming Process Models: executable rewrite rules versus a formalized Java program	Bob Walrave, Kim E. van Oorschot, A. Georges L. Romme
313		Getting trapped in the suppression of exploration: A simulation model	S. Dabia, T. van Woensel, A.G. de Kok
		A Dynamic Programming Approach to Multi-Objective Time-Dependent Capacitated Single Vehicle Routing Problems with Time Windows	
312	2010	Tales of a So(u)rcerer: Optimal Sourcing Decisions Under Alternative Capacitated Suppliers and General Cost Structures	Osman Alp, Tarkan Tan
311	2010	In-store replenishment procedures for perishable inventory in a retail environment with handling costs and storage constraints	R.A.C.M. Broekmeulen, C.H.M. Bakx
310	2010	The state of the art of innovation-driven business	E. Lüftenegger, S. Angelov, E. van der

		models in the financial services industry	Linden, P. Grefen
309	2010	Design of Complex Architectures Using a Three Dimension Approach: the CrossWork Case	R. Seguel, P. Grefen, R. Eshuis
308	2010	Effect of carbon emission regulations on transport mode selection in supply chains	K.M.R. Hoen, T. Tan, J.C. Fransoo, G.J. van Houtum
307	2010	Interaction between intelligent agent strategies for real-time transportation planning	Martijn Mes, Matthieu van der Heijden, Peter Schuur
306	2010	Internal Slackening Scoring Methods	Marco Slikker, Peter Borm, René van den Brink
305	2010	Vehicle Routing with Traffic Congestion and Drivers' Driving and Working Rules	A.L. Kok, E.W. Hans, J.M.J. Schutten, W.H.M. Zijm
304	2010	Practical extensions to the level of repair analysis	R.J.I. Basten, M.C. van der Heijden, J.M.J. Schutten
303	2010	Ocean Container Transport: An Underestimated and Critical Link in Global Supply Chain Performance	Jan C. Fransoo, Chung-Yee Lee
302	2010	Capacity reservation and utilization for a manufacturer with uncertain capacity and demand	Y. Boulaksil; J.C. Fransoo; T. Tan
300	2009	Spare parts inventory pooling games	F.J.P. Karsten; M. Slikker; G.J. van Houtum
299	2009	Capacity flexibility allocation in an outsourced supply chain with reservation	Y. Boulaksil, M. Grunow, J.C. Fransoo
298	2010	An optimal approach for the joint problem of level of repair analysis and spare parts stocking	R.J.I. Basten, M.C. van der Heijden, J.M.J. Schutten
297	2009	Responding to the Lehman Wave: Sales Forecasting and Supply Management during the Credit Crisis	Robert Peels, Maximiliano Udenio, Jan C. Fransoo, Marcel Wolfs, Tom Hendrikx
296	2009	An exact approach for relating recovering surgical patient workload to the master surgical schedule	Peter T. Vanberkel, Richard J. Boucherie, Erwin W. Hans, Johann L. Hurink, Wineke A.M. van Lent, Wim H. van Harten
295	2009	An iterative method for the simultaneous optimization of repair decisions and spare parts stocks	R.J.I. Basten, M.C. van der Heijden, J.M.J. Schutten
294	2009	Fujaba hits the Wall(-e)	Pieter van Gorp, Ruben Jubeh, Bernhard Grusie, Anne Keller
293	2009	Implementation of a Healthcare Process in Four Different Workflow Systems	R.S. Mans, W.M.P. van der Aalst, N.C. Russell, P.J.M. Bakker
292	2009	Business Process Model Repositories - Framework and Survey	Zhiqiang Yan, Remco Dijkman, Paul Grefen
291	2009	Efficient Optimization of the Dual-Index Policy Using Markov Chains	Joachim Arts, Marcel van Vuuren, Gudrun Kiesmuller
290	2009	Hierarchical Knowledge-Gradient for Sequential Sampling	Martijn R.K. Mes; Warren B. Powell; Peter I. Frazier
289	2009	Analyzing combined vehicle routing and break scheduling from a distributed decision making	C.M. Meyer; A.L. Kok; H. Kopfer; J.M.J. Schutten

		perspective	
288	2009	Anticipation of lead time performance in Supply Chain Operations Planning	Michiel Jansen; Ton G. de Kok; Jan C. Fransoo
287	2009	Inventory Models with Lateral Transshipments: A Review	Colin Paterson; Gudrun Kiesmuller; Ruud Teunter; Kevin Glazebrook
286	2009	Efficiency evaluation for pooling resources in health care	P.T. Vanberkel; R.J. Boucherie; E.W. Hans; J.L. Hurink; N. Litvak
285	2009	A Survey of Health Care Models that Encompass Multiple Departments	P.T. Vanberkel; R.J. Boucherie; E.W. Hans; J.L. Hurink; N. Litvak
284	2009	Supporting Process Control in Business Collaborations	S. Angelov; K. Vidyasankar; J. Vonk; P. Grefen
283	2009	Inventory Control with Partial Batch Ordering	O. Alp; W.T. Huh; T. Tan
282	2009	Translating Safe Petri Nets to Statecharts in a Structure-Preserving Way	R. Eshuis
281	2009	The link between product data model and process model	J.J.C.L. Vogelaar; H.A. Reijers
280	2009	Inventory planning for spare parts networks with delivery time requirements	I.C. Reijnen; T. Tan; G.J. van Houtum
279	2009	Co-Evolution of Demand and Supply under Competition	B. Vermeulen; A.G. de Kok
278	2010	Toward Meso-level Product-Market Network Indices for Strategic Product Selection and (Re)Design Guidelines over the Product Life-Cycle	B. Vermeulen, A.G. de Kok
277	2009	An Efficient Method to Construct Minimal Protocol Adaptors	R. Seguel, R. Eshuis, P. Grefen
276	2009	Coordinating Supply Chains: a Bilevel Programming Approach	Ton G. de Kok, Gabriella Muratore
275	2009	Inventory redistribution for fashion products under demand parameter update	G.P. Kiesmuller, S. Minner
274	2009	Comparing Markov chains: Combining aggregation and precedence relations applied to sets of states	A. Busic, I.M.H. Vliegen, A. Scheller-Wolf
273	2009	Separate tools or tool kits: an exploratory study of engineers' preferences	I.M.H. Vliegen, P.A.M. Kleingeld, G.J. van Houtum
272	2009	An Exact Solution Procedure for Multi-Item Two-Echelon Spare Parts Inventory Control Problem with Batch Ordering	Engin Topan, Z. Pelin Bayindir, Tarkan Tan
271	2009	Distributed Decision Making in Combined Vehicle Routing and Break Scheduling	C.M. Meyer, H. Kopfer, A.L. Kok, M. Schutten
270	2009	Dynamic Programming Algorithm for the Vehicle Routing Problem with Time Windows and EC Social Legislation	A.L. Kok, C.M. Meyer, H. Kopfer, J.M.J. Schutten
269	2009	Similarity of Business Process Models: Metics and Evaluation	Remco Dijkman, Marlon Dumas, Boudewijn van Dongen, Reina Kaarik,

			Jan Mendling
267	2009	Vehicle routing under time-dependent travel times: the impact of congestion avoidance	A.L. Kok, E.W. Hans, J.M.J. Schutten
266	2009	Restricted dynamic programming: a flexible framework for solving realistic VRPs	J. Gromicho; J.J. van Hoorn; A.L. Kok; J.M.J. Schutten;

Working Papers published before 2009 see: http://beta.ieis.tue.nl